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BALANCE OF ENERGY, WATER AND NUTRIENTS IN THE AQUAPONIC CYCLE

BILANCE ENERGIE, VODY A ŽIVIN V AQUAPONICKÉM CYKLU

MASTER'S THESIS

DIPLOMOVÁ PRÁCE

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Balance of energy, water and nutrients in the aquaponic cycle

Brief Description:

Aquaponics is a highly sustainable method of agriculture. It combines hydroponics and aquaculture, which is a method of growing plants without soil and fish farming. This technology is on the rise worldwide as well as in the Czech Republic. The primary benefits to Aquaponics are (1) low water and energy consumption, (2) minimum operating requirements: fish feed and small amounts of water, (3) little to no chemical usage, (4) A year–round production regardless of climate. A key requirement for successful aquaponic farming is to ensure the appropriate properties of all process streams (water, energy, nutrients) over time. Applications of process engineering expertise are desirable. The topic is announced in cooperation with an industrial partner.

Master's Thesis goals:

1. A literature review of the current knowledge in the field of aquaponic farming
2. Evaluation of energy and water balance of the selected farm
3. Data processing to assess the flow of nutrients in the aquaponic cycle
4. Design of a mathematical model describing changes in nutrient concentration
5. Assessment of the applicability of the algal bioreactor to the aquaponic cycle

Recommended bibliography:

Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future. New York, NY: Springer Berlin Heidelberg, 2019. ISBN 9783030159436.

COHEN, A., MALONE, S., MORRIS, Z., WEISSBURG, M., and BRAS, B. Combined Fish and Lettuce Culti-vation: An Aquaponics Life Cycle Assessment. Procedia CIRP, 69:551–556, 2018. ISSN 22128271.doi: 10.1016/j.procir.2017.11.029. URL https://linkinghub.elsevier.com/retrieve/pii/S2212827117307989.

ADDY, M. M., KABIR, F., ZHANG, R., LU, Q., DENG, X., CURRENT, D., GRITH, R., MA, Y., ZHOU, W.,CHEN, P., and RUAN, R. Co-cultivation of microalgae in aquaponic systems.BioresourceTechnology, 245:27–34, December 2017. ISSN 09608524. doi: 10.1016/j.biortech.2017.08.151.

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ABSTRACT

The motivation behind this thesis was to provide an overview of current scientific knowledge in the area of aquaponic food production, which would culminate in the creation of a mathematical model. Additionally, an experimental aquaponic farm was to be examined from the viewpoint of water and energy balance to provide real-world data for the creation of the mathematical model. Lastly, the applicability of algal photobioreactor in a general aquaponic cycle was to be assessed. The preliminary part of the work describes the motives behind the need for innovation in agriculture. The definition of aquaponics is provided along with a description of its subcomponents, their working mechanism and design. In this part of the thesis, the nutrient cycle of aquaponics is outlined as well. As the last part of the theoretical portion of the work, the implementation of algal photobioreactor into the aquaponic cycle is examined. Mechanisms both motivating and discouraging from such an implementation are described. Consequently, the reactor in and of itself is examined more closely. The process variables influencing the growth of algae are presented along with possible reactor designs, harvesting methods, and utilizations of the resulting products. In the first part of the experimental section of this work, the examined farm run by Flenexa plus s.r.o. is introduced from the viewpoint of the aquaponic process. Furthermore, the water and energy balances of implemented aquaponic process are provided and evaluated. The focus is then shifted towards the mathematical models which were created based on the knowledge and data gathered in the course of this work. The logic and algorithms behind both models are explained and discussed along with their main features and capabilities. Paths of future development for both models are also outlined in the closing section. Lastly, the findings obtained and gathered during the process of the thesis creation are discussed and summarized in the concluding chapters.

ROZŠÍŘENÝ ABSTRAKT

Předložená diplomová práce byla zpracována s cílem vytvořit přehled poznatků v oblasti akvaponické potravinové produkce. Informace získané během tvorby tohoto přehledu pak měly vést, v kombinaci s daty získanými z funkčního provozu, k vytvoření matematického modelu akvaponického cyklu. Na akvaponické farmě provozované společností Flenexa plus s.r.o., která byla zdrojem potřebných procesních dat, měla být dále zpracována a vyhodnocena bilance energie a vody. Nakonec měla být v průběhu práce posouzena možnost implementace mikrořasového fotobioreaktoru do akvaponického cyklu.

Úvod práce představuje motivaci vedoucí k potřebě inovovat dnešní potravinovou produkci. Kriticky jsou zhodnoceny predikce vývoje lidské populace, a to pak hlavně z pohledu dopadu, který by tento růst měl na zemědělskou produkci. Současná situace se na základě získaných poznatků ukazuje jako neudržitelná, primárně pak v oblastech vodohospodářství a energetické spotřeby. Následně je jako možné řešení vedoucí ke zlepšení udržitelnosti potravinové produkce zkoumána akvaponie. Akvaponie je definována a její jednotlivé komponenty jsou představeny z hlediska mechanismu jejich fungování a z pohledu jejich návrhu. Mezi popsané oblasti patří například principy tzv. *coupled* a *decoupled* akvaponie a popis možných typů hydroponického komponentu. V této části práce je pozornost věnována také představení cyklů jednotlivých živin v rámci akvaponie. Následující a poslední teoretická část práce je pak věnována mikrořasovému fotobioreaktoru. Jsou zde popsány mechanismy, jak motivující, tak odrazující od zakomponování bioreaktoru do akvaponie. V oblasti výhod se jedná hlavně o jeho roli ve stabilizaci pH a spotřebě toxikého amoniaku. Na druhou stranu jeho ekonomické dopady na profitabilitu akvaponie jsou velmi proměnlivé v závislosti na způsobu implementace. Samotný mikrořasový fotobioreaktor je pak v práci detailněji představen. Jednotlivé procesní ukazatele ovlivňující růst řas jsou rozebrány, a to společně s jednotlivými typy fotobioreaktoru, metodami sklizně a využitími pro vyprodukované mikrořasy. Na základě poznatků schromážděných v této práci pak lze jako nejvhodnější k implementaci do akvaponie doporučit hybridní fotobioreaktory, u kterých je většina osvětlení zajištěna v podobě slunečního svitu.

Samotná experimentální část práce pak začíná popisem zkoumaného provozu společnosti Flenexa plus s.r.o. z pohledu aplikovaného akvaponického procesu. Jednotka podrobená měření byla provozně stabilní a využívala implementace hydroponického komponentu typu *Deep Water Culture* (DWC). Spolu s detailním popisem celého provozu jsou poskytnuty a vyhodnoceny vypracované bilance vody a energií. Pozornost je pak přesunuta k matematickým modelům vypracovaným a ověřeným na základě dat a poznatků shromážděných z provozu společnosti Felenexa plus s.r.o. Logika a algoritmy, na kterých jsou oba modely postaveny, jsou v této části vysvětleny a diskutovány společně s hlavními funkcemi a schopnostmi obou modelů. První, primárně statistický model je představen jako nástroj pro použití při uvádění akvaponie do provozu. Druhý, fyzikální model pak v uživatelsky přívětivém formátu představuje základ pro model řízení akvaponické farmy s mikrořasovým fotobioreaktorem. V neposlední řadě jsou nastíněny také cesty možného budoucího vývoje pro oba vytvořené modely.

Práce je následně završena shrnutím a diskusí nad poznatky a výstupy získanými během celého tvůrčího procesu.

KEYWORDS

Aquaponics, aquaculture, hydroponics, food production, microalgae, photobioreactor, mathematical model, nutrients

KLÍČOVÁ SLOVA

Akvaponie, akvakultura, hydroponie, potravinová produkce, mikrořasy, fotobioreaktor, matematický model, živiny

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SIGNED DECLARATION

I, Matěj Szotkowski, hereby declare that this thesis entitled **Balance of energy, water, and nutrients in the aquaponic cycle**, is a product of my original work and was composed by myself under the supervision of doc. Ing. Vítězslav Máša Ph.D. All literature used in the research and creation of this work has been properly referenced.

In Brno 20/05/2021

……………………….…..

Matěj Szotkowski

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INTRODUCTION

The concept of aquaponics stands for a combination of hydroponics, soilless agricultural production method, and aquaculture, controlled farming of aquatic organisms [1]. The basic principle of all aquaponic units is the mutual existence of fish and plant root systems in a shared aquatic environment [2]. In theory, the sole input needed for such a system would be fish feed. After consumption and digestion, the waste products released to the water by fish would act as a fertilizer for planted crops. The nutrient uptake by plants would in turn keep the levels of pollutants in water in check [3]. Albeit novel and still largely untested in the commercial environment, this synthesis of hydroponics and aquaculture creates an efficient and controllable production method of both aquatic animals and chosen produce [1]. However, before proposing any untested approach to a problem, the practical need for such innovation must be assessed.

According to the United Nations (UN) report published in 2019, the global population is expected to grow from 7,7 billion in 2019 to somewhere between 9,4 and 10,1 billion in 2050 [4]. Not only is the growth still relatively high, but as seen in Fig. 1, it is also very localized with 1,05 billion, or 52 % of the total growth, happening in sub-Saharan Africa, and another 25 % in Central and Southern Asia [4]. Furthermore, as these already densely populated regions continue in their development, an additional rise in food consumption can be expected due to an increase in living standards [4]. In Europe and Northern America on the other hand, the population is expected to peak in 2042 and slowly decline thereafter.

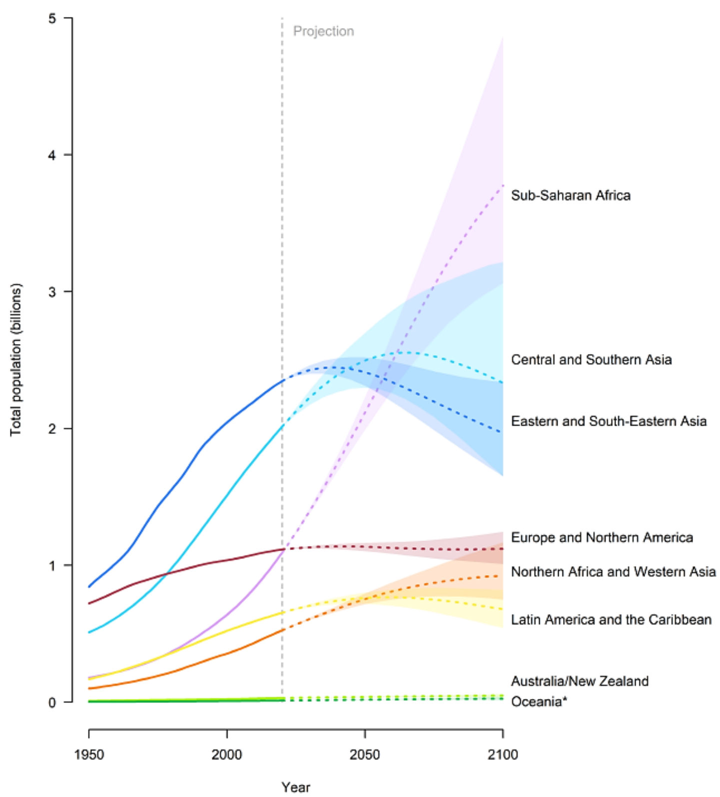


Fig. 1 Projections of global population development in different regions [4]
**(Australia and New Zealand excluded)*
(for license details see page 93)

The projections described in the UN report present the agricultural industry with an unprecedented challenge. In sub-Saharan Africa, Central, and Southern Asia it has to be able to provide relatively cheap produce while often battling poor soil conditions [5], [6], extreme weather [7] and underdeveloped infrastructure [8]. The conditions in Europe and Northern America, while in stark contrast with developing countries, are not without their difficulties. The workforce, mainly in Europe, is expected to continue shrinking, stressing the need for more extensive automation of agricultural processes [9], [10]. Furthermore, due to a trend of stricter environmental regulation, again mainly in Europe, greater emphasis on environmental impacts of all newly implemented technologies in the agricultural sector can be expected [11].

Conventional agriculture, as it is widely employed today, is the largest global consumer of water, accounting for 70 % of total withdrawal [12]. Moreover, conventional food production and its supply chain consume up to 30 % of the energy produced globally [12]. It is unrealistic to expect the agricultural industry to be able to accommodate the needs of additional 1,7 – 2,4 billion consumers without major environmental damage. On the other hand, it is also improbable for a single solution to emerge, which would be able to provide a solution to all the abovementioned problems and challenges. Certain guidelines for successful innovation can however be determined. Among these guidelines, one can expect to see applicability under a wide range of conditions, environmental sustainability, low pesticide and fertilizer use, high efficiency in terms of production and low labour intensity to name but a few.

Aquaponics shows some potential in mentioned categories. Namely, it can be realized both in enclosed conditions of industrial complexes with high-tech means, but also outdoors under improvised shelter using more low-tech methods [13] as seen in Fig. 2.

Fig. 2 Aquaponic unit in rural Indonesia [source: FAO]
(for license details see page 93)

The amount of water for irrigation is low [14], offering a key benefit for arid regions [6]. In the famine-stricken regions of sub-Saharan Africa, aquaponics could help farmers provide the local population with a more complete diet offering both crops and a source of protein from a single farm [1]. The practice of aquaponics can also be made very efficient with respect to land use [6].

By completely leaving out the soil from the crop's lifecycle, the practice becomes considerably more environmentally friendly. The improvement stems from the fact, that traditional agricultural methods with comparable production almost always lead to soil erosion [6], [15]. Furthermore, the use of pesticides and fertilizers can be limited significantly [14], and automation can be introduced more readily [16], again offering significant benefits in comparison with common agricultural methods.

It is important however to consider the demand for products of any proposed solution. No production method can become widely used unless there is a demand for its products. Examination of the status of fish consumption nowadays can be beneficial in this regard. Fish are already an important source of protein supplying more than 4,3 billion people with at least 15 % of their total animal protein intake [17]. In some, often poor regions of the world, fish can even be responsible for 50 – 60 % of total animal protein intake per capita [17]. Lately, there has been an argument for increased consumption of fish not only for their protein content but for the benefits they provide in a form of micronutrients or lipids. Being rich in LC-PUFAs (long-chain polyunsaturated fatty acids) and minerals such as calcium, phosphorus, iodine and zinc, fish can have a beneficial effect on the development and health of both children and adults [17]. Consuming fish can protect an adult against high blood pressure, stroke, and coronary heart disease [17]. These findings are one of many reasons why fish consumption is growing more rapidly than that of any other animal protein, with the exemption of poultry [18]. As can be seen in Fig. 3, fish consumption per capita has risen by nearly 53 % since 1995 (from 13,4 kg in 1995 to about 20,5 kg in 2018 [18]).

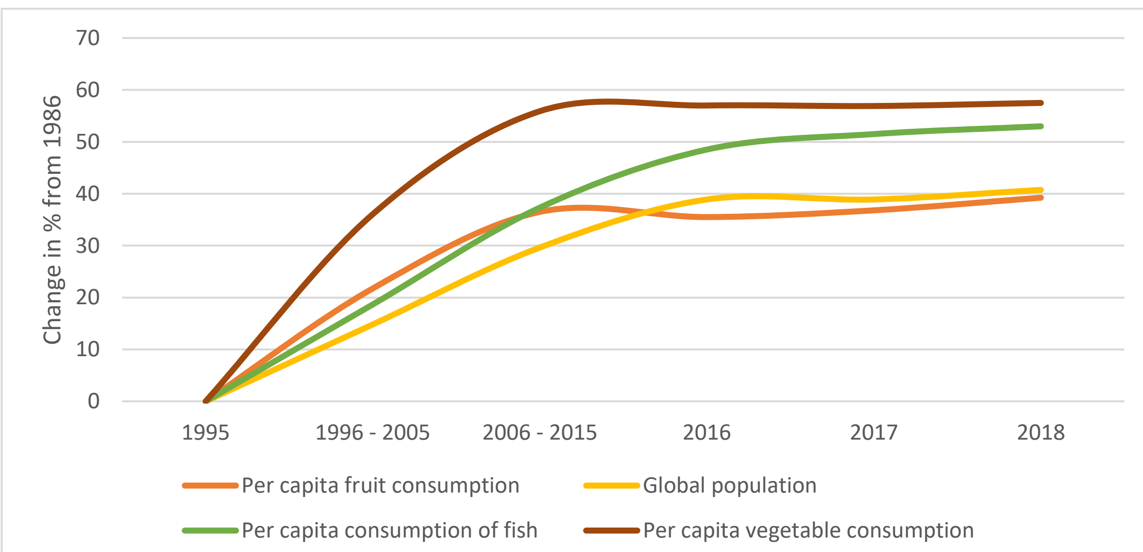


Fig. 3 Rate of change in per capita fish, fruit, and vegetable consumption – a broader perspective [18], [19], [20]
(for license details see page 93)

It seems therefore that fish represent a solid choice of dietary protein for a farmer to produce. They are already integrated into the diets of developing nations and are more and more sought after in the developed world for their perceived complex dietary value [18]. With regards to the crops produced by aquaponic farming, if the plant species is chosen correctly for a given market, there is no rational concern for the market not to demand it. As seen in Fig. 3, both consumptions of fresh fruit and vegetables have risen globally by almost 40 and 57 % respectively since 1995 [19], [20] further illustrating the market demand for products of an aquaponic production system.

Promising as it may be, aquaponics is still in its infancy, and research is needed to attain more comprehensive knowledge about the practice [1]. Aquaponics, being a system comprised of hydroponics and aquaculture, has consequently relatively high complexity and various interactions between both subsystems must be considered. The accurate mathematical model of the aquaponic system could therefore be of a substantial value. Allowing not only for a better understanding of the system, the model could also reveal several areas where greater efficiency, usability or sustainability could be achieved. Moreover, a complete understanding of the aquaponic process would reduce the amount of expertise needed for the successful operation of such a process. The existence of a working model could consequently hasten the implementation of aquaponics outside academia and could bring the technology to a wider audience of potential investors.

It was mentioned in the previous paragraph, that an accurate mathematical model could reveal areas within aquaponics with potential for improvements. It must be stated then, that one such area has already been discovered by earlier examinations of the aquaponic cycle in practical applications. The area being the stability problem arising from fluctuating numbers of plants in the hydroponic sector [21]. The ability of some plants to maintain clean water for fish is already a topic of debate [21]. Self-sustaining aquaponic systems often require large areas for their hydroponic subsystem due to the low nutrient uptake from some plants [22]. It would therefore be beneficial to introduce a way of boosting nutrient uptake from water in instances when the ability of plants is not satisfactory. A period right after harvest when the number of plants is reduced can serve as an example of such a situation. One way to boost nutrient uptake is the integration of an algal bioreactor (similar to that seen in Fig. 4 [23]) into the aquaponic system [21]. Such an introduction done in the right manner could improve the stability of the aquaponic system while providing the farmer with the added benefits of algal biomass production [21]. This biomass could afterwards be used as a fish feed lowering the operational costs, or it could be used as an additional marketable product raising revenues from the business.

Fig. 4 Closed algal photobioreactor [23]
(for license details see page 93)

The following text is going to provide a brief introduction to the concept of aquaponics, covering the basic principles and various types of aquaponic units along with their properties. The nutrient cycle of an aquaponic system is going to be discussed as well. The topic of agal bioreactor implementation into aquaponics will be covered from the perspective of nutrition management and reactor design. The farm examined in the experimental part of the work is going to be introduced and the results of the measurements conducted on this farm are going to be presented. Finally, created mathematical models of an aquaponic system are to be addressed and thoroughly introduced. The work is closed with a discussion of results and a conclusion.

1. State of the knowledge in aquaponics

This part of the text is going to introduce aquaponics as a synthesis of aquaculture and hydroponics. Both the main components are going to be examined from the viewpoint of possible improvements and difficulties arising from their unification into aquaponics. Main design approaches to both aquaculture and hydroponics are going to be covered as well. Additionally, other components of aquaponics will be addressed along with the cycles of main nutrients in the system. Lastly, the chapter concludes with an introduction to coupled and decoupled aquaponics.

1.1 About aquaponics

Aquaponics as a concept stands for a synergistic combination of aquaculture and hydroponics allowing for simultaneous production of plants and fish from a single farm [14]. An example of an aquaponic unit can be seen in Fig. 5 [24].

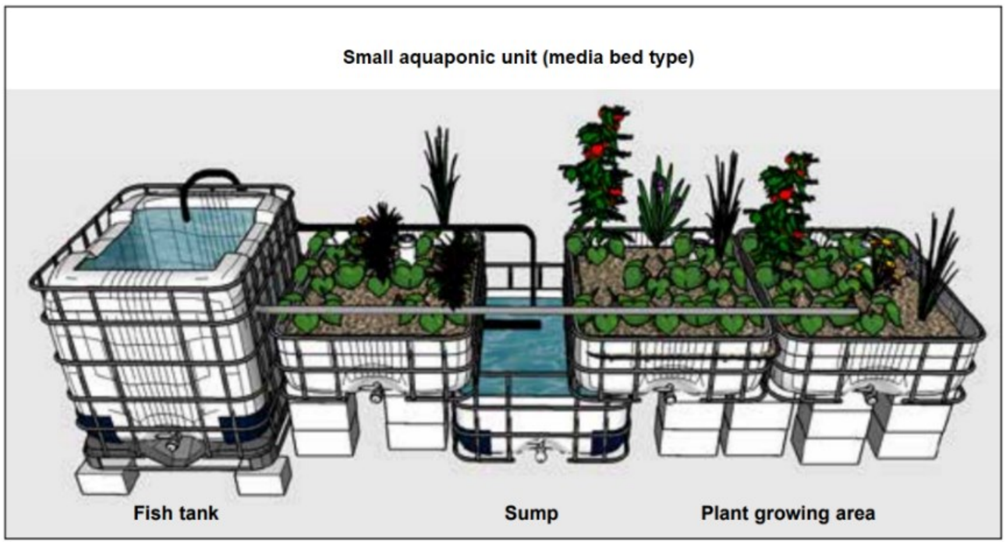


Fig. 5 Illustration of small, low-tech aquaponic unit (media bed type) [24]
(for license details see page 93)

The term aquaculture as defined by FAO (Food and Agriculture Organization of the United Nations) [25] represents the farming of aquatic organisms, including fish, molluscs, crustaceans, and aquatic plants. Hydroponics, on the other hand, is defined as a production of plants in a soilless medium where all required nutrients are supplied in a form of an aqueous solution [26]. Aquaponics is therefore a system where fish production (aquaculture subsystem) is coupled with plant production (hydroponic subsystem) and both systems use a shared water circulation network.

Aquaponics aims to integrate both aquaculture and hydroponics in a mutually beneficial way. In short, it is a classic case of process integration, which turns waste streams of one system into the input stream of another while improving the efficiency of each implemented subsystem. In the case of aquaponics, the efficiency is improved in connection with both nutrients and water use.

Nutrients enter the aquaponic system mainly in the form of fish feed, which is in turn metabolized by fish. The resulting effluent is then transformed by bacterial colonies into a viable source of nutrients for plant growth. The need for additional supplementation of nutrients by fertilizers, which is a requirement for any hydroponic system, is therefore substantially reduced when integrated into aquaponics, fulfilling the promise of process integration – greater efficiency [27].

The efficiency is further improved by the reduction of necessary daily water input. Absorption of previously discussed nutrients by plants remedies water circulating in the aquaponic system allowing for it to be continually reused [2]. This practice lowers the requirements for daily water inputs to only about 2 – 3 % [28] (or 0,3 – 5 % depending on the source [2]) of total system volume compared to 5 – 10 % required in conventional aquaculture [29]. The need for a water input in aquaponics is mainly caused by water evaporation from free surfaces and evapotranspiration of plants [28].

Aquaponics seems to turn deficiencies of its subsystems into strengths promising a more efficient and environmentally sustainable production. However, this implementation of aquaculture and hydroponics does not come without its drawbacks which are going to be discussed later in the text.

1.2 AQUACULTURE

Aquaculture is defined by FAO as a farming of aquatic organisms, including fish, molluscs, and crustaceans [30]. Farming practically implies some form of intervention during the rearing process, for example, feeding, protection from predators, and regular stocking [30]. All these activities are aimed at enhancing production. The aquaculture then allows its operator to produce large quantities of fish from a relatively small volume of water [3].

As can be seen in Fig. 6 [18], the practice of aquaculture is already widely used, and in 2018 was responsible for 46 % of world fish production [18]. It is also evident, that the share of aquaculture in total fish production is steadily growing. The average yearly growth between 2001 and 2018 was 5,3 % [18]. The main reason for the success of aquaculture was the ability to satisfy the market demand for fish which could no longer be met purely by wild fisheries [31]. The number of fish caught has remained relatively stagnant since the 1990s (as also seen in Fig. 6), the world population and consequently demand for fish on the other hand steadily rose in that period [4]. It is reasonable to suspect further growth of aquaculture fish production along with the global population. It is quite important therefore to address the efficiency and environmental problems connect with this production practice.

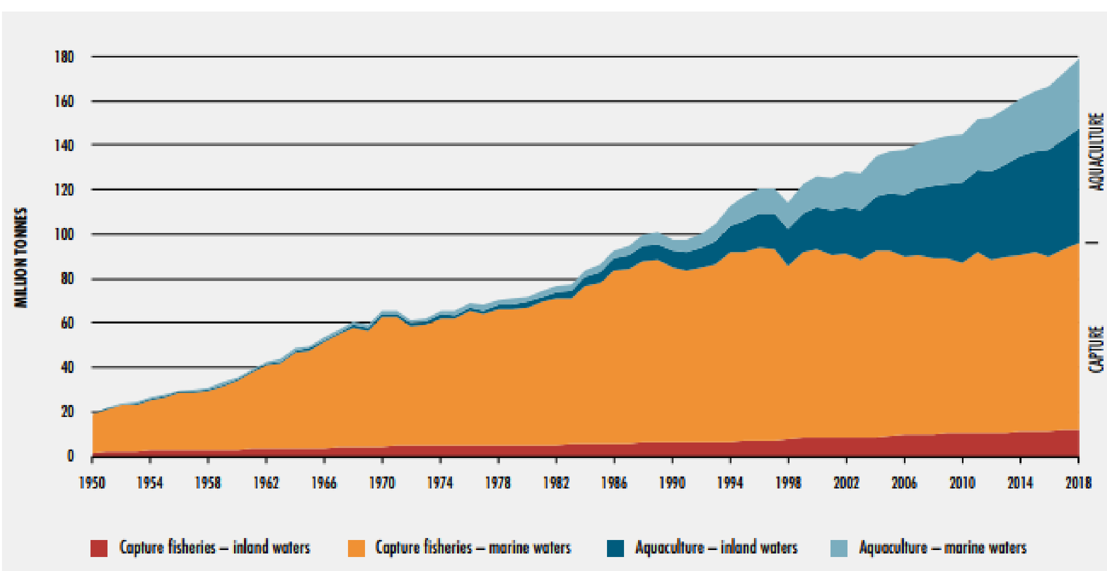


Fig. 6 Shares of various global fish production methods [18]
(for license details see page 93)

To achieve such high productivity, aquaculture must be widely applicable and has therefore branched out into different areas of fish production. More than 600 individual species have been successfully farmed using aquaculture [32]. There are numerous types of aquaculture farms being employed all around the world, they can be operated using both low-tech and high-tech means, either inland or offshore [32]. A non-exhaustive list of possible types of aquaculture production units follows.

1. Rice field aquaculture, example in Fig. 7, is one of the oldest types of aquaculture farming, developed in seasonally flooded river deltas in Asia. Production is typically extensive with lower yields per unit area. The practice can be labelled as self-sustained, not reliant on nutrient supplementation or additional energy inputs [28]. The process is often highly integrated with surrounding production. Rice field aquaculture has therefore only a minor environmental impact [32].

Fig. 7 Rice field aquaculture in Indonesia [FAO/A. Stankus]
(for license details see page 93)

2. Aquaculture ponds (example in Fig. 8), are natural or artificial, closed water bodies mainly filled with fresh or brackish water. The production can be characterized as semi-intensive and stocking densities are comparatively large [32]. Nutrients must be externally supplemented, but oftentimes they are provided in a form of leftovers from local food industries or as cheap pellets [13]. The food management is consequently not optimized to achieve desired feed to fish conversion efficiency [13]. On the other hand, thanks to a higher degree of integration with surrounding agricultural production systems, the practice can be classified as relatively environmentally friendly [28]. This is further improved with the use of rainwater as the main source for necessary water exchange [13]. Furthermore, depending on the legal environment, the utilization of extracted sludge (uneaten feed and dejections) on local farms as manure is also practised [13].

Fig. 8 Pond aquaculture in Kigali, Rwanda [FAO/Menezes]
(for license details see page 93)

3. Cages or net pens, for example in Fig. 9 [33], are suspended artificial enclosures located in natural aquatic systems such as lakes, rivers, or oceans. Production can be characterized as intensive, with high stocking densities and large amounts of nutrient supplementation. Systems are thus completely dependent on external inputs [32]. Environmental impacts of discussed practice vary. When located in lakes, rivers, and coastal areas, the practice can be damaging, introducing pollutants into often sensitive regions [34]. Problems are reduced when locations further from shore are used. However, usage of these locations relates to increased costs stemming from complicated cage design due to higher exposure to elements, complex logistics and overall high initial investment [34]. Another characteristic of systems employing cages are problems with parasites and diseases arising from interactions with surrounding open natural environment [35]. Vaccination or other means of parasite/disease control such as selective breeding to enhance resistance must therefore be employed [35].

Fig. 9 An experimental version of an offshore towed fish cage with automatic feeding [33]
(for license details see page 93)

4. Raceways/tanks with running water (RAS – recirculating aquatic system), for example in Fig. 10 [36] are completely artificial constructed units. RAS is characterized by hyper-intensive production and complete reliance on feed supplements. The system is therefore highly optimized for maximal production, but also highly resource and energy-demanding [32].

Fig. 10 An indoor recirculating aquaculture system [36]
(for license details see page 93)

Among all types of aquaculture production units, RAS is usually the choice for inclusion into aquaponic systems. Therefore, the environmental impacts of RAS are going to be further discussed in the next chapter.

1.2.1 Aquaculture as a part of an aquaponic system

With the increasing intensity of production, associated environmental risks are also growing. Intensive and hyper-intensive methods of production, such as RAS, are less interconnected with surrounding agricultural activities and are therefore both more resource and energy-demanding when compared to semi-intensive or extensive methods. Thus, it would be useful to examine the overall efficiency of fish production more closely and consider possible improvements in areas of influence.

One of the widely used ways to assess the efficiency of animal production is with the use of feed conversion ratio (FCR). An indicator that expresses how much feed is needed for a kilogram of total weight gain in a particular species [37]. Generally, fish have comparatively good (low) feed conversion ratios, as can be seen in Fig. 11 [37].

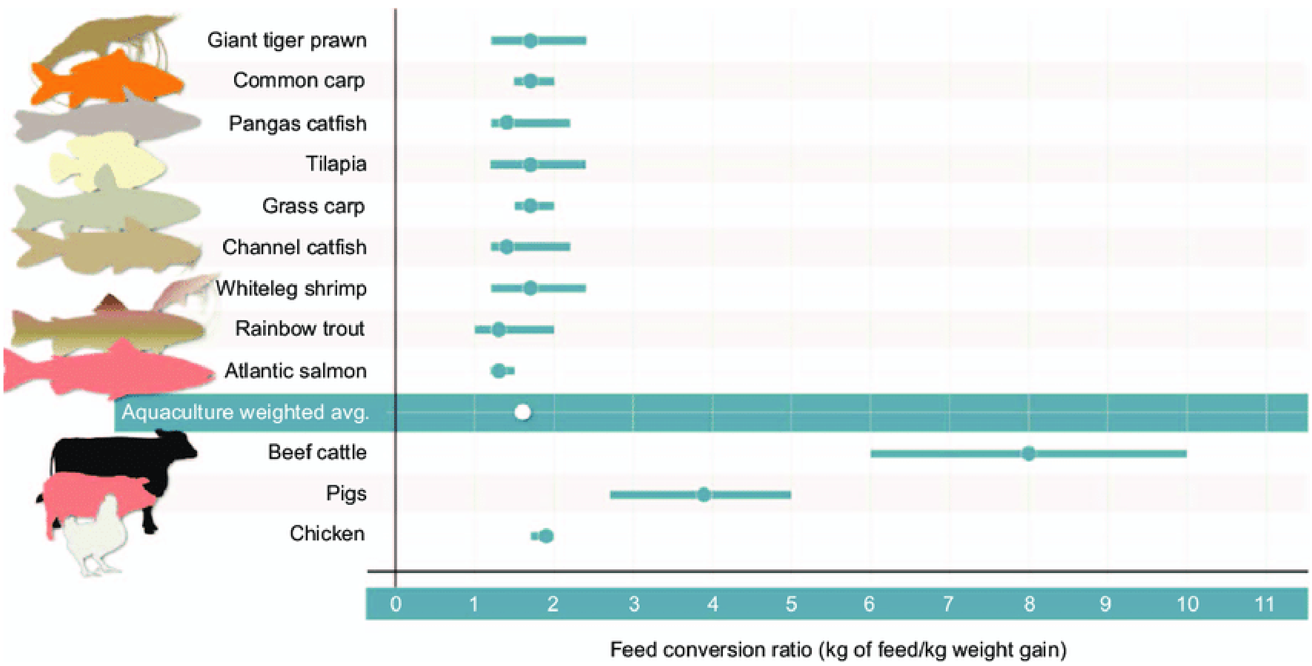


Fig. 11 Feed conversion ratios for selected aquatic and terrestrial farmed animal species (Dots represent sample means and bars represent standard deviations. Lower values signify higher efficiency.) [37]

(for license details see page 93)

The FCR however is not an all-encompassing indicator of efficiency, since it omits two impactful factors: 1. how resource demanding feed individual species requires (measured in terms of feed protein content) and 2. how much of the weight gained for each species corresponds to a marketable and consumable mass [37]. In both areas, fish are comparatively ineffective – they require high amounts of expensive and resource-demanding protein in their diet, while also only a relatively small portion of gained weight is in a consumable form (for some species only about a third) [37].

To compare fish production with other terrestrial species, indicators such as protein and calorie retention defined by the following equations [37] are more suitable.

$$\boldsymbol{PR}\,[\%] = \frac{\omega_{edible\,part}[-] \cdot \omega_{protein\,in\,edible\,part}[-]}{FCR[-] \cdot \omega_{protein\,in\,feed}[-]} \cdot 100$$

Eq. 1 Protein retention (PR) [37]

$$\boldsymbol{CR}\,[\%] = \frac{\omega_{edible\,part}[-] \cdot \rho_{calories\,in\,edible\,part}[\frac{kcal}{g}]}{FCR[-] \cdot \rho_{calories\,in\,feed.}[\frac{kcal}{g}]} \cdot 100$$

Eq. 2 Calorie retention (CR) [37]

Fig. 12 then illustrates how these indicators show a much more balanced situation when it comes to animal production efficiency across multiple species [37].

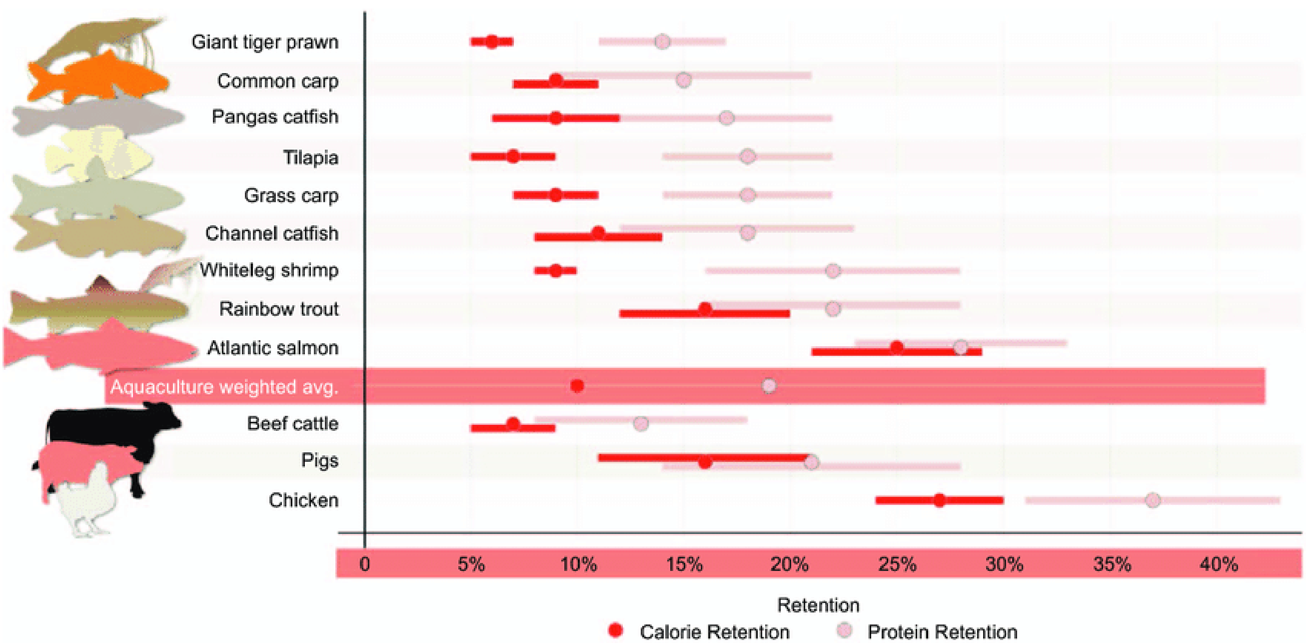


Fig. 12 Protein and calorie retention for selected aquatic and terrestrial farmed animal species (Dots represent sample means and bars represent standard deviations. Higher values indicate more efficient retention.) [37]

(for license details see page 93)

In a production system, when considering its efficiency, waste streams must also be considered. As illustrated in the previous figure, fish are quite ineffective when it comes to nutrient retention. Sizeable waste streams can therefore be expected in fish production.

In the case of RAS (or generally any aquaculture system) the central problem in waste management is the main metabolic waste product of fish – ammonia – which they release into the surrounding environment. To maintain the levels of ammonia for the aquatic environment not to become toxic for fish, the water in the RAS system must be exchanged at a rate of 5 – 10 % of the total system water volume per day [29]. This fact is problematic firstly because of the stress created on natural water supplies, potentially leading to environmental damage. Large quantities of freshwater required to support aquaculture systems also limit the applicability of the practice only to regions with a sufficient source of freshwater. The second problem stemming from large volumes of exchanged water is the low efficiency of such practice from the viewpoint of economics.

Fish convert only about 25 % of all nitrogen contained in fish feed to tissue. The remaining 75 % of nitrogen are released to the surrounding aquatic environment as metabolic waste [29]. Since fish feed represents 50 – 70 % of total fish production costs in aquaculture, such low conversion efficiency to marketable mass should be addressed [29].

Based on Eq. 1 and Eq. 2 presented on the previous page, it could be stated, that the efficiency of species in terms of protein and calorie retention cannot be influenced. This however would be an incorrect conclusion from the viewpoint of process integration. The nutritional value of uneaten or metabolically unused feed is not lost and can be viewed as a potential input. This input could be effectively used thru the inclusion of aquaculture into aquaponics. In aquaponics the efficiency of aquaculture is improved in multiple ways: 1. the use of the nutritional (and consequently monetary) value of fish feed is maximized due to its contribution to plant growth, 2. the use of fresh-water reserves is minimized thanks to the plant (and possibly algal) nutrient uptake serving to remedy the process water.

Fish produced in aquaponics can therefore be viewed as more environmentally and economically effective.

1.2.2 Aquaculture subsystem - design

Integration of an aquaculture subsystem is usually realized in a form of a RAS. Overall, the topic of RAS design is very well described in the work of Somerville Ch. et al. [24], and this chapter is largely based on information provided in their cited publication.

Configurations similar to one presented in Fig. 10 are regularly used and they allow the operator to accommodate multiple fish species or fish in different stages of development [38]. Tanks are designed mostly in a round or oval shape to allow for uniform water circulation, which eliminates any presence of potentially dangerous anoxic spots in the water column. Centripetal force present in a round-shaped fish tank ensures effective settling of the solid waste at the centre of the bottom of the tank, where it can be easily removed. Uses of square or non-geometrically shaped tanks are possible but often require a more active approach concerning waste removal. Furthermore, additional use of air and water pumps to maintain proper water circulation, as well as sufficient levels of dissolved oxygen, is often needed. Round or oval tanks are therefore the most effective design choice in both economic and productivity terms, apart from special cases where fish tank area or aesthetics of the aquaponic unit are of concern. Lastly, the depth of the tanks should be considered along with their volume, since some fish species require a certain height of a water column to prosper [24].

When it comes to a material selection for a fish tank, either inert plastic (UV-resistant, food-grade LDPE for example) or fibreglass are preferable due to their durability, comparatively low investment demands, and long lifespan. In some markets, cement or plastic-lined natural ponds can offer a more economically feasible alternative, but plumbing should be carefully considered since it can be a major problem. Both steel and natural ponds without lining are not usually considered due to high initial costs and possible rust issues (steel tanks) or nutrient management problems due to bacterial colonies present in soil (natural ponds).

Finally, if the aquaponic production system is located in an open or semi-open environment, the colour, and shading (or covers) of the tanks should be considered. White tanks are beneficial due to their ability to provide a certain level of thermal insulation as well as allow the operator to inspect the behaviour of fish more easily (better visibility inside of the tank). Tank covers also contribute towards thermal insulation but also minimize evaporative water loss and the risk of tank contamination by external elements [24].

1.3 HYDROPONICS

Hydroponics represents a type of soilless agricultural crop production method. The adjective soilless indicates that soil is not utilized during the crop's life cycle in any way [24]. Instead, for support and water retention, hydroponics either uses different growing media (volcanic gravel, limestone gravel, light expanded clay aggregate, coconut fibre, recycled plastic etc.), typically referred to as a substrate, or plants can be directly grown in an aqueous environment with bare roots [24].

Plants are usually located in boxes where irrigation lines are installed, nutrition is then provided in a form of an aqueous solution straight to the plant's roots. Plants can also be grown directly in this nutrient solution, in such scenarios floating rafts are usually utilized for plant support (as can be seen in Fig. 13) [24].

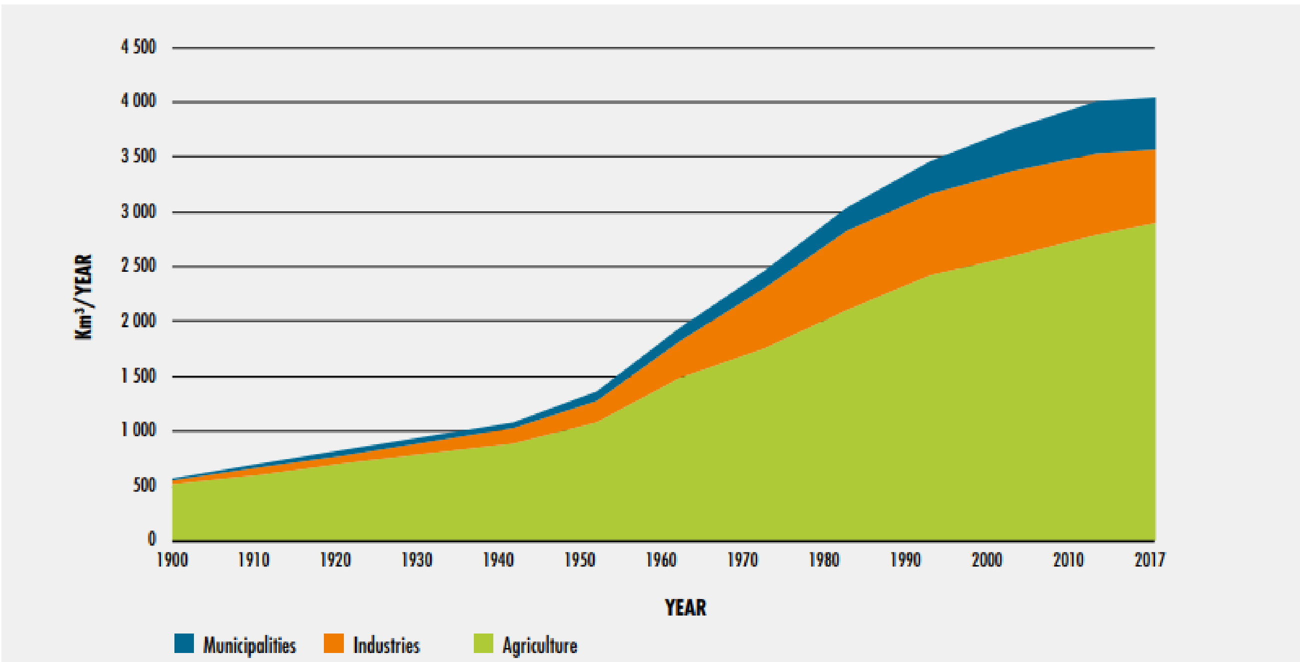
Fig. 13 Lettuce grown using hydroponics – floating raft
(for license details see page 93)

Leaving out soil from the crop's life cycle provides the hydroponic farmer with numerous benefits. Compared to traditional field cultivation of vegetable, hydroponics (alone or as a component of aquaponics) has higher productivity both quantitatively and qualitatively [38]. The environment within hydroponics is more stable and easier to manipulate, monitor, and control [24]. Diurnal temperature is lowered, light swings during the day are also reduced [39]. Moreover, some substrates used in hydroponics show better properties concerning water retention and oxygen availability to the roots [24].

Lettuce can serve as an example of improved efficiency of hydroponics in comparison with traditional field cultivation. With all the abovementioned benefits combined, lettuce in hydroponics/aquaponics can reach the harvest period in 32 – 35 days after it had been planted, compared to 45 days it usually takes using in-field cultivation [39].

Hydroponics also promises much greater efficiency concerning water use when compared to traditional crop production [24]. Water can be reused, and refills are needed only due to evaporation from free surfaces and plant transpiration [2]. For example, hydroponic lettuce production can achieve 11 times higher yield per acre with 13 times less water used compared to lettuce grown in open-field agriculture [40].

As seen in Fig. 14 [41], agriculture is responsible for almost 70 % of global water withdrawal. It must be noted, however, that within agriculture, animal production is the primary consumer of water [41]. Nevertheless, since potential savings can be substantial, any possibilities for improvements of water use efficiency within agriculture should be considered if economically feasible. Such feasibility is often determined by local resources availability. In regions with insufficient freshwater reserves, or in regions where intensive agriculture places unnecessary stress on said resource (regions highlighted in Fig. 15 [41]) implementation of hydroponics could have a sizable impact.



NOTE: Agricultural water withdrawal refers to the annual quantity of self-supplied water for irrigation, livestock and aquaculture; industrial withdrawal is the annual quantity of self-supplied water for industrial uses, such as cooling thermoelectric and nuclear power plants (but excluding hydropower); and municipal withdrawal is water withdrawn for the direct use of the population.

Fig. 14 Global water withdrawal per sector [41]
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The next major benefit of soilless crop production is the ability of substrates to be sterilized and reused between crops. This practice then highly reduces the threat presented by soil-borne pests and diseases consequently decreasing the number of chemical pesticides necessary for crop production [24]. Various problems connected with soil overuse (soil-tiredness, erosion etc.) are also mitigated by the use of substrates [42].

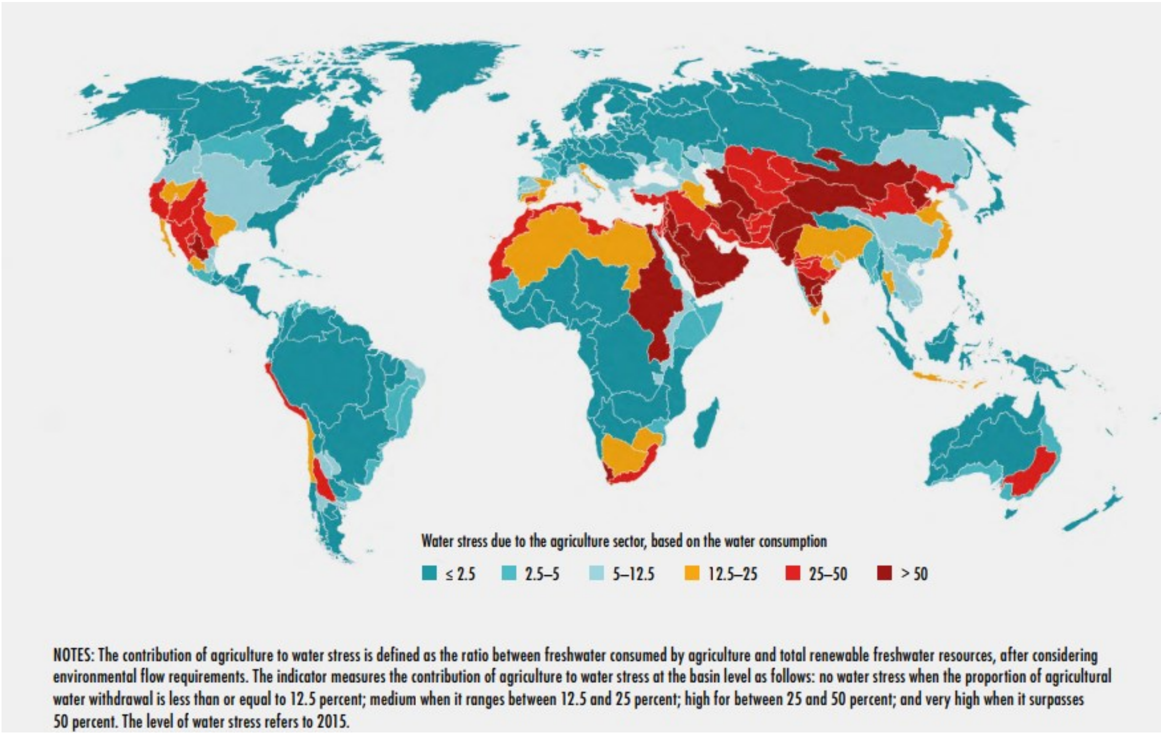

Fig. 15 Water stress due to agricultural sector [41]
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Surprisingly, soilless agriculture has lower requirements for nutrition supplementation in the form of fertilizers. Nutrients can reach roots directly and in a more controlled manner resulting in much higher efficiency when it comes to the uptake of nutrients [24]. Such quality is becoming more and more important since some components (phosphorus and potassium mainly) of fertilizers are mined from finite reserves [43]. The continuing trend of higher worldwide fertilizer consumption (106 kg/ha in 2002 to 137 kg/ha in 2015 as can be seen in Fig. 16 [44]) then presents a growing sustainability and food security challenge [45].

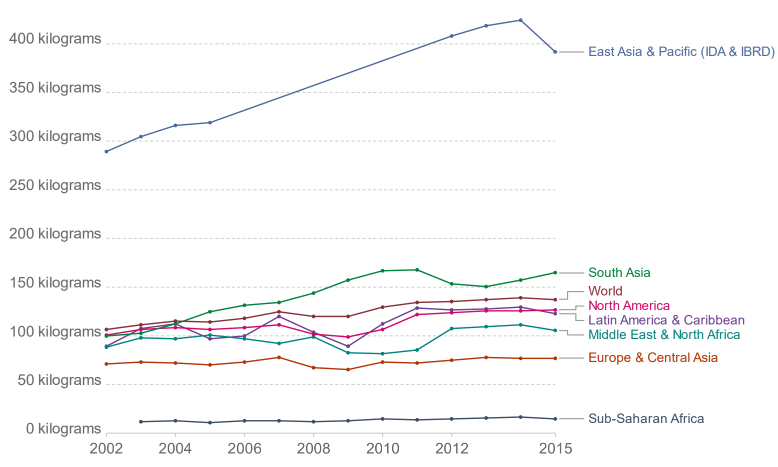

Fig. 16 Fertilizer use per hectare of cropland, 2002 to 2015 [45], [44]
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Furthermore, hydroponics could bring intensive agricultural production into areas where various obstacles have long prevented its emergence. Large parts of the world suffer from low soil fertility making crop production very difficult if not impossible [42]. The rise in agricultural production observed in recent decades is largely contributed (~90 %) to increased cropping intensity and higher yields, not so much to expansions of arable land (~10 %) [38] as is demonstrated in the example of cereal production in Fig. 17 [46].

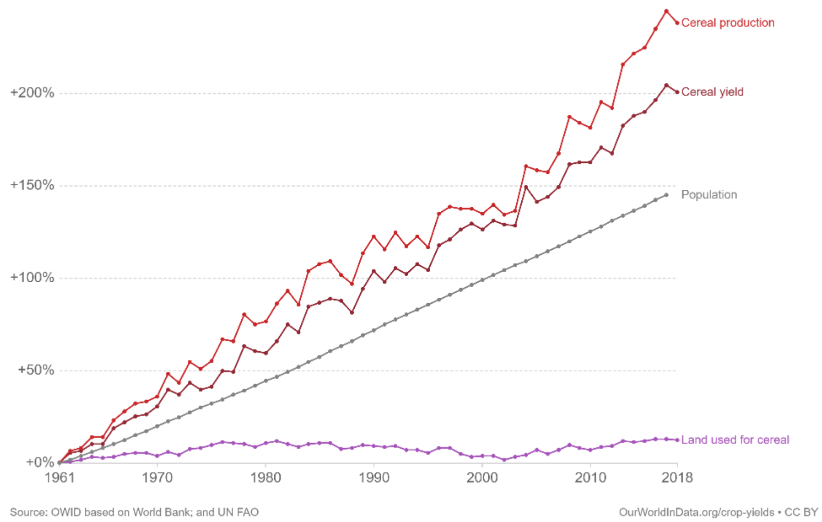

Fig. 17 Change in cereal production, yield, and land use in the period between 1961 and 2018 [46]

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Since soilless production methods do not rely on soil, the poor fertility of local soils is no longer of concern. Old factories, rooftops of commercial and residential buildings or other unused urban spaces could also be viewed as areas with potential for implementation of hydroponics [47]. Such applications could bring jobs into impoverished neighbourhoods and simultaneously provide urban centres with local produce improving self-reliance and lowering transport emissions and costs [47].

1.3.1 Hydroponics as a subsystem of aquaponics

Hydroponics, as a subsystem of aquaponics, has both positives and negatives depending on the specific type of hydroponic implementation in the aquaponic system.

Starting with positives, it has been shown that aquaponic systems exhibit a higher rate of production while environmental impacts of the practice are mitigated. In a study conducted by Chen P. et al. [40], the value of aquaponic production per month of cultivation period had reached amounts twice as high as the ones from the purely hydroponic system. Moreover, the studied aquaponics system exhibited a 45 % lower endpoint environmental impact than compared hydroponic scheme.

The lesser environmental impact of aquaponics stems from its improved water use efficiency. It has been shown that aquaponics usually requires water inputs of 2 – 3 % [28] (or 0,3 – 5 % [2]) of total system water volume per day, depending mainly on the types of plants being cultivated [28]. In comparison, a basic recirculating hydroponic system requires complete nutrient solution replacement after 2 – 3 weeks [2]. Aquaponics in its worst-case scenario is then comparable with hydroponics in the best-case scenario, further illustrating possible improvements in the efficiency of the practice when incorporated in the aquaponic system.

Lastly, the implementation of hydroponics into aquaponics has exhibited benefits in terms of lower overall fertilizer use [2]. The importance of such reduction can be illustrated by the energy requirements connected with the production and use of fertilizer in modern agriculture. In the US agricultural sector, for example, it accounts for the highest energy consumption per energy input (in this case mainly indirect thru means of fertilizer production, as can be seen in Fig. 18) [48].

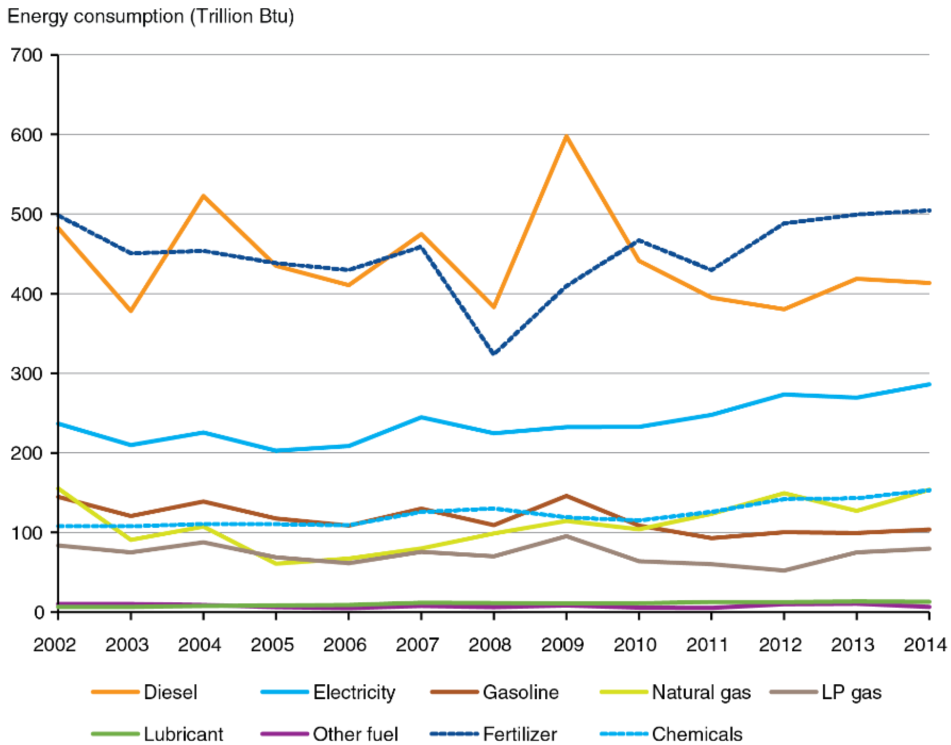

Fig. 18 Direct and indirect energy consumption by fuel in the agricultural sector of USA [48]

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Any possible decrease in reliance on fertilizers is therefore beneficial for the overall environmental impact of any agricultural practice. Moreover, the reduction also improves food security greatly, as was previously mentioned.

However, the question of lower fertilizer use is more complex and cannot be viewed solely as beneficial. Plants need certain macro and micronutrients during their life cycle. As mentioned in the previous discussion, in hydroponics these nutrients are usually provided in the form of an aqueous solution with fertilizer as the nutrient source [41]. This nutrient solution can be modified based on the plant species and stage of the lifecycle allowing for nearly perfect growing conditions with regards to nutrients. The basic premise of aquaponics however states that the primary (and if possible singular) source of nutrients should be fish feed [38]. Since fish feed is designed to accommodate only the need of fish, crops in the hydroponic component of coupled aquaponics must endure nutrient levels suboptimal for their growth [38]. Nitrogen levels are usually sufficient, however, if not supplemented, phosphorus, potassium, calcium, and iron often become limiting to plant growth [38]. Furthermore, each fish species requires different feed composition to reach the optimal feed-to-mass conversion ratio. The aquatic environment, from which plants source their nutrients, is therefore going to have different nutrient concentrations depending on present fish species. This variance requires the aquaponic farmer to raise/grow only optimal fish/crop pairs to minimize the need for additional costly nutrient supplementation specifically for crops [1].

1.3.2 Hydroponic subsystem - design

When it comes to designing hydroponic subsystem, there is a wide array of possibilities compared to aquaculture subsystem design. Among the basic and most commonly occurring are:

1. **Solid substrate/media bed type system** – can be seen in Fig. 5. In media bed systems, crops are grown in a plastic (food grade, inert) or fibreglass tank [24] where the substrate is used for plant support and water retention [38].

   The tank itself is designed in a rectangular shape to maximize the use of the available area. The depth of the tank must be sufficient so as the implemented type of media can provide adequate structural support for produced plant species along with satisfactory volume for root development [24]. The tank material, its colour and possible shading or cooling must be considered when dealing with open or semi-open systems. If left uncontrolled, root temperature can quickly rise on hot days causing major damage to root systems and consequently to plants [42].

   The media beds can serve as efficient biological and mechanical filters, providing an area for the growth of nitrifying bacteria as well as for capturing and mineralizing fish waste [24]. This filtration capacity can be both beneficial and risky. Mineralization allows for more complete use of nutrients provided initially in a form of fish feed, but in a configuration with high fish stocking density, the media bed might become clogged and create dangerous anoxic zones [2]. Additional filtration is therefore advised unless the media bed filtration area is carefully considered with respect to the stocking density of the system [24].

Fig. 19 Hydroponic growing medium: light expanded clay aggregate (LECA) [24]
(for license details see page 93)

   The selection of the media (type of which can be seen in Fig. 19 [24]) is one of the most crucial design steps when it comes to media bed type aquaponics. The bulk density of the material should fall into the range between 150 and 500 kg/m^3 [42]. The considered material should have a porosity greater than 75 % and be structurally stable over time and during the drainage phase [42]. The water holding capacity (calculated as a difference between the amount of water at the retention capacity and the wilting point) should be 30 to 40 % of apparent volume to avoid either inadequate levels of moisture or at the other end, root asphyxia [38]. The pH of the material in question should be either neutral or slightly acidic (easier to adjust and suits a wider range of plant species) [38]. The material should be cost-effective and sustainable. The question of sterilization (steam, chemical) should also be addressed – either for organic materials with the natural presence of pathogens or after a prolonged period of use where the possibility of pests or pathogen introduction into the system exists [49].

The following table offers a non-exhaustive list of possible materials along with their characteristic properties.

Table. 1 Materials used as a growing medium for aquaponic production [38]

CATEGORY	EXAMPLES	CHARACTERISTICS
ORGANIC	- Peat - Coconut fibre (coir)	- external contamination might be a problem - preferred for crops with a shorter growth cycle (due to increased decomposition under higher bacterial load) - often used in mixtures with inorganic materials
INORGANIC	- Expanded clay - Volcanic gravel - Light expanded clay - Sand - Perlite - Stone wool - Zeolites	- no occurrence of decomposition - properties are not easily generalized, each material should be considered individually - can often immobilize certain nutrients - can often be reused for extended periods
SYNTHETIC	- Expanded polystyrene - Polyurethane foam	- no occurrence of decomposition - often used in mixtures to improve drainage and porosity - low density makes standalone use problematic - inert and do not offer any useful nutrients - easier to manage

Another consideration for media bed systems is the type of irrigation used. Most commonly, the system is periodically flooded and drained – this type is referred to as an ebb-and-flow system [27]. The frequency of flooding can range from 2 per hour to only 3 per day based on the requirements of plant species and the type of media used [38]. The goal of this system is to provide both water and nutrients (flooding phase) and sufficient oxygen levels for the root system and nitrifying bacteria (drainage phase) [27].

Other options for irrigation are drip irrigation, where a network of small diameter pipes is required to transport nutrient solution directly to plants, or a continuous flow system, where water is maintained at a constant level in the media bed. These systems are generally more complex but offer better nutrient distribution without the risk of anoxic zones developing [38].

Media bed aquaponic configurations are quite common in systems centred around research as well as small scale experimental production [2]. They are well equipped to handle even large plants and have a major benefit in a form of bio and mechanical filtration capability [2]. Among the main negative characteristics of the media bed system are its inability to efficiently upscale the production [2], the requirement of large sum tank (for ebb-and-flow type), heavy infrastructure (sizable structural support might be required for certain growing media types) and difficult maintenance and cleaning of the media bed [27].

2. **Nutrient film technique (NFT) -** As can be seen in Fig. 20 [38], NFT is a technique of hydroponic plant production, where plants are situated in cut-outs of a water canal and their root systems are in direct contact with continuously flowing nutrient solution [47].

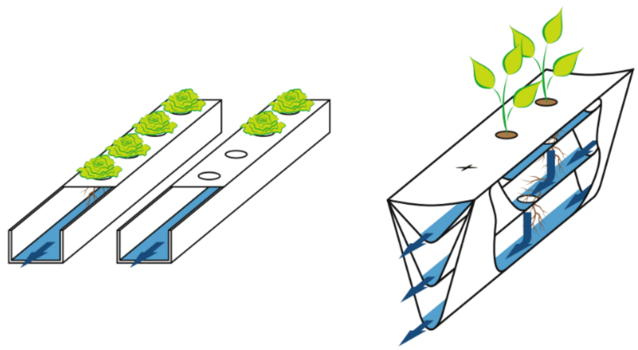

Fig. 20 Illustration of nutrient film type of hydroponic production [38]
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Plants are anchored in plastic cups with small amounts of growing media (for example previously mentioned LECA). Plastic cups have perforated bottoms which allow roots to reach into the flowing water and obtain necessary nutrients [24].

Water canals are formed by a network of pipes, each branch up to 12 m in length. Nutrient deficiency at the ends might occur for larger lengths [24]. The system is therefore usually set up with growth canals in a parallel configuration with respect to process water.

Wherever possible, rectangular canals (wide and shallow) are used since they allow for maximum root-to-water contact area [24]. PVC is regarded as the best material for NFT canals for its availability and low cost [24].

Water flowing inside NFT canals is maintained at a height of only 10 to 20 mm. This allows for both sufficient nutrient uptake and adequate availability of oxygen in the root zone [24]. However, since the cooling capacity of process water is limited by current height, the nutrient film technique is susceptible to temperature fluctuations inside the canals. Such changes are stressful for plants and can lead to diseases [38]. White coloured PVC or shading/cooling should therefore be considered in hotter locations [24].

The low height of flowing water creates further difficulties – part of the root system suspended in air experiences early ageing and loss of functionality. NFT is therefore limited when it comes to the length of the plant life cycles to about 4 to 5 months [38]. In addition, NFT cannot accommodate plants with excessive root development – tomatoes or mint plants can quickly clog the water canals and cause overflows and losses of water [24], [49]. The system visible on the right side of Figure 20, marketed as NGS (New Growing System) has however successfully managed to overcome this limitation by the implementation of multiple layers in a cascade configuration [38]. Clogged passages are bypassed, lowering the risk of nutrients not reaching certain root systems.

Despite the abovementioned limitations, NFT's comparatively low efficiency [2] and inherent vulnerability (rapid deterioration of plants after pump or power failure) [38], [49] it is still one of the most widely used configurations in industrial applications [2]. One of the reasons the technique is popular is due to the efficient use of the area - canals can be arranged in various ways, and lightweight support systems even allow for horizontal configurations [47]. Other positives are a simple design, ease of operation, ease of automation [38], and comparatively low initial costs when upscaled [2].

3. **Deep Water Culture (alternatively deep flow technique or floating raft culture) (DWC, DFT or FRC)** is a configuration of hydroponic subsystem which utilizes rafts (commonly made from polystyrene [24]) with cut-outs for plants, floating on top of nutrient solution [38]. Similarly to NFT, plants are anchored in plastic cups filled with hydroponic growth media (LECA for example) [24]. Root systems are in continuous and direct contact with water, allowing for more efficient uptake of nutrients when compared to the previously mentioned NFT technique [27]. An example of DFT hydroponics can be seen in Fig. 21 [38].

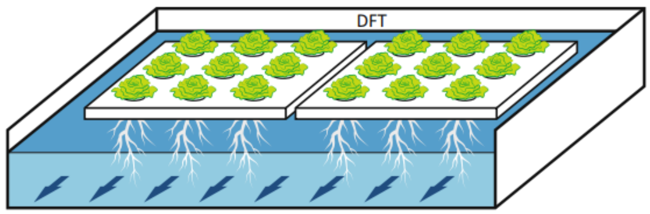

Fig. 21 Illustration of DWC/DFT type hydroponic production [38]
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The height of the water column in tanks (or canals) is maintained at 200 to 300 mm [38]. The system is consequently more resilient – both to temperature fluctuations in the root area and to unexpected component failure (pump or power) [2].

Water retention time should fall in the range of 1 to 4 hours for each grow unit [24]. Shorter retention time favours higher plant growth achieved by better nutrient availability in turbulent flow conditions. Longer retention times reduce expenses on energy and equipment since lower flow rates allow for use of smaller, less energy demanding pumps [24].

The dimensions of tanks are not limited by nutrient availability due to large volumes of nutrient-rich water present in the system. Tanks should therefore be designed around available polystyrene rafts and tank supports. Large amounts of nutrient solution present in the system also allow for grow tanks to be set up in a series without any risk of nutrient deficiency at the end of the system. This possibility reduces the amount of necessary piping and consequently expenses associated with the system set up and maintenance [24].

One of the largest challenges in connection with DWC is maintaining adequate oxygen levels in process water, especially in systems with longer retention times (lower flow rates, lower turbulence) [2]. Oxygen in DWC is consumed on multiple fronts - by plants, by beneficial nitrifying bacteria which naturally develop on polystyrene rafts, and by any decomposing organic matter within the grow tanks [24]. Additional aeration is therefore usually required and is achieved by the introduction of air stones or the addition of Venturi siphons into water inflow pipes [38]. Alternatively, Dynamic Root Floating Technique [2], [50] (DRFT, or Kratky method [24]) can be used. The technique works on principles of DWC, but instead of floating rafts implements raised polystyrene structures. Root systems of plants are then submerged in water only partially, leaving the top 30 to 40 mm of the root system exposed to air. Air circulation in the root area is then able to maintain sufficient oxygen levels without the costly addition of air stones or venturi siphons [24]. However, such a system requires additional raft support in a form of plastic structures submerged in the grow tank [50]. Fig. 22 illustrating the mechanism behind DRFT is on the following page.

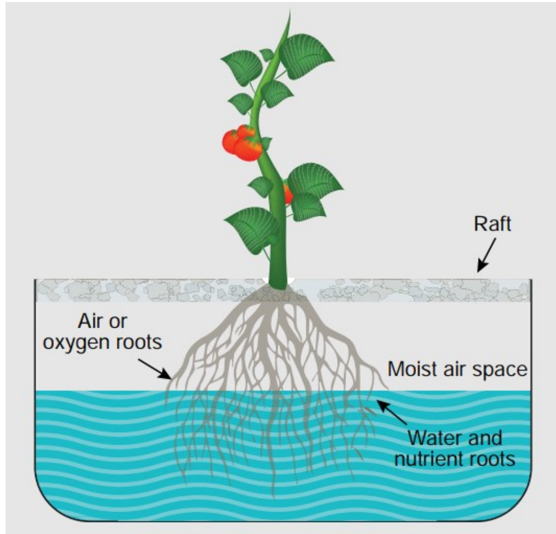

Fig. 22 Dynamic root floating technique (DRFT) [24]
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Most often, standalone bio and mechanical filtration are required for any DWC system to facilitate nitrification. However, the size of the biofilter is reduced when compared to NFT since polystyrene rafts can too harbour the growth of beneficial nitrifying bacteria [24]. The bacterial colonies present on the grow rafts should be accounted for when cleaning of the rafts is practised. Rafts should not be dried or be put in contact with any chemicals harmful to said bacterial colonies [24].

DWC can be labelled as a technique most widely used in commercial services [24]. The system is low maintenance and efficient due to maximized root-to-water contact area [2]. Out of the three examined configurations (media bed, NFT and DWC), DWC has the most rapid reduction of material cost per crop added when upscaled [2]. DWC is environmentally efficient in water use, with some configurations requiring only 1 % of total water volume to be replenished daily. This efficiency is achieved thanks to larger parts of water surfaces being covered by rafts, reducing surface evaporation of water [2].

DWC setup is utilized in the experimental farm in the focus of this work.

1.4 OTHER COMPONENTS OF AN AQUAPONIC SYSTEM

Apart from the economically productive subsystems – aquaculture and hydroponics – the effective service of an aquaponic system also requires additional process units to be implemented. Among them, biofilter, mechanical filter, pumps and oxygenation devices are the most prominent.

1.4.1 Biofilter

The biofilter is a flowthrough tank incorporated into the aquaponic loop and usually packed with Pall, Raschig or other rings maximizing the filter surface area [51]. This is required since the function of the biofilter – nitrification – is facilitated by strains of nitrifying bacteria dwelling on underwater surfaces.

Regarding the development of these nitrifying bacterial strains - such strains occur naturally in water, but in aquaponics, where their function is crucial for the entire system stability, they are seeded by the operator of the production [51]. It is essential to start the biofilter before the entire aquaponic production as not to endanger the fish population.

The aquaponic system is thus usually run without fish during the initial stages of system start-up, and fish are only introduced after the biofilter is already fully operational [51].

The nitrifying bacterial biofilm will eventually develop on other compartments of the aquaponic system as well, further strengthening the resilience of the whole nitrifying apparatus. The cleaning of the aquaponic unit between fish/plant production cycles should therefore be performed in a manner friendly towards these bacterial colonies.

As for the design of the biofilter, the nitrifying process is highly oxygen-demanding, and the incorporation of additional aeration of biofilter should be considered. Furthermore, a regular discharge mechanism for accumulated organic matter should be implemented into the biofilter. Without such a mechanism, the biofilter can become infested with heterotrophic bacteria highly competitive with respect to nitrifying bacteria [38].

1.4.2 Filtration of solid particles

Clarifiers, sedimenters or swirl separators are most commonly used to remove solid particles from the stream of aquaponic process water [38]. Such periodical removal is necessary due to the possible creation of anoxic zones with denitrifying effects in areas where large quantities of organic sludge are left to accumulate. Denitrification is a reversed process to one described in Eq. 3 (chap. 1.5.1) leading to a decrease in concentrations of plant-available nitrates and should therefore be prevented [24].

The solid particle filter is usually designed as a tank with lamella or plate inserts and conical shaped bottom to assist with a more local sludge accumulation [38]. The tank is also equipped with an outlet located at the apex of the conical bottom. After a certain time, the filter is flushed using the bottom outlet and the sludge is either discarded or further processed. Periodical sludge discharges are however accompanied by a loss of nutrient-rich process water [24].

Moreover, considerable amounts of nutrients are lost during the sludge discharges, since the sludge is composed of mainly organic particles originating from fish excretes. Some aquaponic farms utilize digesters where organic sludge is processed into a viable source of nutrients for the hydroponic subsystem [2]. The use of such digester can minimize the need for costly sourcing of fertilizers required, in some cases, for proper plant growth.

Even in configurations utilizing digesters, significant volumes of process water are lost during the filter flushing. To solve this inefficiency, technologies applying vacuum cleaning techniques are used [2]. The additional benefit of this configuration is the decrease in sludge dilution allowing for a more effective downstream processing.

1.4.3 Pumps – circulation and oxygenation

Pumps are used for two main reasons in aquaponics, firstly to maintain circulation in the entire system, and secondly to increase dissolved oxygen (DO) levels [52].

The implementation and sizing of circulating pumps is influenced by the system configuration. The goal of a design of an aquaponic system should be to minimize operational costs – hence principles utilizing natural gravitational flow are usually employed. In properly designed aquaponic units use of only a single circulation pump can be achieved [38].

As for the air pumps, oxygen is utilized in many ways in aquaponic systems. By fish for breathing, by nitrifying bacteria during reaction facilitating nitrogen conversion, and lastly by plant roots to serve in their metabolism. Consequently, DO levels must be increased in the areas where the largest demand occurs. Air pumps are employed in the process, introducing a stream of air bubbles that enrich surrounding water raising the DO levels [24].

1.5 THE NUTRIENT CYCLE OF AQUAPONICS

Aquaponic production systems are designed to maximize the use of nutrients originating in fish feed [27]. However, this concept is given a different priority in coupled and decoupled systems. Thus, both types of aquaponic production differ significantly in the implementation of nutrient management methods. Since the farm examined in this work is of coupled type, the following text is going to be focused on nutrient management of a coupled aquaponics production system.

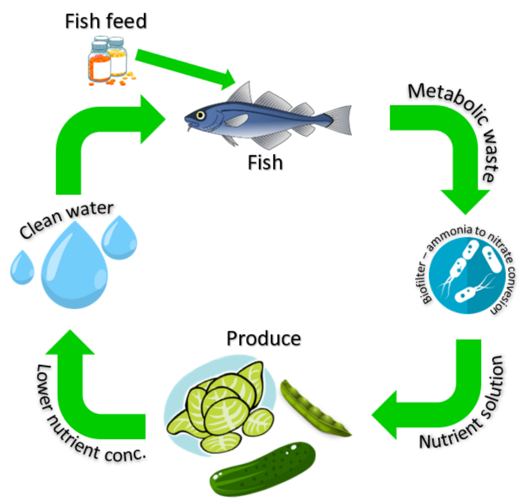

Fig. 23 Simplified illustration of the aquaponic nutrient cycle
(for license details see page 93)

A simplified illustration of the aquaponic nutrient cycle is provided in the form of Fig. 23. In aquaponic systems, fish (or other aquatic animals) are kept in water tanks where feed is provided as a main form of sustenance. Upon consumption of said feed, the cultured animals release metabolic waste products into their surrounding aquatic environment. Finfish release their main waste product, ammonia, mainly through gills in a form of ammonia gas. It is estimated that roughly 1 kg of ammonia is released per 45 kg of feed [53]. In this manner, fish feed is a major source of nitrogen, but also phosphorus, entering the aquaponic system. However, other macronutrients are needed for effective plant growth. Some enter the system in a form of regular freshwater inputs, these are namely, magnesium, calcium, and sulphur [38]. Other essential nutrients, such as iron and potassium, must often be added into the system by its operator in a form of fertilizer, or a specialized additive [38].

1.5.1 Nitrogen

It was outlined during the previous paragraph that nitrogen enters the aquaponic system in a form of fish waste-product, ammonia gas. The transformation of ammonia gas into a form both available for plant uptake and non-poisonous to fish is a major part of the whole aquaponic process. Thus, the procedure is going to be described in greater detail.

Ammonia, upon entering the aquaponic system, can exist in two forms – as ionized NH_4^+ or in the un-ionized form as NH_3. The un-ionized form being extremely toxic to fish leading to reduced appetite, slowed growth rate, tissue damage and in higher concentration even death [51]. Catfish for example show signs of tissue damage and slower growth at concentrations of NH_3 as low as 0,06 ppm [53]. In closed recirculation systems with low daily water exchange, fish waste products would accumulate creating an environment too toxic for fish to thrive in. The concentrations of ammonia must therefore be closely monitored and continuously reduced.

To maximize efficiency aquaponics uses waste ammonia of its aquaculture component for the growth of crops in the hydroponics subsystem [3]. To allow for the uptake of nutrients by plants and to reduce the toxicity of the aquatic environment, the waste ammonia must first be transformed into nitrate through a process called nitrification [29]. The nitrification process can be described by Eq. 3 [51].

$$\boldsymbol{NH_3}(\boldsymbol{toxic})\ \overrightarrow{Nitrosomanas}\ \boldsymbol{NO_2^-}(\boldsymbol{toxic})\ \overrightarrow{Nitrobacter}\ \boldsymbol{NO_3} \qquad \textit{Eq. 3 Nitrification}$$

Nitrate is a form more readily available for plant utilization while considerably less toxic to fish [51]. Nitrate is tolerated by most fish species up to concentrations of 150 – 300 mg/L, however, certain species cope with even higher levels [38].

The aquaponics takes advantage of bacterial colonies located in a biofilter to facilitate the nitrification transformation [3]. The mechanism of a biofilter was already described in chapter 1.4.1.

1.5.2 Phosphorus

Phosphorus is a crucial macronutrient taking part in the process of photosynthesis, energetic metabolism, and respiration. Furthermore, it promotes root growth, enhances fruit quality, and increases plant water use efficiency [54]

In aquaponics, phosphorus enters as a part of the excreted metabolic waste of fish. Generally, plants can absorb the nutrient in its ionic orthophosphate form ($H_2PO_4^-$, HPO_4^{2-}, PO_4^{3-}) [47]. Only limited information is available on the precise dynamics of phosphorus in aquaponics. However, studies recently connect bacterial communities naturally present in aquaponics with increased rates of phosphorus transformation from originally present phytates into more plant-available forms of phosphorus [55]. This fact should therefore be taken into account when considering UV-light treatments, or other disinfecting methods of aquaponic water.

Furthermore, it is well documented that phosphorus can precipitate as struvite ($MgNH_4PO_4 \cdot 6H_2O$) and hydroxyapatite ($Ca_5(OH)(PO_4)_3$), forms unavailable for plant uptake, in environments with pH over 8 [56]. The environment of an aquaponic farm should thus be managed in a way to avoid pH values exceeding 8.

1.5.3 Potassium

Potassium, an essential plant macronutrient, serves many functions in plant metabolism. Among these are protein synthesis, adjustment of pH within cells, better CO_2 fixation during photosynthesis, and transport of chemical compounds within the plant [54].

In aquaponics, where most of the nutrients originate in fish feed, potassium can often become a growth-limiting factor if not supplemented. Potassium is not essential for the proper development of fish and therefore is not contained in fish feed in high quantities. This disbalance is usually addressed by the usage of KOH as a pH buffer since the use of an agent to counter pH decreases due to nitrification is necessary [38].

1.5.4 Other nutrients

Magnesium, calcium, and sulphur enter the aquaponic system dissolved in freshwater inputs. However, both calcium and sulphur do so in unsatisfactory quantities and must therefore be supplemented. Furthermore, many essential micronutrients are present in aquaponic water in low concentrations. Both copper and iron deficiencies should be closely monitored and if needed supplemented (for example using chelated iron or available copper additive) [38].

1.6 Types of aquaponic units

Aquaponic farming mainly exists in two modes of operation – coupled and decoupled [38]. The coupled system can be denoted as archetypal since the first aquaponic units were designed in this manner. The term coupled suggests the main components (hydroponics and aquaculture) are both arranged in a single process loop sharing the process water [38]. However, a coupled configuration cannot avoid certain compromises – for example, suboptimal pH or nutrient concentrations outside the desired range for both aquaculture and hydroponics [6]. Therefore, decoupled systems are more recently gaining traction [38]. Such systems have a minimum of two process loops, one for each of the main components. In this manner, the process water can be more tightly controlled and conditions closer to optimal for each of the main systems are therefore reached [38], [6]. The decoupled approach also allows for a more creative design, for example, the introduction of distillation or/and an anaerobic bioreactor [38].

Both coupled and decoupled systems are going to be introduced. However, the experimental unit in the focus of this work is of a coupled type and hence this type is going to be examined more closely.

1.6.1 Coupled aquaponics

Coupled aquaponics is a mode of operation most commonly associated with the word aquaponics. Often when aquaponics is mentioned, authors refer to coupled aquaponics, and it has been done so during the course of this work as well. A basic configuration of a coupled aquaponics system can be seen in Fig. 24 [38].

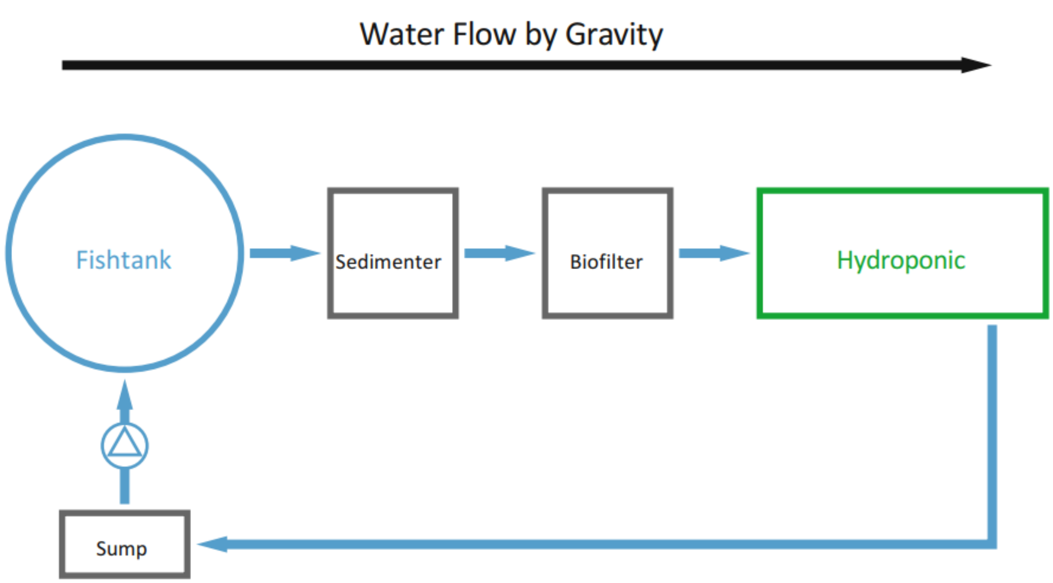

Fig. 24 The basic mechanism of a coupled aquaponic system [38]
(for license details see page 93)

To reiterate, coupled aquaponics denotes a system combining aquatic organisms, plants, and colonies of bacteria, most notably nitrifying, in a mutually beneficial way [28]. These organisms share an environment where recirculating water serves as a medium for nutrient transport. Nutrients come mainly in a form of fish feed, and upon digestion are converted by bacteria into a form accessible for plant uptake [6]. When combined in coupled aquaponics, fish and plants exhibit higher growth rates in comparison to standalone production systems [12].

Generally, commercial coupled aquaponics systems are comprised of fish tanks (RAS), clarifiers or sedimentation units, sump, and, based on the type of hydroponic unit, biofilter. Furthermore, the need for additional oxygen supply, UV light treatment, and filtration can be expected for large commercial systems (> 100 m^2 of production area) [28]. Components of the coupled systems are connected via pipes to form a closed recirculating unit [28].

The entire coupled system is centred around nutrition management. The fish feed provides a nutritional input into the system. Uptake from the hydroponic component is then necessary to maintain plausible conditions for fish. To facilitate the uptake, nutrition transformation by bacteria is mandated. Based on this described interconnectedness, individual components must be designed with respect to each other. This consequently makes the design of coupled aquaponics complex and rigid. The rigidity stems from the inability of coupled aquaponics to increase production in a single subsystem without the need to also change the volume/productivity of other system components. For example – if market demand for fish is high, to accommodate for this demand, the aquaponic farmer must also produce larger quantities of plants, for which there might not be a lucrative market.

Starting with the negatives of coupled aquaponics. As was previously mentioned, one of the known drawbacks is the need for compromises, namely in nutrient concentrations and pH [6]. Fish and plants have different needs which cannot be met simultaneously in a system where process water is shared. Coupled aquaponics is therefore limited to certain fish-plant pairs with respective optimal conditions not exaggeratedly divergent [38]. Generally, well suited are fish species with good acceptance of higher concentrations of toxic substances and plant species that fare well in environments with low nutrient concentrations [38]. It is important to note, that the productivity under the suboptimal conditions of coupled aquaponics is still higher in comparison with standalone optimized systems [57], [58]. Many sources stipulate the need for further research in this area, since the mechanisms behind the better productivity of aquaponics are still unknown [38], [59]. Complex interactions between fish, plants, and beneficial bacterial colonies are often credited for this otherwise unexplained efficiency [59].

Recently, the idea of nutrient supplementation by the addition of fertilizer has been gaining popularity. It must be noted however, not all fish species can tolerate consequently raised nutrient levels [38].

Among aquatic species with a proven record in coupled aquaponic farming are various species of tilapia (*Tilapia mossambica, Oreochromis aureus, Oreochromis niloticus*) [52], [60], various species of catfish (*Clarias gariepinus, Ictalurus punctatus*) [61], common carp (*Cyprinus carpio*) [52], white shrimp (*Litopenaeus vannamei*) [62] and freshwater prawns (*Macrobrachium rosenbergii*) [63], [38]. The practice of polyculture (inclusion of multiple aquatic species in aquaculture subsystem) is also gaining attention [63].

The exact pairing of species with plants is a concern of many scientific publications and is not within the scope of this work. Therefore, only a list of some well-proven species of plants for aquaponics is provided here: Chinese cabbage (*Brassica rapa pekinensis*) [38], pakchoi (*Brassica rapa*) [38], spinach (*Beta vulgaris* var. *bengalensis*) [64], water spinach (*Ipomoea aquatica*) [64], lettuce (*Lactuca sativa* in different variations – iceberg, butterhead, romaine) [24], [57], basil (*Ocimum basilicum*) [65], tomatoes (*Lycopersicon esculentum*) [62], or mint (*Menta* sp.) [24]. Other species are showing potential, among them for example, cauliflower (*Brassica oleracea* var. *botrytis*), broccoli (*Brassica oleracea* var. *italica*), cabbage (*Brassica oleracea* var. *capitata*), eggplant (*Solanum melongena*), celery (*Apium graveolens*), chillies (*Capsicum frutescens*), beans (*Phaseolus vulgaris*), or peas (*Pisum sativum*) [24].

The positives of a coupled aquaponic systems are mainly in the efficiency of the entire system, and more importantly in the fact, that this efficiency can be achieved without the use of additional resources and infrastructure [13]. This quality makes coupled aquaponics widely applicable, scalable, and sustainable from the environmental viewpoint [13]. Additionally, research has lately been investigating the potentially positive effects of aquaponics on fish welfare. The plant root systems together with beneficial bacterial colonies seem to have a positive impact on fish health. Comparison of behavioural patterns in fish raised in aquaponics and pure aquaculture has shown a reduction in agonistic tendencies accompanied by a decrease in fish injuries. Certain compounds released by bacteria and plants into the water are credited with this positive impact on fish [66].

1.6.2 Decoupled aquaponics

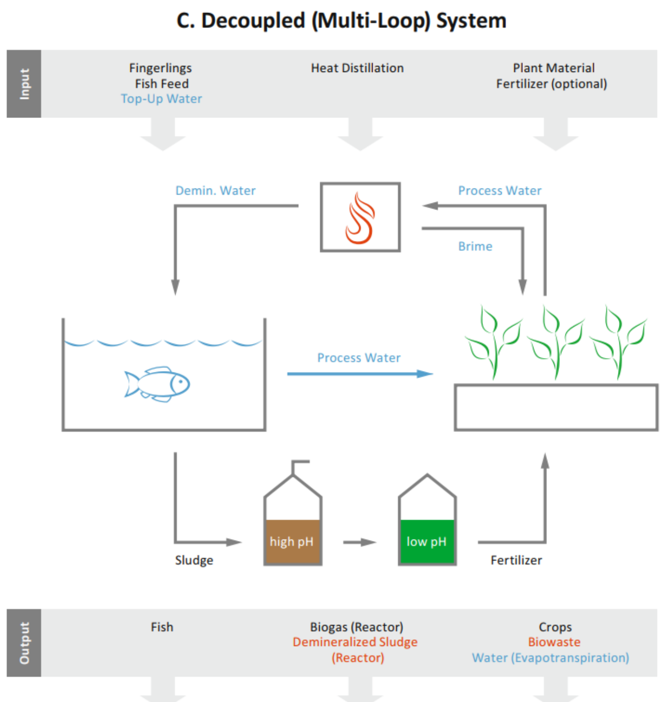

Fig. 25 Mechanism of a decoupled multi-loop aquaponic system [38]
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Decoupled aquaponic systems, as seen in Fig. 25 [38], differ from coupled systems in their base design. The aquaculture and hydroponic subsystems are not interconnected by a water recirculation network. The flow of process water from RAS to hydroponics is unidirectional and equal to the rate of water loss by evapotranspiration and fixation in plant biomass [38]. Such configuration with a low flowrate allows for greater control and optimization of water quality parameters [38]. Consequently, decoupled aquaponic systems have higher productivity when compared to coupled systems, both in fish and plant production [57]. However, to maintain adequate water purity in RAS and to comply with the idea of resource conservation, decoupled aquaponics requires the implementation of additional process units.

The first of these process units is a two-stage anaerobic reactor. The term aquaponics is founded on the idea of maximum utilization of nutrients present in the fish feed. In decoupled aquaponics, a large portion of these nutrients ends up settled at the bottom of the fish tank as sludge. Thus, a mineralization loop is utilized to transform nutrients present in the extracted sludge.

The two-stage anaerobic reactor described in Fig. 25 serves this purpose. In the first, methanogenesis stage, a pH of around 7 is maintained and organic matter present in the fish sludge is broken down [67]. This stage produces methane as a by-product which can be further utilized. The second stage of the reactor, where a pH of approximately 4 is kept, serves to increase plant availability of nutrients remaining in the digested sludge [67]. Its product is then a digestate which can be used directly in the hydroponic subsystem to minimize the need for any additional nutrient supplementation by fertilizers.

The second utilized process unit is a distillation/desalination device [68]. With the slow unidirectional flow of water from RAS, nutrient concentrations in the fish tank would soon reach levels toxic for fish. A measure to dilute nutrients present in the fish tank was therefore required. The hydroponic water distillation/desalination has been implemented as a solution. The resulting system then serves as a "nutrient filter", concentrating dissolved salts and nutrients in the hydroponic subsystem while allowing for the circulation of demineralized water into the RAS [68].

However, because of the implementation of the abovementioned process units, the development of decoupled aquaponic farm involves higher initial investments [38]. As a result of greater capital and operational expenditures required by the decoupled aquaponics, a debate whether the system is more economically advantageous than coupled aquaponics is still ongoing [38]. The sustainability of decoupled aquaponics with respect to their higher energy requirements is also questioned. However, from the viewpoint of circular economy, the increase in nutrient utilization (mainly of phosphorus) allowed for by the digestion of extracted fish sludge in the anaerobic reactor is worth the increase in energy demands. The energy can be provided using a renewable source, which would increase the sustainability of the decoupled aquaponics [38].

2. IMPLEMENTATION OF ALGAL BIOREACTOR INTO AN AQUAPONIC CYCLE

The presence of microalgae in the aquaponic system is usually regarded as worrisome. The influence and mechanisms of algae presence in aquaponics were well described by Addy et al. [39], and this chapter is largely based on the information provided in this publication.

Microalgae can clog water piping [39] and if left untreated their decomposition leads to large consumption of oxygen dissolved in water, potentially endangering the lives of fish. The presence of uncontrolled algae in aquaponics also causes larger diurnal pH and DO (dissolved oxygen) swings due to the cycle of photosynthetic daytime growth and night-time perspiration.

Implementing microalgae in a controlled manner can on the other hand provide an aquaculture system with added benefits. Microalgae can help remove large quantities of nutrients while concurrently improving the water quality. If managed properly microalgae can help balance pH drops caused by the nitrification process and can also increase DO in water. The potential of microalgae to generate additional income should also be mentioned. Increased levels of income can be achieved either by using microalgae as a feed supplement, reducing the costs of fish feed or by selling the microalgae for further processing [39].

2.1 MECHANISM AND POTENTIAL OF ALGAL BIOREACTOR

The potential of a microalgal bioreactor for the removal of nutrients and water purification can be assessed only after one has first reviewed the equivalent mechanisms in conventional aquaponics. Such review must consider the function of the biofilter and the ability of plants to remove nutrients from the water.

A biofilter is a crucial component in most aquaponic configurations and serves to maintain a steady-state of an entire system. Toxic forms of nitrogen such as ammonia and nitrite are converted in a biofilter to a less toxic form, nitrate, which is also more accessible for plant uptake [29]. However, the process of nitrification taking place in the biofilter is quite pH-sensitive, requiring the pH to be in the range of 7 – 8 for the ideal functioning [39], [51]. The biofilter thus requires precise and quite delicate pH management. The need for such pH stability could be viewed as a potential weak point of the aquaponic system. Furthermore, even in cases where ammonia conversion is stable, the system still needs a steady rate of nitrate removal by plants. Nitrate is not nearly as toxic as ammonia or nitrite but in large quantities, it still creates considerable stress for the fish population [42]. For the successful large-scale implementation of aquaponics, a backup system for ammonia and nitrate removal should be considered.

Algae, differing from most plants usually implemented in aquaponics, can utilize both ammonia and nitrate for their growth. Furthermore, this utilization of ammonia and nitrate can be done in wide ranges of pH (5,5 – 9) [39]. Microalgal bioreactor could therefore act as a sort of backup for ammonia and nitrate removal. Was the function of biofilter to be hindered in any way, or the nitrate uptake capacity of plants reduced, conventional aquaponics farm has no backup system for ammonia or nitrate removal. In both cases, the fish population and consequently revenue generation of the entire production are threatened.

The microalgal bioreactor is also capable of balancing the pH of the aquaponic system. The nitrification process, discussed in the previous paragraph, among other outcomes, lowers the pH of the environment where it takes place. In autotrophic growth, algae can conversely increase the pH of their surroundings acting as a counterweight to nitrification. In this manner, microalgae can improve the stability of the aquaponic cycle [39].

As it was previously mentioned, another potential benefit of microalgal bioreactor is the increase in DO levels in the process water. Under photoautotrophic conditions, algae produce oxygen through the process of photosynthesis (simplified in Eq. 4) [39].

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

Eq. 4 Photosynthesis (simplified) [39]

It is evident from an examination of Eq. 4 that for one mole of carbon dioxide one mole of oxygen is released. Since there are low quantities of organic carbon in the process water itself, the carbon needed for photosynthesis is supplied from the atmosphere. The oxygen released from photosynthesis is then effectively added to the aquaponic process water from outside of the process boundaries [39]. It must be mentioned however that the enrichment of water by oxygen provided from photosynthesis is only effective when algae are periodically harvested from the aquaponic farm, preventing their decomposition within the system [39]. Furthermore, the reduction in night-time perspiration should be addressed to maximize the addition of oxygen. This is most easily achieved by continuous or prolonged artificial illumination of algal bioreactors. Benefits should be contrasted with a potential increase in electricity consumption.

The ability of the algal bioreactor to improve the economic feasibility of aquaponics is founded on multiple ideas. Firstly, any aquaponic system is out of principle heavily dependent on fish feed [3]. It has been shown that fish feed represents 50 – 70 % of total fish production costs in aquaculture [29]. The reduction in the use of externally source fish feed would therefore dramatically improve the systems economic efficiency. Also, a debate has been recently ongoing whether the use of fishmeal-based fish feed in aquaculture and consequently in aquaponics is sustainable [69]. The algal-based fish feed has therefore been a focus of multiple studies [70], [71], and it has been shown to be an effective fishmeal-based fish feed replacement [69]. The studies have been successfully conducted on both omnivores' and carnivores' fish. Namely channel catfish (*Ictalurus punctatus,* omnivores'), tilapia (*Oreochromis* sp., omnivores') or red drum (*Sciaenops ocellatus,* carnivores'), were among the species to have taken algae-based fish feed supplements well [69]. However, the tests were mainly conducted utilizing only partial supplementation of a traditional fishmeal-based fish feed. One of the reasons behind the limitation is the fact that microalgae have large variations in their biochemical composition [69]. Species considered for a total replacement of traditional fish feed are therefore rare and can be hard to source. The economic benefit of algal-based fish feed is, however, apparent even for applications with only partial supplementation. Furthermore, applications, where a much wider range of algae can be used, offer an opportunity for process integration. Biodiesel production can serve as a good example. One of the outputs of biodiesel production, lipid extracted algae (LEA) has insofar been viewed as non-profitable. However, studies have shown the possible use of LEA as a fish-feed supplement [69]. In itself, biodiesel cannot as of now compete with traditional diesel when it comes to production costs. Together, the processes mutually improve their economic and environmental efficiency. Biodiesel production combined with bioreactor utilizing aquaponics could therefore present an interesting opportunity.

2.2 FACTORS INFLUENCING THE GROWTH OF ALGAE

The decision to include algae into aquaponics can be economically and environmentally beneficial only when conditions governing their growth are at least somewhat supportive. Among such conditions the concentrations of nutrients in the water, amount of natural/artificial light, available source of CO_2, and favourable range of water temperature can be named.

2.2.1 Nutrients

Most of the studies conducted on the integration of algae into aquaculture, hydroponics or aquaponics have shown a major potential in the removal of total dissolved solids (TDS), nitrogen and phosphorus [21], [72], [73].

Integration of microalgae into aquaponics is usually discussed with respect to nitrogen. The preferred types of nitrogen for assimilation differ among individual species of microalgae, with many favouring ammonium, a form highly toxic for fish [72]. After ammonium, nitrates are usually the preferred form, with some species even having the ability to utilize dissolved atmospheric nitrogen [74]. Generally, microalgae were shown to remove between 94,6 and 97,6 % of total nitrogen [72], up to 99,8 % of nitrates [73] and the levels of ammonium were shown to be practically immeasurable after two weeks following microalgae addition into the system [72]. Such high effectivity could however present a problem since apart from harvesting, the growth of microalgae is hard to manage. A concern could be expressed if a sufficient amount of nitrogen is going to be left for hydroponic component and nitrifying bacteria in a system utilizing a microalgae bioreactor. The idea has been debated by some authors and it was indeed shown that algae compete for nitrogen with both nitrifying bacteria and plants [39]. To prevent the bioreactor from potentially inhibiting the productivity of the hydroponic subsystem or biofilter, several approaches were proposed. Firstly, a bioreactor could be added into the aquaponic system after both biofilter and grow beds. Such configuration would allow adequate nutrient concentration for nitrifying bacteria and plants while also utilizing the supreme purification abilities of algae [39]. Alternatively, a bioreactor could be introduced in a decoupled manner, serving as a separate purification device after the nutrients were utilized first by plants.

To discuss the influence microalgae bioreactor could have on the aquaponic system, its ability to reduce concentrations of nutrient other than nitrogen is going to be discussed as well. Starting with phosphorus, the element is usually present in aquaponics in a form of phosphates. Species such as *C. vulgaris* or *T. obliquus* were shown to effectively remove up to 99,7 % of all phosphates present in the RAS [73]. Additionally, algae have been shown to have a much greater ability to effectively utilize all forms of phosphorus present in the aquaponic system compared to higher plants [72]. The utilization of microalgae in aquaponics would thus contribute toward a greater environmental effectiveness of this production system.

Generally, algae can take advantage of nutrient sources that are usually not available for uptake by higher plants. In the context of aquaponics, this can lead to the reduction of TDS present in the system. This ability was shown to be facilitated by the absorption of a wide range of salts and solids present in the process water, for example in the study focusing on *C. minutissima* [75]. A capability to reduce TDS could be beneficial towards fish welfare.

2.2.2 Source of CO_2

Along with phosphorus and nitrogen, carbon is the main nutrient for microalgae. To illustrate its crucial role, it can be shown that carbon is responsible for 30 to 50 % of microalgae dry weight [76].

As was discussed in chapter 2.1, carbon plays a critical role in the photosynthesis process and must be attained from outside of the aquaponic system. The carbon can be sourced by algae from CO_2 naturally present in the atmosphere, however, the effectivity of such a process is rather limited. It was shown in several studies [38], that if additional CO_2 is not added into the algal culture, its productivity might be reduced by up to 80 %. The most efficient way to add carbon into the bioreactor is by direct transfer from CO_2 gas. Carbon dioxide bubbles are introduced into the bioreactor using a system of pipes or porous stones.

However, using this method, large quantities of CO_2 are lost into the atmosphere due to the short retention time of the gas bubbles in the bioreactor fluid [38]. Modes of algal production utilizing the addition of carbon dioxide should therefore be considered mainly in areas where large quantities of flue gas or different CO_2-rich waste streams are present.

2.2.3 Light

Algae, being autotrophic organisms, need sufficient amounts of light to survive [77]. Light intensity above or below optimum range can cause photoinhibition or compromised photosynthetic activity. Both mentioned states negatively affect the efficiency of photosynthesis and consequently the rate of nutrient removal from the surrounding environment [78]. For example, in a study focused on the possible use of algae for purification of aquaculture wastewater, Fernandez et al. [79] reported N and P removal of 2 – 10 and 0,2 – 1,1 t/ha y^{-1} for low efficiency of photosynthesis, however for high efficiency, the removal reached 5 – 25 for N and 0,5 – 2,5 t/ha y^{-1} for P. The study was conducted on the topic of open photobioreactors which are usually described in terms of their area, hence the unit of nutrient removal per hectare. Generally, the study illustrates the importance of sufficient light intensity for an effective operation of an algal photobioreactor.

The source of required radiation can either be the sun or an artificial light source (typically LEDs). The crucial parameter is the length and intensity of provided illumination. Sun can be successfully used as a primary source if the location of an aquaponic farm can provide at least 2800 hours of sunlight per year, has annual mean daily temperatures of 12 °C or greater, and has at least 200 freeze-free days per year [77]. However, to reach maximal efficiency, continual illumination is preferred [78]. Either combination of natural sunlight during the day and artificial light during nigh-time or pure artificial lighting can be used. The work of Sukačová et al. [80] comparing the removal of total phosphorus from tertiary wastewater using algae under different illumination modes during the period of 24 hours can be used as an example. In the study, 97 % removal (3,25 mg/l to 0,082 mg/l) of total phosphorus by algae has been reported for continuous artificial illumination, whereas only 41 % removal (2,96 mg/l to 1,6 mg/l) was achieved under natural day/night light cycle.

Furthermore, sufficient illumination should be maintained in the entire body of the bioreactor, otherwise self-shading might become a limiting factor for algal growth. To maintain adequate levels of irradiance throughout the reactor, certain design choices can be made. Firstly, gentle mixing can be introduced [76]. In addition to the provision of illumination, this process also reduces the occurrence of nutrient gradients in the system, further improving the productivity of algae. Alternatively, shallow, or film reactors might be used. However, such designs often require large surface areas and are thus economically inefficient in most areas [76].

As was demonstrated in the previous paragraph, algal photobioreactors have multiple modes of operation with differing productivity, energy requirements and consequently economic outcomes. The design of any proposed aquaponics farm with photobioreactor included should be therefore based on an economic analysis, which closely examines discussed modes of operation and their consequent yields in relationship with additional costs for electric energy.

2.2.4 Temperature of the process water

The temperature of the environment is known to have an impact on the productivity of microalgae. Algal biomass is generated during daytime (under illumination) and lost during nighttime due to the metabolization of reserve biomolecules [81]. Both daytime generation and night-time loss are influenced by the temperature of the surrounding environment [81].

The goal of design or controlling should therefore be to maximize daytime growth and minimize night-time loss. To achieve such a goal, the ideal conditions for examined algae strain must be discussed.

Each strain of microalgae has a slightly different optimal growth temperature. For purpose of design, it can be generally stated, that temperatures in the range of 25 – 30 °C were found to be optimal for most strains of microalgae during their daytime biomass generation [78].

However, for the needs of finer regulation within the system, it must be mentioned that individual chemical elements are removed from the surrounding environment at different rates depending on the temperature of said environment. For example, Huo et al. [82] have reported maximal removal efficiency of 93,11 % for total nitrogen at 30 °C using cultures of *Tribonema sp.* Nevertheless, for total phosphorus and NO_3^- the peak efficiencies of 94,11 % and 98,75 ˇ% respectively were found to be at 25 °C. This phenomenon could allow the operator of the bioreactor to finely adjust the rate of uptake of individual nutrients based on the current needs of the system, by regulating the temperature of the system. Designs featuring adjustable shading or covers of bioreactors could be considered.

Algae can be placed both indoor and outdoor, often depending on the desired mode of operation and local conditions. Outside, natural temperature variance can be substantial, changing daily and seasonally. Such conditions result in lower productivity. Furthermore, the risk of contamination is high and is reflected in the market potential of algae produced in this manner [78]. On the other hand, outside configurations are cheaper to build and run. The consumption of electricity is reduced substantially by omitting the need for LED illumination [78]. In a contrast, an inside-located production allows for closer regulation of the temperature, higher productivity, and better marketability of the resulting product [78]. When designing an algal photobioreactor, all the abovementioned properties of inside and outside-located production should be closely considered.

2.3 METHODS OF ALGAE CULTIVATION

There is a large number of possibilities when it comes to choosing the method of algae cultivation. Differing in complexity and productivity, the main motivation behind the final selection is usually an economic consideration followed by an examination of local environmental constraints (temperature, amount of natural sunlight etc.). The three main systems used for algae cultivation are open ponds, closed photobioreactors and their combination under the name of hybrid algae production systems.

2.3.1 Cultivation in open ponds

Open ponds, most commonly implemented in the form of raceways, were one of the first types of algal bioreactors to be used [76]. In principle, they are formed when an open, rectangular area is divided into two or four channels. In these channels, a suspension of nutrient-rich water and algae is circulated using a system of paddles. Canals are relatively shallow with depths ranging from 200 to 400 mm to maintain adequate illumination in the entire body of the reactor [76]. The entire system has a width to length ratio between 1:10 and 1:20. Commercial units are often constructed only by using a system of walls on a polymer lined compacted soil, such a configuration can be seen in Fig. 26 [83]. Generally, the productivity of a raceway system is highly dependent on utilized algae strain with values in the range of 10 to 40 g m^{-2} day^{-1} [76].

Fig. 26 Commercial raceway microalgae bioreactor [83]
(for license details see page 93)

Overall, raceway systems are easy to construct and operate [38]. On the other hand, they offer only limited atmospheric CO_2 and light utilization, have comparatively large water losses due to evaporation and require large areas (100 to 5000 m^2) [76]. The resulting biomass productivity is among the lowest of any bioreactor type due to low mass transfer caused by inefficient stirring. Furthermore, as with any open system, there is a risk of outside contamination, both biological and chemical. In extreme cases, the reactor might become infested with an organism predatory towards algae, endangering the entire operation [77]. Despite all the abovementioned drawbacks, the raceway systems are among the most frequently used designs for the commercial production of microalgae, mostly utilizing fast-growing, resilient strains [76].

2.3.2 Cultivation in closed photobioreactors

Closed photobioreactors, as the name suggests, are reactors with algal cultures separated from an external environment by a type of barrier. They are generally found in two basic configurations, tubular and flat-plate [76].

Tubular photobioreactors are the most common design, and the units are composed of two main subsystems, a photostage loop, and a mixing (or retention) tank. The photostage loop is an arrangement of usually glass or plastic tubes with a typical diameter of 100 mm. The suspension of algae and nutrient-rich water is kept circulating in the photostage loop using pumps [76]. Photosynthesis and biomass growth of algae occurs in the photostage loop. Afterwards, the suspension continues into the retention tank where it is stripped of the dissolved oxygen [76].

The reduction in levels of dissolved oxygen is necessary in closed systems due to the accumulation and consequent saturation of the process water with photosynthesis products (oxygen). Upon reaching oxygen saturation, the chemical reaction occurring during photosynthesis cannot take place and the resulting biomass production is inhibited. To prevent this from happening, tubular PBRs implement two design choices. Firstly, they are limited in the lengths of the photostage loop to values between 20 and 400 m based on the flowrate of the suspension (0,1 to 0,8 m s^{-1}) [76]. Secondly, a retention tank is implemented into the closed tubular PBRs. Here, the levels of DO in the suspension are lower by surface diffusion into introduced bubbles of air [76]. Furthermore, CO_2 is typically added to the suspension in the retention tank. The mixing/retention tank is also the location where integration with aquaponics would take place. Instead of streams of air bubbles, the DO levels would be decreased by plants, fish and biofilter.

The alternative design to a tubular PBR, as mentioned at the beginning of this chapter, is a flat-plate photobioreactor. Similarly to tubular, flat-plate PBRs are comprised of photostage and a retention tank. The main difference is in the design of the photostage, which here is a system of interconnected units where a suspension of algae and water is circulated using pumps. Each unit is composed of two parallel panels (PVC, glass, polycarbonate, polyethylene) with a thin layer of microalgal suspension in-between [76]. The basic units are then stacked vertically as displayed in Fig. 27 [84].

Fig. 27 Flat-plate algal photobioreactor [84]
(for license details see page 93)

The advantage of a flat-plate configuration in comparison with tubular design stems from the increase in area under direct illumination and the ease of maintenance. The resulting system has high productivity and efficiency. Furthermore, designs with direct implementation of oxygen degassing into the plate units have been proposed and successfully tested [76].

One of the considerations that must be made when designing a closed photobioreactor is its cooling. No evaporation is effectively allowed in closed PBRs, and consequently, the suspension circulated in the photostage loop can be heated to dangerous temperatures, potentially compromising the health of the algal cultures. Mechanisms such as automated shading, surface water cooling or implementation of heat exchangers are thus usually considered [76].

Stacks of two flat-plate PBRs similar in configuration to a plate heat exchanger, where a cooling solution is circulated in the central level, were also investigated [76].

Lastly, the productivity of closed photobioreactors is measured as a weight of gained biomass per volume and day. For both tubular and flat-plate PBRs, the productivity between 0,5 and 2 g L^{-1} day^{-1} can be achieved [76].

When compared to open raceways, closed photobioreactors (PBRs) offer many benefits. The risk of contamination is reduced, closed systems do not require large areas to be built on, and achieved yields are greater. The overall evaporative loss from PBRs is also greatly reduced, making the practice more efficient with respect to freshwater sources [38]. Furthermore, the system can be more closely managed in terms of temperature, pH, CO_2 supplementation or mixing [77]. However, all the abovementioned benefits come at a price of increased complexity, and consequently, higher initial capital costs. The difference can be substantial, in certain scenarios even making the cost-per-weight of algae produced in the PBRs comparable with raceways [77]. The choice between open and closed bioreactors is therefore often made based on land cost and availability or on the ability of desired algae strain to sustain itself in the environment of the respective reactor [76].

2.3.3 Hybrid algae production systems

Hybrid algal production systems are a mix of closed and open systems, trying to achieve a synthesis with benefits of both maximized, and drawbacks minimized [77]. The system is again separated into two sections, photostage and retention (degasser) tank. The photostage is an open area, where a thin layer of algal suspension flows on an inclined platform or system of cascades [76]. The flow is comparatively fast and turbulent with natural evaporation maintaining relatively stable temperatures of the mixture. The direct exposure to the sun and shallow depths of the flowing film ensure high photosynthetic effectivity [76]. The photostage has an outlet into the degasser tank, where the DO levels of the suspension are decreased. Furthermore, CO_2 addition can be easily incorporated into the degasser tank, making the system more productive [76]. Afterwards, the solution is recirculated to the top of the inclined platform or cascade with a pump.

Generally, the system preserves the ease of maintenance and simplicity typical for open reactors while also reaching high volumetric productivity and relatively good manageability associated with closed systems [77]. The design also displays qualities favourable with respect to potential integration into aquaponics. A configuration can be envisioned where the inclined cascades are situated on the top of the hydroponic component, serving as a sort of roof. Such configuration would also maximize the use of available sunlight. The harvesting of produced algae could also be well managed, with only partial harvests possible.

2.4 HARVESTING AND PROCESSING OF ALGAE

Microalgae range in size from 1 to $30 \cdot 10^{-6}$ m. While this form-factor allows them to easily stay afloat in a suspension, it also makes microalgae hard to harvest [77]. Effective harvesting method must in some cases achieve an increase in mass concentrations from a 0,05 % to 15 – 25 % [38].

The choice of harvesting method is a crucial step in designing a microalgal bioreactor since it can impact both the economic and ecological efficiency of the whole bioreactor setup. Generally, the required high increase in concentration is most effectively achieved using a combination of methods depending on the final use of the product and harvested algal strain. Some possibilities along with a general summary are therefore presented on the following page. However, the harvesting of microalgae is a dynamically developing field, and it is not possible to provide an in-depth overview within the limits of this work.

Table. 2 Summary - harvesting methods suitable for microalgae [76], [77]

CATEGORY	TYPES	SUMMARY
FLOCCULATION	- pH dependent autoflocculation - Electrocoagulation - Using metal salts ($FeCl_3$, $Al_2(SO_4)_3$) - Bioflocculation - Using (bio)polymers	- possible incompatibility with aquaponics (large shifts in pH) - some are very promising (electrocoagulation) - possible contamination of final product (metal salts) - the process water cannot be reused after usage of some flocculants
TECHNOLOGIES UTILIZING GRAVITY	- Centrifugation - Flotation - Gravity settling	- highly energy-demanding (centrifugation) - only work in combination with other methods (gravity settling + flocculation, flotation + flocculation)
TECHNOLOGIES UTILIZING FILTRATION	- Filtration - Membrane filtration	- high recovery efficiency - can be used on shear-sensitive strains - only work in combination with other methods (filtration + flocculation) - allow for process water recycling

2.5 POTENTIAL USE OF THE PRODUCTS OF AN ALGAL BIOREACTOR

The areas for the potential use of microalgae-based products are numerous. It is not within the scope of this work to discuss these areas in detail, however, a broad outlook is provided in the form of a Table. 3 and Table. 4.

Table. 3 A broad outlook into areas of the possible use of microalgae-based products, part 1 [76]

CATEGORY	ADDITIONAL INFORMATION	AREA OF USE/STATUS
HIGH-VALUE EXTRACTS	Proteins (Phycobilins)	Pharmaceutical and cosmetics industry
	Polhydroxyalkonates (PHA)	Biodegradable plastics
	Polyunsaturated fatty acids (Omega 3 acids)	Feed supplements and farmaceutical industry
	Carotenoids (β-Carotene)	Feed supplements and farmaceutical industry

Table. 4 A broad outlook into areas of the possible use of microalgae-based products, part 2 [76]

CATEGORY	ADDITIONAL INFORMATION	AREA OF USE/STATUS
ENERGY PRODUCTION	Biogas production	Research is ongoing – uncompetitive costs
	Bioethanol production	Research is ongoing – uncompetitive costs
	Biohydrogen production	Research is ongoing – uncompetitive costs
	Biodiesel production	Research is ongoing – uncompetitive costs
FOOD AND FEED PRODUCTION	Food supplements	Powders, tablets, and capsules made from whole microalgae
	Food and feed ingredients	Protein, lipid, and peptide food additives
	Feed supplements	Whole or extracted microalgae-based supplements for poultry, pork, aquaculture, and ruminant feed

3. EXAMINED AQUAPONIC FARM

One of the aims that were set out to be achieved in the thesis is to construct a mathematical model of nutritional flows in an aquaponic farm. Created model should be capable of estimation of process conditions based on ratios of fish/plants and theoretically the size of microalgae bioreactor. Such a model must however be tested or built using real-world data to ensure its capabilities. To attain viable data from a real-world aquaponics farm, a measurement by an accredited laboratory was conducted. The farm taking part in the measurement was an experimental unit run by Flenexa plus s.r.o., a company situated near Olomouc, Czech Republic. The company and its representatives kindly cooperated and were very accommodating during the entire process of writing this work.

3.1 INTRODUCTION OF THE STUDIED SYSTEM

The farm in question was created mainly for experiments and as a proof of concept. It is therefore desirable for the farm to be as close to a future "industrial" standard as possible. The farm has a total water volume of 5900 l and is comprised of a single water-circulating loop, making it a coupled system. The hydroponic part is realised in a form of four DWC grow beds, which are illuminated by LED lights. The aquaculture part produces catfish, trout, and sturgeon from a singular fish tank. The system also utilizes mechanical and biological filtration complemented by aeration. The circulation is maintained using two pumps, one sump pump and one after fish tank. The examined farm itself is situated in an old military bunker, where thick concrete walls provide stable ambient temperature and humidity. According to an international survey conducted by Love, et al. [65] in 2015, 77 % of aquaponic farms were using deep water culture (DWC), either alone or in combination with other production types. An average aquaponic farm was culturing two fish species, but more than 30 % were producing three or more. As for individual species, the choices were quite diverse, however, catfish (25 %) and trout (10 %) were among the most common. The aquaponic farm in operation by Flenexa plus s.r.o. is, therefore, a very good representation of an average industrial practice.

The information contained in the following chapters (subchapters of chapter 3) is based on updated measurements conducted by Ing. Ondruška [85], measurements by an accredited laboratory, and consultations with representatives of Flenexa plus s.r.o.

3.1.1 Aquaculture section

The aquaculture section of the examined farm is composed of a fish tank, air pump, automatic fish feeder, freshwater inlet, circulating pump, and a regulating reverse stream with a hand-operated butterfly valve [85].

The fish tank level is maintained at approximately 2200 l and its maximum capacity is 120 kg of fish. Generally, a single growth cycle for utilized fish species takes approximately 6 months, which makes the productivity of the system to be a total of 240 kg/y. The conditions within the fish tank (temperature, electrical conductivity, pH) are monitored to ensure the presence of a favourable environment for fish. Furthermore, the levels of dissolved oxygen are also increased in the fish tank by an air pump.

Additionally, the fish tank is a location where any system water losses are compensated by the operator, who periodically adds freshwater into the system using a hand-operated valve at the freshwater inlet. The volume of fresh water added to the system is recorded via a flow recorder.

After the water has been enriched in nutrients in the fish tank, the circulating pump provides the work necessary to transport the water to grow beds. The circulating pump maintains a flowrate of 1077 l/h.

The circulating pump is also equipped with an emergency stop, which is controlled based on the sump tank critical level transmitter. Should the sump tank pump, or any necessary sensors fail, the circulating pump would be stopped in time as not to cause sump tank overflow.

Detailed information on water circulation is provided in the following table.

Table. 5 Water balance of the aquaculture component

FISH TANK - MAINTAINED AT 2200 L			FLOWRATE
INLET	Within system boundaries	**Return from the sump tank**	1076 l/h
	Outside system boundaries	**Freshwater inlet**	1 l/h
OUTLET	Within system boundaries	**Circulating pump**	1077 l/h
	Outside system boundaries	**Evaporation**	Not measured

In the aquaculture component, the electrical energy is mainly consumed by illumination, circulating pump and air pump. Since the entire system is situated in an old military bunker, the fish tank is artificially illuminated using a conventional light bulb. Automatic feed is also utilized in the described farm, however, its electrical consumption can be neglected.

Detailed information on electrical energy consumption is provided in the following table.

Table. 6 Energy balance of the aquaculture component

DEVICE	POWER CONSUMPTION
CIRCULATING PUMP	1,44 kWh/d
ILLUMINATION	2,4 kWh/d
AIR PUMP	1,8 kWh/d

3.1.2 Filtration

After the process water is enriched by nutrients originating from a fish feed in the fish tank, it continues into mechanical and biochemical filtration units. Apart from these units, the filtration section also consists of two hand-operated water outlets and an air pump.

Firstly, the process water is purified from any solid particles in the mechanical filter. The filtration is necessary to separate any undissolved solids from the water stream. Otherwise, such solids, mainly composed of organic matter, would settle, and decompose either inside grow beds or in the sump tank. Decomposition of organic matter consumes dissolved oxygen and consequently inhibits plant nutrient uptake and reduces fish welfare. Both outcomes are inadmissible in an aquaponic system.

Next, water purified from solid particles continues into biofilter. Inside the unit, nitrogen present in the process water is transformed from a compound highly toxic towards fish (ammonia) into a form that is more accessible for plant uptake (nitrates). The process of nitrification utilizes special strains of bacteria, which are seeded into the biofilter at the process start-up [51]. The bacteria require a large surface area to latch onto and hence, the biofilter tank is filled with Pall rings.

The bacteria can also be susceptible to water quality changes, for this reason, both mechanical and biochemical filters are equipped with temperature, electrical conductivity, and pH monitors. Furthermore, the process of nitrification consumes a large amount of dissolved oxygen. To maintain sufficient levels of DO in the system, an air pump is connected to the biofilter.

As was already discussed, mechanical, and to a certain extent, even biochemical filter are locations where solid particles concentrate in an aquaponic system. Thus, both units require regular removal of amassed sludge and for that purpose are equipped with hand-operated outlet valves. In the examined farm, the process of sludge removal accounts for a 1 l/h loss of process water.

Detailed information regarding water and energy balances are presented in Table. 7 and Table. 8.

Table. 7 Water balance of the filtration section

FILTRATION SECTION			**FLOWRATE**
INLET	Within system boundaries	**Circulating pump**	1077 l/h
OUTLET	Within system boundaries	**DWC grow beds**	1076 l/h
	Outside system boundaries	**Sludge discharge**	1 l/h

Table. 8 Energy balance of the filtration section

DEVICE	**POWER CONSUMPTION**
AIR PUMP	0,816 kWh/d

3.1.3 Hydroponic section

Following the purification and nitrification processes in the filters, the process water continues to the hydroponic section of the aquaponic cycle. The complete hydroponic section of examined farm incorporates an air pump, 4 DWC grow beds, 4 LED panels, a ventilation system, and a water quality control system.

Firstly, before the water enters the grow beds, additional DO is supplied by an air pump to improve nutrient uptake of plants. In the examined farm, the subsequent hydroponic section is configured as two pairs of DWC grow beds connected in parallel. The water stream is therefore split into two branches, one with a flowrate of 516 l/h and the other with 560 l/h. The grow beds themselves have a volume of 800 l each and the hydroponic section has a total capacity of 400 plants. The farm grows lettuces, mainly a more profitable Cousteau variety. With a typical growth cycle length of 20 days, the farm can produce up to 7300 pieces of vegetable per year. To make such productivity possible, each grow bed is paired with an adjustable LED panel supplying the plants with sufficient illumination. Due to the insulation provided by the thick concrete walls, the panels are also used as a sole heating element of the whole farm.

Air circulation is another critical element when it comes to maintaining proper conditions for plant growth. In the farm in question, the circulation is maintained by a system of fans comprising of a central fan and a smaller fan for each of the grow beds. Lastly, each grow bed is equipped with temperature, electrical conductivity, and pH monitors.

Detailed information regarding water and energy balances are presented in Table. 9 and Table. 10.

Table. 9 Water balance of the hydroponic component

4 DWC GROW BEDS – EACH 800 L, 100 PCS OF LETTUCE			FLOWRATE
INLET	Within system boundaries	**Branch 1**	560 l/h
	Within system boundaries	**Branch 2**	516 l/h
OUTLET	Within system boundaries	**Sump tank**	1076 l/h
	Outside system boundaries	**Evaporation**	Not measured
	Outside system boundaries	**Evapotranspiration of plants**	Not measured

Table. 10 Energy balance of the hydroponic component

DEVICE	POWER CONSUMPTION
AIR PUMP	1,8 kWh/d
LED PANELS	4·8,64 = 34,56 kWh/d
CENTRAL FAN	0,46 kWh/d
GROW BED FANS	4·1,92 = 7,68 kWh/d

3.1.4 Sump tank

After the plants strip the process water of some of the present nutrients, the water continues into the sump tank. Here, to enable the circulation of the stripped water back to the fish tank a sump pump must be implemented. Furthermore, being the lowest point of the entire system, the sump tank inherently accumulates process water. Should a failure in some of the components occur, the threat of sump tank overflowing exists. To counter this threat a system of sensors and controllers is implemented.

The sump tank is only a flow-thru element and does not require a detailed water balance. Generally, the element is designed as a stabilization measure. To avoid the introduction of additional stress to fish, the recirculatory pump system is set up in a way to allow for minimum level changes in the fish tank. Three level transmitters are implemented in the sump tank, high, low and critical-high. The high-level transmitter triggers the sump pump, which continues its operation until the low-level transmitter is activated. The third, critical-high-level transmitter, cuts off power from the fish tank pump in the event of sump tank levels uncontrollably growing. Without the fish tank pump in operation, the circulation is stopped and the flooding is avoided.

Table. 11 Energy balance of the sump tank

DEVICE	POWER CONSUMPTION
SUMP PUMP	0,54 kWh/d

3.2 BALANCES OF THE STUDIED SYSTEM

Complete information regarding flowrates and volumes of crucial process components is presented in the following Fig. 28. The information provided here has been incorporated into the mathematical models which are going to be introduced in chapter 4.

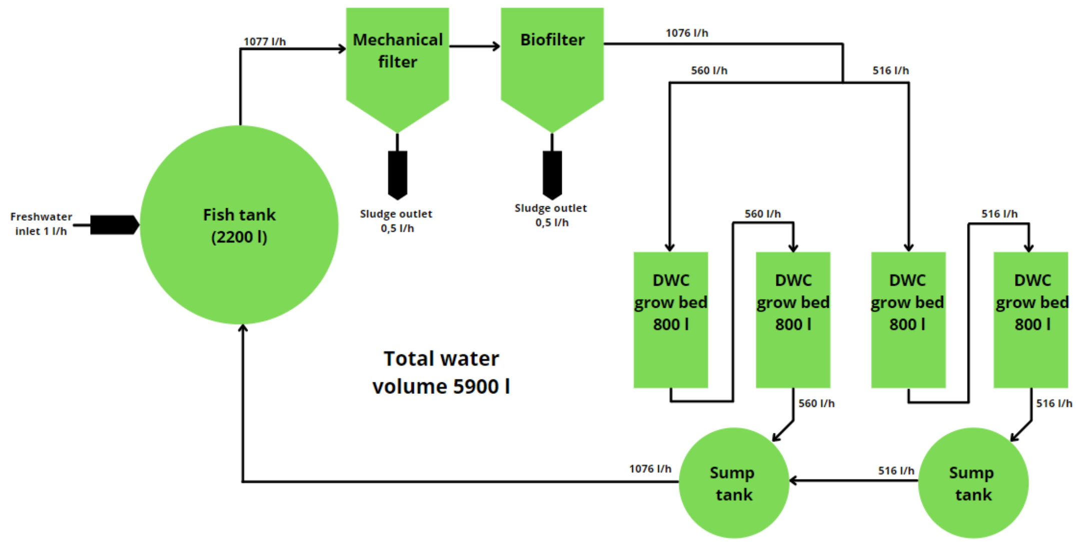

Fig. 28 Simplified diagram of an aquaponic cycle utilized in the examined farm
(for license details see page 93)

The total electrical energy consumption is summarized in the graph in Fig. 29.

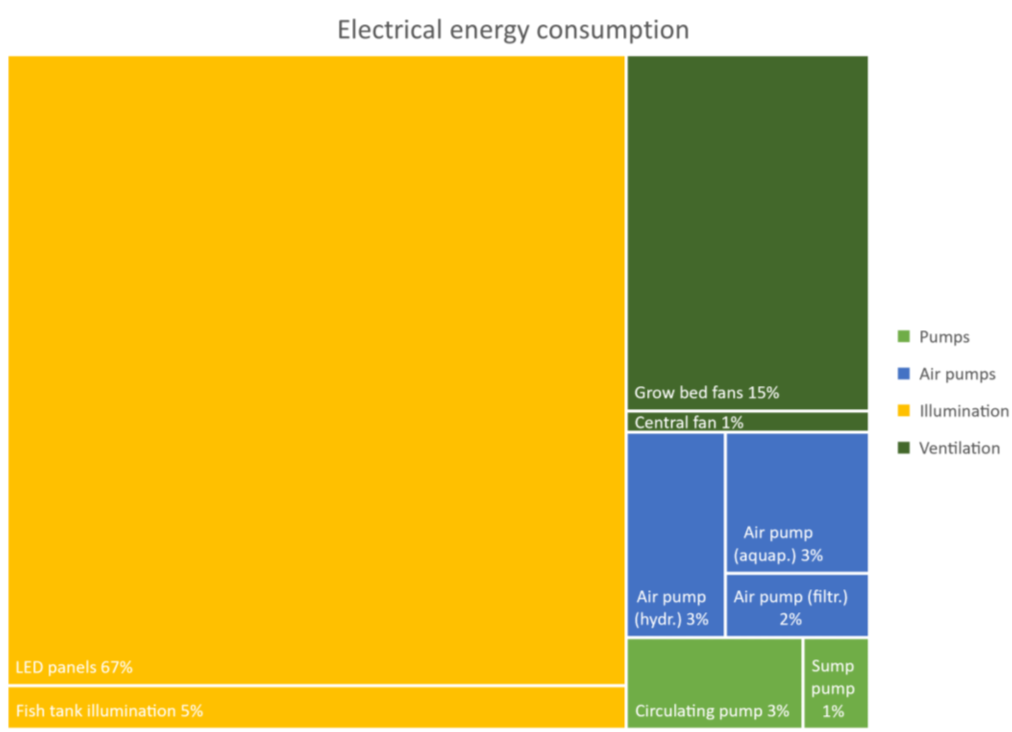

Fig. 29 Summarization of electrical energy consumption of examined aquaponic farm
(for license details see page 93)

Several conclusions can be drawn based on the data presented in Fig. 29. Firstly, the illumination system has by far the greatest contribution towards the total electrical power consumption. The efficiency of illumination systems should be a priority when designing aquaponic farms. Furthermore, when considering the integration of algal bioreactor(s), the power consumption of required additional LED panels should be closely contrasted with the benefits of such integration. As was discussed earlier, bioreactors provide the highest benefits when the night-time perspiration period is reduced to a minimum. This effectively means maximized artificial illumination and consequently a notable increase in power consumption. The idea of implementation of outdoor bioreactors in a commercial setting thus seems to present a more viable option both from the economical and environmental point of view.

Secondly, the power consumption of ventilation systems could present an interesting area for improvements. A system for utilization of natural air movement and circulation could be integrated into farms located in greenhouses where automation of windows or air ducts is imaginable. Such installation would however inevitably increase shifts in ambient temperature and humidity of the hydroponic subsystem climate. Additional challenges in the overall management can therefore be expected.

Lastly, during the design of an aquaponic system, attention should be focused more on minimizing the need for additional air pumps, rather than circulation pumps. The difference in electrical power consumption between designs utilizing one and two circulating pumps is going to be minimal compared to the difference in designs actively incorporating aeration and thus reducing the number of air pumps in the system. The design presented in Fig. 22 is a great example of a direction the industry could take to minimize the need for aeration. Alternatively, the ability of microalgae bioreactor to increase levels of DO has been previously discussed in this text. The inclusion of such a bioreactor could then reduce the need for air pumps, and at least in this area, reduce electrical power consumption.

3.3 SELECTED AND MEASURED NUTRIENTS

In the measurements conducted by an accredited laboratory between 19th January and 20th April 2021, several nutrients were monitored to create a complete nutritional description of three aquaponic farms. Measurements were performed as a part of an ongoing project based on the cooperation between Flenexa plus s.r.o. and several working groups in connection with the Institute of process engineering, Brno University of Technology. All farms partaking in the project were run by Flenexa plus s.r.o., one of the farms being the unit described in the previous chapter.

The parameters monitored during the measurements can be divided into two main categories, 1. Inorganic nutrients, where the focus was on various forms of nitrogen and phosphorus compounds but also a sulphur compound. The 2. category was Dissolved metals, where additional macro (Ca, K, Mg) and micronutrients (B, Cu, Fe, Mn, Mo, Zn) along with known pollutants (Ag, Na) were assessed. The most influential of the mentioned nutrients were already described in the previous parts of the text.

Detailed results and additional information cannot be provided due to concerns regarding intellectual property and know-how violations. However, general outcomes regarding the farm described in the previous chapter are going to be discussed. Furthermore, graphs showing trends in the development of nutrient concentrations which were used during the formation of the mathematical models are going to be provided in the next chapter and as the appendix. To maintain transparency and avoid the need for this work to be classified, the values of concentration on these graphs were left out.

3.3.1 Results of the measurements

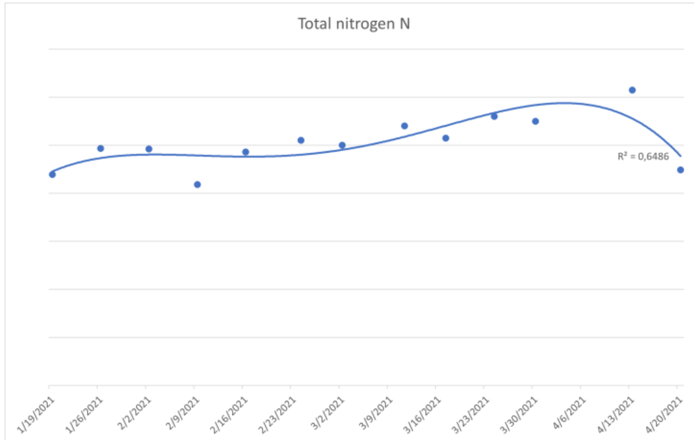

Fig. 30 Total nitrogen concentration development in the examined aquaponic farm between 19th January and 20th April 2021 – concentration values were left out due to possible issues with know-how and intellectual property violations
(for license details see page 93)

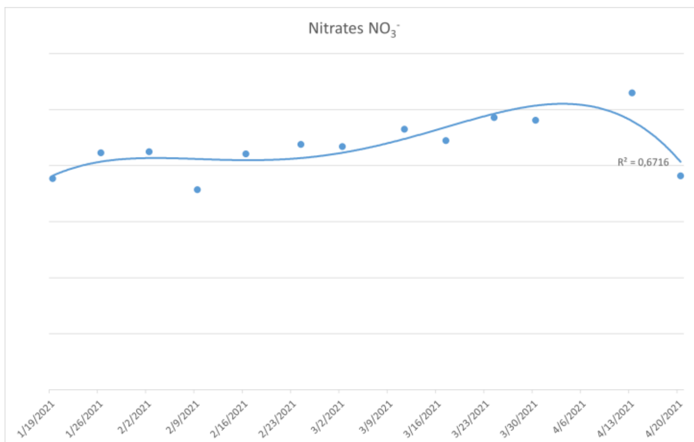

Fig. 31 Concentration development of nitrates in the examined aquaponic farm between 19th January and 20th April 2021 – concentration values were left out due to possible issues with know-how and intellectual property violations
(for license details see page 93)

It is evident from the comparison of the two figures above (Fig. 30 and Fig. 31), that the concentration developments are practically matching for total nitrogen and nitrates. This effectively means that nitrogen is present mainly in various forms of nitrates. It is therefore clear that the biofilter present in the examined aquaponic farm is working as intended. Furthermore, the concentration levels are relatively steady throughout the whole period of measurement, indicating a solid, constant nitrogen uptake by plants. An adequate source of nitrogen is therefore present in the system at all times. However, the relatively high levels of nitrates also suggest that the hydroponic component fulfils its water cleaning role only partially. Consequently, there is a clear potential for the implementation of either additional grow beds or the previously discussed algal photobioreactor into the examined aquaponic system. Both the economic profitability of the system and fish welfare would be improved.

The concentration developments for total phosphorus and potassium levels are provided in Appendix A – total phosphorus and potassium concentrations development.

4. MATHEMATICAL MODEL

The following chapter is going to deal with the completion of some of the main goals of this work. Namely, it is the creation of a mathematical model predicting the changes in nutrient concentrations in an aquaponic system and an implementation of an algal bioreactor into such a model. It has been decided by the author of this work to create two separate models utilizing different approaches to demonstrate potential possibilities for this task. Both models have been written using Visual Basic for Applications and the user environments have been created in a form of Microsoft Excel workbooks.

The first model (Model 1) is strictly statistical and deals with a pure aquaponic system, without an algal bioreactor. One of the strengths of said model is the inbuilt database, which offers a significant advantage when it comes to the initial stages of the aquaponic cycle. This database was created based on measurements conducted on a real-world aquaponics farm. Furthermore, the model is capable of a continuous improvement of the background mathematical models based on the data provided by the user during individual growing cycles. Such a feature offers a certain level of flexibility with respect to the types of aquaponic systems it can accommodate. However, this comes at a cost of neglecting some phenomena influencing the nutrient concentrations. The basic mechanism of Model 1 is presented in Fig. 32, the model is going to be described in greater detail in chapter 4.1.

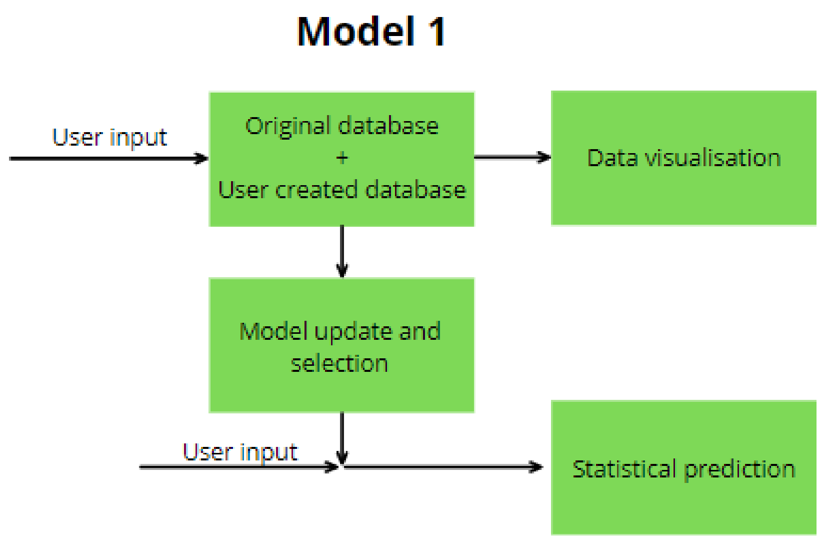

Fig. 32 Diagram of a continuously improving model of nutrient concentration in aquaponic cycle
(for license details see page 93)

The second model (Model 2) implements a more physics-based approach and also accounts for an influence of an algal bioreactor. It offers data for particular species of plants, algae and types of fertilizers and fish feed. These datasets were created based on measurements of a real-world aquaponics system described in the previous chapter and an extensive literature review. To avoid any conflicts regarding intellectual property and know-how, the names of plant and algae species, along with fertilizers and feed were anonymized. Overall, the model is more in-depth when it comes to the calculation of individual nutrient concentrations, it is however more constrained when it comes to the types of aquaponic units it can accommodate for. The basic mechanism of Model 2 is presented in Fig. 33, more information on this model is provided in chapter 4.2.

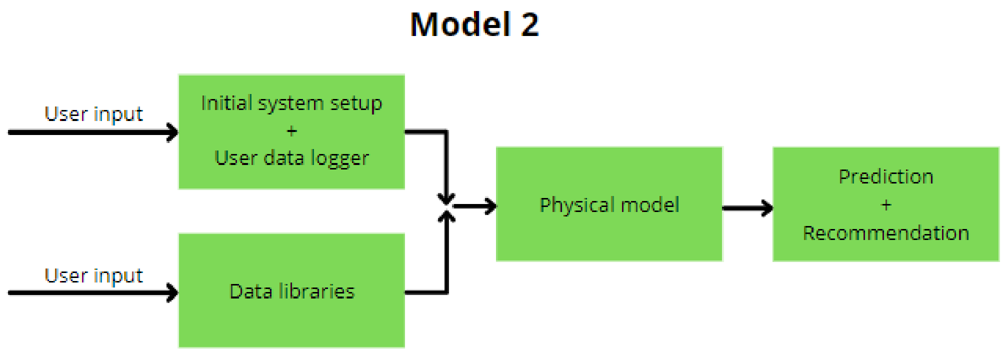

Fig. 33 Diagram of a model for aquaponics with nutrient removal by algae
(for license details see page 93)

It must be noted that both models were created with the possibilities of future development in mind. As of now, they provide predictions and calculations for three foundational macronutrients, nitrogen (or NO_3), phosphorus and potassium. However, they are written in a way that allows for a quite simple expansion and addition of other important nutrients. Furthermore, the physics-based model has libraries for nutrient-related data of plants, fish feed, fertilizer, and algae, which are open for editing, allowing the user to provide data measured or otherwise obtained by themselves. It must also be stressed that aquaponics is a highly complex system with numerous influences. Any created models can thus be considered, to a varying degree, simplistic. It was of utmost importance to the author of this work to create models sufficiently capable to serve as a base for further development and to provide most of the value in the form of decision methodology used behind both models.

4.1 CONTINUOUSLY IMPROVING MODEL FOR GENERAL AQUAPONIC CYCLE

The founding idea behind the creation of Model 1 is the need for a prediction tool to help bridge situations where the knowledge of the system mechanisms is limited. Such need might for example arise when a new system is entering working service. In such situations, the behaviour of the system can become difficult to predict with the use of purely physics-based models due to the operation of individual subsystems (biofilter, plant root system) not yet being stabilized. For complex systems, such as aquaponics, statistical models based on previous experience can be of great service in such dynamic settings. Model 1 is therefore based on statistical analysis and helps solve these situations by utilising a database built from past industrial experience with similar, difficult to model situations. Model 1 then allows the operator of the aquaponic system to predict, with a certain degree of confidence, the nutrient concentrations present in the system and consequently prevent critical situations from happening. The model aims to provide its user with a qualified estimate of a nutrient concentration, rather than a precise value which would be hard to model. In situations similar to system start-up, qualified estimates can provide feedback value to a user and serve as a good basis for decision making.

4.1.1 Mechanism

To better introduce the continuously improving model, a basic workflow is now going to be described with detailed information on each essential process presented in the following chapters.

The procedure of Model 1 starts with user input. The model allows its user, even retrospectively, to input several key information about their aquaponic system. Namely measurement date, measured nutrient concentration, the weight of the feed and fertilizer added in that day, system volume and if an event has taken place. These indicators are recorded for each nutrient and are logged into two databases, one so-called Original, and the other Alternative. In the databases, logged indicators serve as a basis for the formation of three regressors which in turn are the substructure for the mathematical models.

During the procedure, models are created both based on the Original and Alternative dataset. The mathematical model based on the Original dataset is always linear and follows Eq. 5. Coefficients a, b, c, and d are obtained using VBA built-in ordinary least square method (OLS).

$$a \cdot x_{index} + b \cdot x_{feed} + c \cdot x_{fertilizer} + d = y_{nutrient\ conc.}$$

Eq. 5 Linear model based on Original dataset

This model is primarily used during the immediate start-up of an aquaponic system. When enough data has been gathered for the system on which the model is used, alternative mathematical models are created. The minimal size of the alternative dataset for the alternative models to be created is based on the recommendation made by T. Agami Reddy [86] and expressed in Eq. 6. For this application, 20 data points are set as the limit, since three regressors and intercept are used with 5 chosen as a multiplicator.

$$(5\ to\ 8) \cdot x_{maximum\ number\ of\ regressors} = y_{minimal\ dataset\ size}$$

Eq. 6 Minimum size of the dataset [86]

Created alternative models are of three types, linear, exponential, and polynomial. The mechanism behind their formation and selection is going to be described in detail in chapter 4.1.3.

Upon creation/update of original and alternative models, the best fitting one is chosen, and the tool is ready to be used for prediction. When a user wishes to make a prediction, they provide information about planned events, amounts of feed, and fertilizer to be added. The tool then uses the previously selected best-fitting model to compute nutrient concentrations. These are provided in a form of a range with a 95 % probability of occurrence.

Furthermore, the model allows for a visualisation of both the Original and Alternative datasets. The interface of Model 1 along with worksheets for data visualization is presented in *Appendix B – Continuously improving model for general aquaponic cycle, the interface*. The data visualization worksheet for alternative models is not presented in a complete form, as indicated by the grey bar. This part has been left out since it is a repetition of what is already displayed, only for each type of alternative models.

4.1.2 Database and user database creation

It was described in the previous chapter that the first step in Model 1 workflow is logging of measured data. The date of measurement, nutrient concentration, the weight of the feed and fertilizer added in that day, system volume and an event occurrence are recorded. Out of these, an index, added fish feed per litre of system volume, and added fertilizer per litre of system volume are computed to serve as regressors for mathematical model creation. The computation follows Eq. 7 and Eq. 8.

$$x_{feed}[g/l] = \frac{m_{fish\ feed\ added}\ [g]}{V_{process\ water}[l]}$$ *Eq. 7 Regressor – fish feed added per system water volume*

$$x_{fertilizer}[g/l] = \frac{m_{fertilizer\ added}[g]}{V_{process\ water}[l]}$$ *Eq. 8 Regressor –fertilizer added per system water volume*

The importance of the chosen regressors stems from the fact that feed and fertilizer are the main sources of nutrients entering the aquaponic system. The index then expresses a time that has elapsed since an occurrence of an irregular event which is hard to precisely describe in terms of influence on nutrient concentrations. An event is for example when the slurry is discharged. In this version of the model, only events which decrease concentrations are accounted for. This decision is further discussed in chapter 4.3.

Computed regressors are stored in two parallel datasets, Original and Alternative, for each of the monitored nutrients. The need for two separate datasets arises out of the basic idea behind Model 1. The tool aims to provide data from other aquaponic installations to help predict concentrations in hard-to-model situations. This feature is realised in the form of Original dataset. Regressors in Original dataset, mainly data about nutrient concentrations, were constructed from measurements conducted on an experimental farm described in chapter 3. These measurements were carried out by a certified laboratory between 19th January 2021 and 20th April 2021. The original dataset provided by the laboratory was modified by the author of this work to avoid any intellectual property and know-how violations. Original dataset is then based on these experimental farm measurements and offers gathered information for future users. The model is created in a way as to allow for further expansion of this dataset, which would increase its informational value.

However, as was said, the model concurrently creates Alternative dataset. This feature originates in an assumption that individual aquaponic farms differ in mechanisms that reduce or increase nutrient concentrations – be it in types of plants grown, species of fish cultured or in the general design of the aquaponic farm. Most of the aquaponic farms would thus differ in behaviour from farm(s) upon which the Original dataset is based. It is, therefore, necessary to transfer to either a detailed physics-based model or assess the compliance of the studied aquaponics farm with the Original dataset as soon as possible. Alternative model, which is comprised out of data recorded purely on an individual aquaponic farm, then allows to statistically examine whether data measured on the examined farm are in agreement with data contained in Original dataset. In the case of both datasets statistically differing, only models based on the Alternative one would be used.

4.1.3 Model selection and improvement

The central parts of the Model 1 tool are its databases. The tool improves as the databases grow. To allow for such improvement, mechanisms continuously enhancing mathematical models were implemented. Upon an event of the addition of new data, several actions take place.

Firstly, the original model is updated using the newly obtained data by recomputing coefficients a, b, c and d as described in Eq. 5.

Secondly, if the condition of sufficient size of Alternative dataset is met, alternative models are created/updated as well. Alternative models are not limited when it comes to the number of used regressors. However, every model is utilizing an intercept, which is essentially a fourth regressor. Thereafter, the intercept is always discussed separately and by the word regressor, either index, feed or fertilizer are implied.

The process of model creation/update is underlined in Fig. 34. The underlying code utilizes the method of *All possible regression models* [86] for each of the model types and is described on the following page.

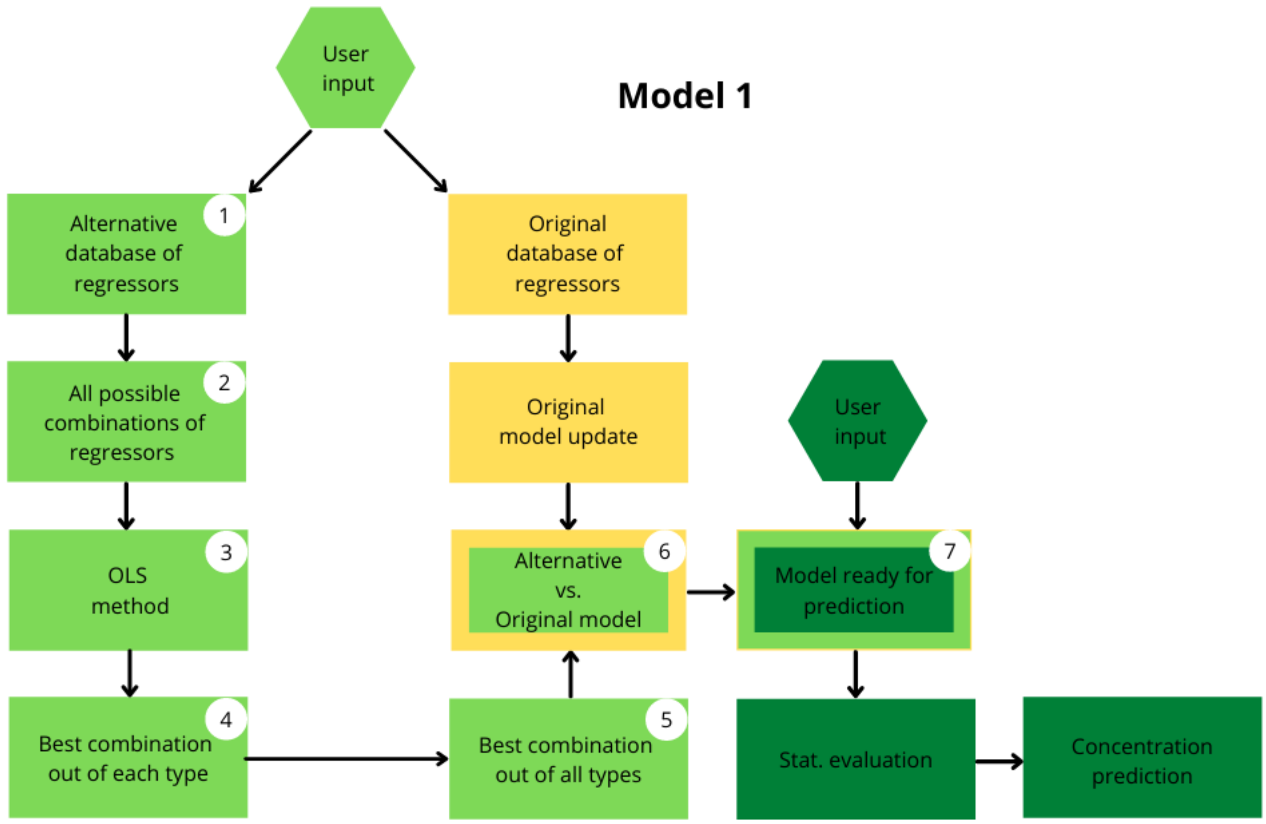

Fig. 34 Detailed diagram a continuously improving model of nutrient concentration in the aquaponic cycle (for license details see page 93)

Block 1 along with the yellow path were already described in the previous chapters, the rest of this chapter then covers light green blocks from 2 to 6.

Starting with block 2. As was already mentioned, the tool uses three types of mathematical models, linear, exponential and polynomial. For each of these models, the update/creation process starts with a recursive function. This function takes all available regressors (3 for this model, however, the function would work for any reasonable number in an event of future expansion) and creates an array of all possible combinations of these regressors expressed in a "binary" format. For example, a model utilizing index and fertilizer would be expressed as 101 following the order of regressors outlined in Eq. 5 (first regressor is index, second feed and third fertilizer). As discussed earlier, the inclusion of intercept is implied.

For n regressors used in a model, the function produces 2^n of combinations. In the model, the first combination is always left out since it is one where none of the regressors are used. The output of block 2 is then an array of all possible combinations of available regressors without the 000 (or equivalent if a larger number of regressors is used) combination. This process is concurrently happening for each type of the model (linear, exponential, and polynomial) and each followed nutrient (N, P and K).

In block 3, a corresponding number of coefficients a, b, c or d are computed for each combination and model type using a VBA built-in *OLS method solver*. The estimated form of linear model was already described in Eq. 5, exponential model (the type 111) is then depicted in Eq. 9 and polynomial model (111) is in Eq. 10.

$$d \cdot \left(a^{x_{index}} + b^{x_{feed}} + c^{x_{fertilizer}}\right) = y_{nutrient\ conc.}$$

Eq. 9 Form of exponential model used in Model 1 tool

$$a \cdot {x_{index}}^{e_1} + b \cdot {x_{feed}}^{e_2} + c \cdot {x_{fertilizer}}^{e_3} + d = y_{nutrient\ conc.}$$

Eq. 10 Form of polynomial model used in Model 1 tool

The coefficients e_1, e_2 and e_3 are computed in VBA code utilizing Solver to maximize models R^2 value, which signifies Coefficient of determination as defined by T. Agami Reddy [86].

Next, various statistical indicators were computed for each model in the resulting set to later allow for a selection of the best combination of regressors. The first indicators are a *Coefficient of determination* R^2, which is taken from the result provided by the VBA built-in *OLS method*, and a *Corrected coefficient of determination* $\overline{R^2}$ as defined by Eq. 11.

$$\overline{R^2} = 1 - (1 - R^2) \cdot \frac{n-1}{n-k}$$

Eq. 11 Corrected coefficient of determination [86]

Both are widely used goodness-of-fit measures and provide values in the range between 0 and 1, where a value closer to 1 signifies a better model fit with respect to founding data [86]. Other computed indicators are a *Standard error of the estimate* (RMSE) defined in Eq. 12, and two Coefficients of variation, first (CV) based on Eq. 13 and second (CV*) according to Eq. 14. RMSE is an absolute measure of model error and has units corresponding to a dependent variable. CV and CV* are then measurements of an error which is expressed as a percentage of the mean value of a dependent variable. A large difference between CV and CV* signifies inadequateness of the model in extreme ranges of variation of the response variable [86] and is therefore undesirable.

$$RMSE = \left(\frac{\sum(y_i - \hat{y}_i)^2}{n-k}\right)^{1/2}$$

Eq. 12 Standard error of the estimate [86]

$$CV = \frac{RMSE}{\bar{y}}$$

Eq. 13 Coefficient of variation [86]

$$CV^* = \left\{\frac{1}{n-k}\sum_{i=1}^{n}\left[\frac{(y_i - \hat{y}_i)}{y_i}\right]^2\right\}^{1/2}$$

Eq. 14 Coefficient of variation based on alternative definition [86]

The last statistical indicators were Mean absolute deviation (MAD), F-statistic and its critical value for each combination along with student t-statistics (and their critical values) for each regressor present in respective combination.

MAD is defined in the form of Eq. 15, the F-statistic was taken from a result of VBA built-in OLS solver and was compared to an F-critical value. To be able to reject the null hypothesis that all regressors are equal to 0, and thus prove the significance of the respective model, the F-critical value was obtained using VBA built-in function. This function F.INV.RT provides an F-critical value for right-tailed F-distribution and was set up to 95 % confidence level, k-1 degrees of freedom in the numerator and n-k degrees of freedom in denominator. The t-statistic was computed as defined in Eq. 16 and was used to test individual coefficients obtained in OLS ($\widehat{\beta_1}$) against the alternative hypothesis of them being equal to 0 ($\beta_{1,0}$). Standard error value for the respective coefficient ($se(\widehat{\beta_1})$) was again obtained from result of the built-in VBA OLS method solver LinEst. The t-critical value to compare with t-statistic was obtained using VBA built-in function T.INV.2T. This function provides t-critical values for two-tailed distribution and was set up to 95 % confidence level and n-k degrees of freedom. T-stat being larger than t-critical would then confirm the significance of the respective regressor.

$$MAD = \frac{\sum_{i=1}^{n} |y_i - \hat{y}_i|}{n-k}$$

Eq. 15 Mean absolute deviation [86]

$$T_0 = \frac{\widehat{\beta_1} - \beta_{1,0}}{se(\widehat{\beta_1})}$$

Eq. 16 Student t-statistic [86]

After all the statistical indicators are computed, the tool then uses them to select the best combination of regressors for each type of model – block 4 from Fig. 34. The selection process utilized in block 4 and designed by the author of this work is described in Fig. 35.

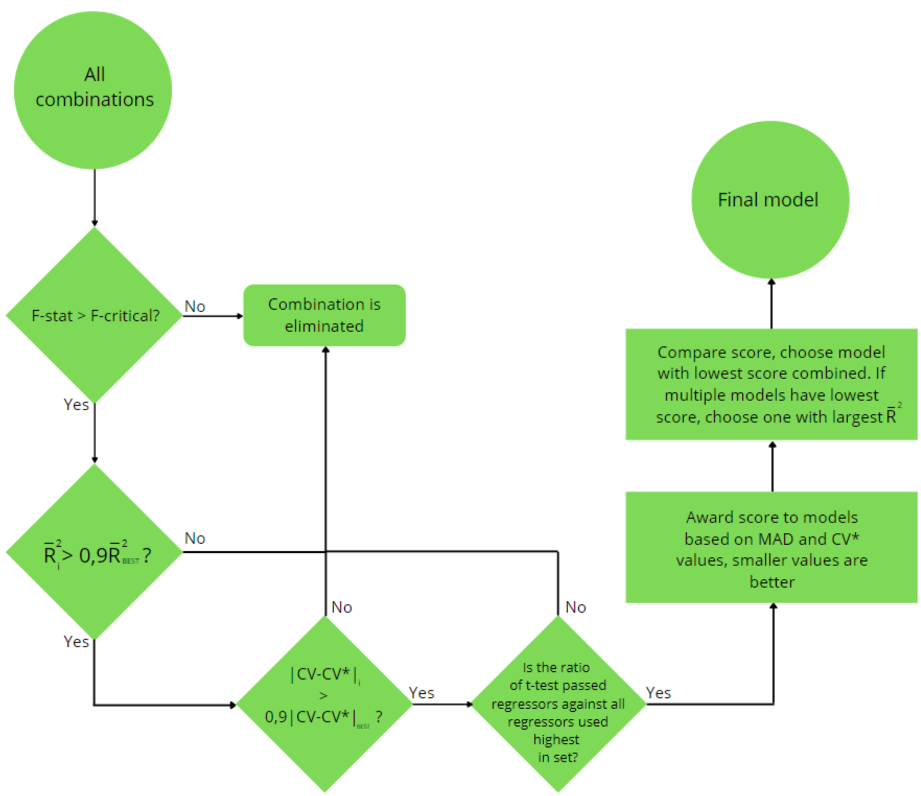

Fig. 35 Model selection algorithm
(for license details see page 93)

The algorithm described here is employed several times. First to find best-of-its-type models for each type (linear, exponential, and polynomial), then out of these the best alternative model (block 5, Fig. 34), and finally to compare the best alternative model and the original one (block 6, Fig. 34).

Firstly, the statistical significance of a particular model is checked using F-test. Next, only the models with the best goodness-of-fit expressed by the corrected coefficient of determination are allowed to continue in the selection process. The difference of CV and CV* is checked afterwards, and to ensure adequateness of selected models on the entire range of response variable, only models with the smallest difference continue. To prevent models with statistically insignificant regressors from occurring in the selection, the ratio of t-test passed regressors against the number of regressors used in a particular combination is checked. Again, only models with the highest reached ratio continue. Finally, all models present in the selection are awarded a score based on their MAD and CV* values, with smaller, preferred values awarded with a smaller score. Both scores for MAD and CV* are added and a model with the lowest overall score is selected as the best model of its type. If more than one model has the same, lowest score, a model with the best goodness-of-fit is selected.

Generally, the process in blocks 4, 5, and 6 of Fig. 34 is identical. However, the selection process between the best alternative and the original model has its specifics. The statistical indicators for both models are based on different datasets and are therefore incomparable. To solve this problem, an additional set of statistical indicators based only on data measured on the particular aquaponic farm is constructed for the original model. This set then allows a comparison between original and alternative models to choose the best overall nutrient concentration predicting model.

4.1.4 Prediction

This chapter follows the dark green path outlined in Fig. 34, where utilising the best overall model, the user can predict future nutrient concentrations occurring in the aquaponic system. Upon the input of all necessary indicators (weight of fish feed, fertilizer, and event occurrence) the algorithm produces a range of nutrient concentrations into which a future value will with a probability of 95 % belong. The upper (URB) and lower range boundaries (LRB) are computed as described in Eq. 17 and Eq. 18.

$$LRB = y_{pred.nutrient\ conc.} - t_{crit} \cdot \sqrt{Var(\tilde{e})}$$

Eq. 17 Lower range boundary of prediction [86]

$$URB = y_{pred.nutrient\ conc.} + t_{crit} \cdot \sqrt{Var(\tilde{e})}$$

Eq. 18 Upper range boundary of prediction [86]

The value t-critical mentioned in Eq. 17 and Eq. 18 is obtained using VBA built-in function T.INV set to 95 % confidence level and n-k degrees of freedom. The term $\sqrt{Var(\tilde{e})}$ a standard error of the forecast is defined by the Eq. 19, the bold font refers to the matrix form of the term.

$$Var(\tilde{e}) = \sigma^2\left(\mathbf{1} + \widetilde{\boldsymbol{X}} \cdot (\boldsymbol{X}^{\boldsymbol{T}} \cdot \boldsymbol{X})^{-\mathbf{1}} \cdot \widetilde{\boldsymbol{X}}^{\boldsymbol{T}}\right)$$

Eq. 19 Definition of a standard error of the forecast [86]

Based on calculations discussed on previous pages, the model can provide its user with a qualified estimate of concentrations of key monitored nutrients. It can also serve as a basis for future development since the underlying code was written in a general, easily adaptable way.

4.2 MODEL OF AN AQUAPONIC CYCLE WITH NUTRIENT REMOVAL BY ALGAE

The model of an aquaponic cycle with nutrient removal by algae, or Model 2 as it is referred to during the following chapters, is physics-based. The model works on the idea of nutrient flows, where after the definition of input and output flows along with the initial system state, the tool can predict changes in nutrient concentrations. Furthermore, the tool suggests actions available for the operator in the event of the prediction falling outside of the recommended range for a particular nutrient.

To make the tool more user-friendly and flexible, it is equipped with data editable libraries filled with information founded on measurements conducted on a real-world aquaponics farm or based on extensive literature review. Users can select plants, algae species, types of fertilizers or types of fish feed from a drop-down list, which lessens the need for a highly skilled aquaponic operator. Additionally, the libraries are opened for editing. Users can therefore add any information on fertilizers, fish feed or plant and algal species of interest which makes the tool future-proof to the potential developments in the industry.

4.2.1 Mechanism

To better introduce the model of an aquaponic cycle with nutrient removal by algae, a basic workflow is now going to be described with detailed information on each essential process presented in the following chapters. A diagram of Model 2 is in Fig. 36 to better illustrate its inner operations.

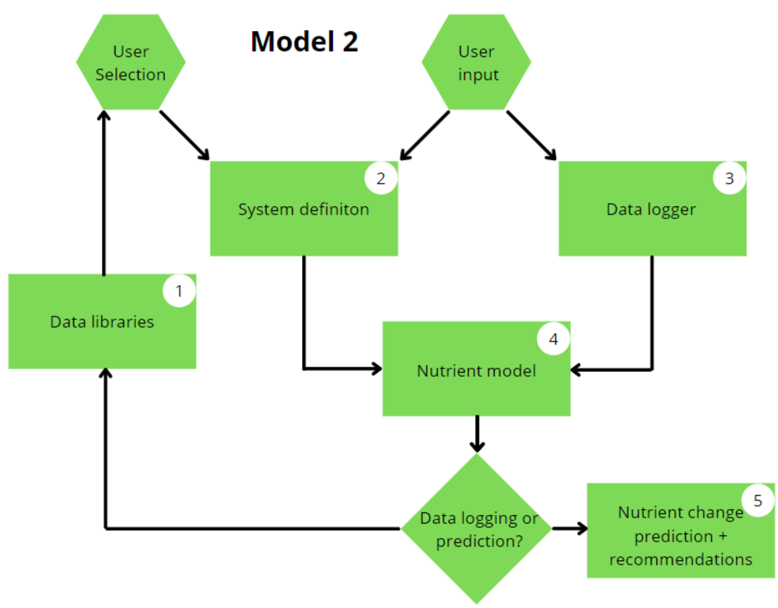

Fig. 36 Detailed diagram of a model of an aquaponic cycle with nutrient removal by algae
(for license details see page 93)

The procedure of Model 2 begins with the user defining the aquaponic cycle. Starting with general information, the total volume of water present in the system, along with daily evaporative loss is determined. For the hydroponic subsystem, the number and the species of plants are defined, and concerning the algal bioreactor, species of plants and the volume of the reactor are established. Lastly, the user must provide starting concentrations for monitored nutrients, in this case, phosphorus, potassium and nitrate (NO_3). In the process of system definition, the user already utilizes the data libraries prepared in the tool.

In the next step, the tool provides the user with two options. Either to log daily changes in the system without any predictions or to predict the nutrient changes which would occur under provided circumstances. In both processes, a computational model is applied to calculate nutrient concentrations. The model for i-the nutrient and j-th time-period is described in Eq. 20 and Eq. 21, their use is governed by the process water. The first equation is used when a discharge has occurred, the second equation then serves for all other scenarios.

$$c_{i,j}\left[\frac{mg}{l}\right] = \frac{m_{i,j-1} - \Delta m_{i,j} - m_{alg,i} - m_{plnt,i} + m_{fert,i} + m_{feed,i}}{V_{sys,j}}$$

Eq. 20 Equation for a nutrient concentration in the event of process water discharge

$$c_{i,j}\left[\frac{mg}{l}\right] = \frac{m_{i,j-1} - m_{alg,i} - m_{plnt,i} + m_{fert,i} + m_{feed,i}}{V_{sys,j}}$$

Eq. 21 Equation for a nutrient concentration for events excluding process water discharge

Now, individual components from Eq. 20 and Eq. 21 are defined in the following equations. All variables are then described in the Nomenclature. However, the element describing nutrient uptake by algae is notable in its implementation of dimensionless η_{j-1}. This variable is called reactor productivity and was used by the author to express the exponential nature of algal activity concerning 1. Their natural growth cycle and 2. Time elapsed since the last algae harvest. The percentage of algae harvested is provided by the user in the system update. Based on this information, the tool updates the reactor productivity [87].

$$m_{i,j-1}[mg] = c_{i,j-1}\left[\frac{mg}{l}\right] \cdot V_{sys,j-1}[l]$$

Eq. 22 Total weight of the nutrient in the system j-1 time-period

$$\Delta m_{i,j}[mg] = c_{i,j-1}\left[\frac{mg}{l}\right] \cdot \left(V_{sys,j-1}[l] - V_{sys,j}[l]\right)$$

Eq. 23 Weight of the nutrient lost in the event of process water discharge

$$m_{alg,i}[mg] = V_{PBR,j-1}[l] \cdot \eta_{j-1}[-] \cdot \rho_{alg,i}\left[\frac{mg}{l}\right]$$

Eq. 24 Weight of the nutrient lost to an algal bioreactor

$$m_{plnt,i}[mg] = n_{plnt,j-1}[pcs] \cdot \rho_{plnt,i}\left[\frac{mg}{pcs}\right]$$

Eq. 25 Weight of the nutrient lost to plants

$$m_{fert,i}[mg] = c_{fert,i}[-] \cdot m_{fert}[g] \cdot 1000$$

Eq. 26 Weight of the nutrient added in a form of fertilizer

$$m_{feed,i}[mg] = (m_{feed}[g] - m_{feed}[g] \cdot \eta_{ret}[-]) \cdot c_{feed,i}[-] \cdot 1000$$

Eq. 27 Weight of the nutrient added in a form of unretained fish feed

With the concentrations prepared, the tool provides recommendations based on the resulting values. Interface which facilitates user interaction with Model 2 is provided in *Appendix C – Model of an aquaponic cycle with nutrient removal by algae, the interface*.

4.2.2 Data libraries

Model 2 has a built-in database for plant species, fish feed, fertilizers, and algae species. As of now, the contents of libraries are relatively sparse and serve mainly as a foundation for future development and proof of concept. However, the values included in libraries are based on either real-world measurements, information kindly provided by RNDr. Kateřina Sukačová Ph.D. or information obtained from extensive literature review [57], [88], [89], [90], [91], [92], [87].

4.2.3 Recommendations

Based on the literature review, allowable ranges for studied nutrients were set as follows: total potassium 50 – 200 mg/l, total phosphorus 5 – 50 mg/l and NO_3 50 – 200 mg/l [42]. If a prediction falls outside any of these ranges, the algorithm offers its user a solution to prevent such a situation from occurring.

Generally, there are two possible unwanted scenarios, either the concentration of nutrient is above, or below the allowable limit. In both scenarios, the model localizes the nutrient with the highest deviation from its respective limit value. This nutrient is then used to calculate suggestions.

For the scenario of one or more nutrients exceeding their limit value, the system suggests the addition of freshwater into the aquaponic system. The amount of water is computed using the following Eq. 28. The need for a limit of system water volume is discussed in chapter 4.3.2.

$$\Delta V_{fresh}[l] = \frac{m_{i,j-1} - m_{alg,i} - m_{plnt,i} + m_{fert,i} + m_{feed,i}}{c_{i,critical\ high}} - V_{sys,j}$$

Eq. 28 Suggested amount of fresh water to be added

The second scenario is the one where insufficient concentration is present in the system for at least one of the monitored nutrients. In this event, the system computes the amount of additional fertilizer of chosen type that must be added to the system. This process is conducted based on the following equation.

$$m_{fert}[g] = \frac{c_{i,critical\ low} \cdot V_{sys,j} - m_{i,j-1} - m_{feed,i} + m_{alg,i} + m_{plnt,i}}{c_{fert,critical} \cdot 1000}$$

Eq. 29 Suggested amount of fresh water to be added

The resulting weight added to the aquaponic system then ensures that at least the minimum recommended concentration is maintained for all monitored nutrients. Based on calculations discussed on previous pages, the model can provide its user with information regarding concentrations of key monitored nutrients. It can also serve as a basis for future development since the underlying code was written in a general, easily adaptable way.

4.3 Comments and ideas for further development

Some of the ideas for further possible improvements of Model 1 and Model 2 are going to be discussed in the following chapters.

4.3.1 Model 1

Starting with Model 1, the idea of the addition of larger numbers of events into its database has been mentioned in the text previously. The model should account for more events that decrease nutrient concentrations, such as system cleaning, or hydroponic substrate exchange, which can both inhibit the function of naturally occurring bacterial colonies facilitating nitrification [24]. Furthermore, an entire class of events that lead to an increased presence of nutrients in the system ought to be considered. The exceeding of nutrient limits in aquaponics is much more serious when compared to the presence of lower concentrations. Higher nutrient concentrations can dramatically increase the stress of fish and consequently their mortality [42]. From the viewpoint of both animal welfare and economics, the events increasing nutrient concentrations should be a priority in the future development of Model 1.

Other, more fundamental change in the Model 1 has also been considered by the author. This would be the shift from a prediction of total nutrient concentration to the prediction of a daily change in concentration. This modification would lead to greater precision of the entire model and would also simplify the potential fusion of Model 1 with Model 2. The reason behind not implementing this mechanism from the start was the concern of loss of ability for retrospective data logging. The concern has however proven to be unfounded during further research. The shift to the prediction of daily change would therefore be highly beneficial towards the overall precision of Model 1. It is however reasonable to expect a need for larger changes in the code of the tool when implementing this proposed shift.

4.3.2 Model 2

When it comes to Model 2 there are several ideas for its improvement. The tool is physics-based, and therefore when modelling a complex system, certain simplifications were unavoidable. Several dynamic aspects of the aquaponic system were neglected and described as unchanging, mostly for the lack of data. For example, the nutrient uptake by plants changes depending on the stage of their development, and for some aquaponic configurations, the daily evaporative loss changes seasonally. Both processes could be described in detail by utilization of additional data libraries.

The tool also neglects irregular events which were described in Model 1, for example, sludge discharges. Since these events are quite hard to model using a purely physics-based approach, it was decided by the author to not include them. The model would thus benefit from integration with Model 1, as was already proposed earlier. Moreover, this unification would also improve the ability of Model 2 in terms of data logging. In the presented version, the model does not allow its user to log nutrient concentrations measured in the system. The system always predicts them using the underlying computational model and this approach might be problematic.

Another idea regarding potential improvements of Model 2 is the introduction of the system volume limit. When suggesting the addition of fresh system water in the event of nutrient concentration exceeding their upper limit, the tool does not have any information regarding maximum system capacity. Could the tool access similar information, it would be able to suggest a process water exchange, rather than top-up. Upon implementation of this feature, it is reasonable to expect a decrease in fresh-water requirements of the system and consequently improvements in its environmental efficiency.

Lastly, were the model to be adapted to predict concentrations of micronutrients, rather than macronutrients some aspects would have to be changed. For example, the model utilizes a single index to express fish nutrient retention along with mineralization. Even if simplifying, this approach is not as problematic for macronutrients as it would be for micronutrients, where even small changes in concentration can have lasting consequences. The quantities of nutrients mineralized or retained by fish change for each nutrient, and the introduction of a larger number of indexes would have to be considered to ensure a higher precision of the prediction.

5. SUMMARY

AQUAPONICS

Aquaponic production systems are a new, emerging technology, representing a synergistic combination of aquaculture and hydroponics [14]. In a world with growing populations [4], where a long-term growth in demand for food can be expected [18], [19], [20], the shortcomings of traditional agriculture must be addressed. With 70 % of fresh water and 30 % of energy consumption worldwide traceable back to food production [12], aquaponics offers a promising alternative. The founding idea behind aquaponics is the principle of process water recirculation. Apart from substantial savings in freshwater inputs, aquaponics then also maximizes the utilization of nutrients contained in the fish feed. Consequently, the practice displays significant savings in water, fertilizer and pesticide inputs when compared to traditional agriculture [6]. Furthermore, aquaponics can be highly flexible when it comes technological complexity of its design. High-tech, automated aquaponic farms would find their application in rich urban centres where they could present a more local, and more sustainable alternative to traditional food production [13]. On the other hand, low-tech configurations would offer an economically accessible way to improve the food security of the developing world [1]. Additionally, the products of aquaponics are already well integrated into the diets of populations worldwide [18]. Thus, if the produced species are chosen correctly for the local market, the lack of demand should be of no concern.

In general, every aquaponic farm has an aquaculture and a hydroponic subsystem. The configuration of these subsystems then defines whether the aquaponic farm is of coupled or a decoupled type. The decoupled system is a more novel one, implementing distillation/desalination units along with an anaerobic digester [68]. The system has only a unidirectional flow of process water from aquaculture to hydroponics. Consequently, both main subsystems can be managed separately, and achieve conditions closer to their respective ideals [57]. However, the resulting increase in productivity over a coupled system must be contrasted with larger production expenses. Thus, the debate over which system is a more profitable one is ongoing [38]. In contrast, the coupled system has all the components as a part of a single water recirculation loop. Apart from the aquaculture and hydroponic subsystem, coupled aquaponic farms are comprised of a biofilter, mechanical filter and pumps [38]. The environment of the aquaponic farm must be managed as a single unit and resulting conditions are therefore a certain compromise between fish and plant needs. However, the productivity of such a system is still higher than that of standalone aquaculture and hydroponics [57], [58]. Complex interactions between fish, plants, and bacterial colonies occurring in the aquaponic water are credited for this otherwise unexplained phenomenon [66]. In the course of this work, when an aquaponic system is discussed, a coupled type is implied. Additionally, since the experimental farm examined in this work is of a coupled type, this design has been the main focus during the creation of the thesis.

Starting with the aquaculture component, it is commonly designed as a recirculatory aquatic system (RAS). In RAS, fish of a chosen species are located in artificial tanks under high stocking densities. Feed is provided for them in a form of pallets, however, only about 25 % of nitrogen (and other nutrients) contained in the fish feed is utilized by the fish metabolism [29]. The remaining nutrients are released into the surrounding environment as waste products. Without the implementation into aquaponics, daily water exchange of 5 – 10 % of total system volume is required in RAS to keep the waste concentrations at levels non-poisonous for fish [29].

However, when implemented into aquaponics, the required system freshwater inputs are reduced to 2 – 3 % of the total system volume per day [28]. Furthermore, the nutrients not utilized by the fish are converted in a biofilter to be then available for plant uptake and not wastefully discarded [51].

After the RAS, solid particle filtration usually follows. Here, clarifiers or swirl separators are used to remove solid particles from the stream of aquaponic process water [38]. The removal is necessary to prevent the creation of anoxic zones with denitrifying effects which would decrease levels of dissolved oxygen and plant-available nitrogen.

The levels of plant-available nitrogen are also the focus of the adjacent process unit – the biofilter. Inside the biofilter tank, colonies of nitrifying bacteria are growing on the available surfaces (usually Pall rings) where they facilitate nitrification [51]. A process during which ammonia, a nitrogen form highly toxic to fish, is transformed into nitrates, form both available for plant uptake and less harmful for fish [51].

Consequently, the nutrient-rich water is subjected to nutrient removal by plant uptake in the hydroponic subsystem. Three main types of hydroponic component designs are possible based on the intended scale of the system.

- Media Bed type – is a design using tanks filled with a type of growing media (coconut fibre, stone wool, polyurethane foam etc..) in which plants are anchored. The system has different properties based on the media type used. Generally, it allows for the production of large plants which can be problematic under different system designs. The design is often used in non-commercial settings, where the benefits of inherent mechanical and biological filtration capabilities are most valued [27]. Upscaling of media bed-based systems is difficult due to their need for heavy infrastructure to hold the medium and difficult cleaning and maintenance [2].

- Nutrient Film Technique (NFT) – is one of the most commercially implemented designs. Plants are situated in cutouts in growth canals, where root systems are in contact with a thin film of nutrient-rich process water. The use of canals with only small amounts of water allows for horizontal stacking. Consequently, NFT configurations are highly efficient in their land use [47]. Furthermore, the systems are easy to automate, maintain and have low initial capital costs [38]. On the other hand, NFT systems are subjected to rapid deterioration in cases of a power outage or equipment failure and are therefore demanding in the area of process management precision. [2].

- Deepwater Culture (DWC) – is a design implemented in the experimental farm examined in the course of this work and also the commercially most utilized one [24]. The design uses polystyrene rafts floating on the nutrient solution. The rafts are equipped with cutouts where plants are anchored in plastic cups [24]. The roots are in a complete or almost complete contact with the nutrient solution making the system stable, relatively easy to manage, and efficient in nutrient uptake [2]. Furthermore, the system exhibits a rapid reduction in capital costs when upscaled and maintains low rates of process water evaporation [2].

After the hydroponic subsystem has fulfilled its role in the reduction of nutrient concentrations in the process water, the fluid is recirculated back to the RAS using a recirculation pump. Generally, the system can be designed to implement only one recirculation pump which leads to a reduction in electric energy consumption [24]. Furthermore, the aquaponic system requires the implementation of air pumps to increase the levels of dissolved oxygen in the process water. The quantity of air pumps is influenced by the particular design choices and the overall scale of the system [52]. However, air pumps are usually required in RAS, in the biofilter, and in the hydroponic component as various mechanisms reducing DO levels take place in these locations [38].

IMPLEMENTATION OF ALGAL PHOTOBIOREACTOR

As it was outlined in the previous section, aquaponic food production presents a novel approach to dealing with the unsustainability of present-day agriculture. However, as with any novel production system, certain problematic areas within aquaponics were uncovered. The stability of the entire system is inherently dependent on two components. Firstly, on the biofilter where toxic ammonia reduction is facilitated by colonies of nitrifying bacteria, and secondly, on the hydroponic subsystem where nutrients are removed by plant uptake [21]. Should any of these systems fail the lives of cultured fish, and consequently the economic performance of the entire production, could become critically endangered. Hence, a backup system for ammonia reduction and nutrient removal in a form of a microalgal photobioreactor was offered as a possible solution [22].

Species of certain microalgae prefer ammonia as a nitrogen source that they can absorb under a wide range of pH [39]. Additionally, microalgae can consume forms of nutrients otherwise unavailable for plant uptake [75]. In this manner, algae can both help decrease nutrient levels in cases when plant uptake is not sufficient and utilize otherwise discarded nutrients [72]. The processes implemented by algae further benefit the aquaponic system by increasing the DO levels and balancing pH drops occurring in the process water due to nitrification in the biofilter [39].

However, the benefits connected with the use of a microalgal photobioreactor come with certain requirements. To maintain high levels of photosynthetic productivity, microalgae require the addition of CO_2 into the system along with intensive illumination. The resulting increase in production expenses can make the implementation of algal photobioreactor economically unfavourable.

One of the areas highly influential on the final economic performance is bioreactor design. Generally, the biofilter can be implemented as an open, closed or hybrid system.

- Open systems – mainly in a form of raceways, are rectangular areas with shallow canals where a suspension of nutrient-rich water and microalgae is circulated using a system of paddles [76]. Raceways are easy and inexpensive to both construct and operate [38]. On the other hand, they require large areas, have considerable losses to evaporation and have limited CO_2 and light utilization due to low turbidity of the flow [76]. Consequently, the productivity of open photobioreactors is limited. External contamination of the system is also a concern [77].

- Closed systems (PBRs) – take mainly forms of either a tubular or a flat-plate system. In both cases, suspension of microalgae and process water is circulated in a translucent system where both illumination and effective use of area are maximized [38]. PBRs offer higher productivity, a reduction in the risk of contamination, and a possibility of much closer management [77].

Evaporative losses are highly reduced, but cooling of the reactor might be necessary in some environments [38]. Additionally, PBRs can be highly complex and therefore expensive to acquire and operate [77].

- Hybrid systems – combine elements of both closed and open systems. Their main goal is to decrease costs while maintaining high productivity. To achieve this, hybrid reactors implement a combination of inclined platforms and a retention tank [76]. A thin film of microalgae suspended in water flows on inclined platforms where light utilization is maximized. Subsequently, the solution is stripped of oxygen in the retention tank, where the addition of CO_2 is also possible, and recirculated to the top of the inclined platforms [76]. The system offers relative ease of maintenance, high productivity, and low capital cost requirements [77]. The problem of external contamination remains. Generally, the hybrid photobioreactors seem to be the best candidate design for implementation into the aquaponic system.

After the selection of the design for the implementation of the algal photobioreactor in aquaponics, the method for harvesting algae must be chosen. The algal biomass must be extracted from the system to prevent its decomposition which could critically lower the DO levels [39]. However, harvesting microalgae which range in sizes from 1 to 30 μm is quite problematic. Three general approaches can be applied, flocculation, technologies utilizing gravity, and technologies utilizing filtration [77]. The choices wary in economic effectivity and some can potentially contaminate the final product [76]. For aquaponics, a two-step process utilizing a combination of technologies seems most optimal. An example of such a process could be electrocoagulation combined with filtration or gravity settling [76].

If a proper harvesting technology is applied, the final microalgal product could have a wide range of uses. In such a case, an algal photobioreactor would not only increase the stability and efficiency of aquaponics it could also raise its revenues or reduce production costs. Among potential uses of microalgae are microalgal feed supplements for fish, or a wide range of pharmaceutical, cosmetic, and food products [76], [70], [71].

MATHEMATICAL MODELS

Lastly, the management and automation of a highly complex system, such as aquaponics, requires an implementation of a prediction model. The control of a process, where multiple interactions between individual subsystems take place, demands a considerable amount of expertise. Thus, if an economic agent were to conduct business selling aquaponic units, it would not be rational to expect wide market acceptance of such a product without the inclusion of a working process management model. The model would represent the complete know-how behind the aquaponic nutrient cycle and would allow for a smooth operation of the acquired aquaponic production unit [38].

Starting with the farm upon which the model is based on. The unit run by Flenexa plus s.r.o. was an ideal candidate for data acquisition to facilitate any base model development. The farm, with its implementation of DWC hydroponics and production of catfish, trout, and sturgeon, came relatively close to an unofficial ”industrial standard” in aquaponics. The system also implemented mechanical filtration, biofilter, three air pumps, and two recirculatory pumps. The unit had a total system volume of 5900 l with a yearly production rate of 240 kg of fish combined with 7300 pcs of various types of lettuces. The flow rate in the system was kept at 1077 l/h with hourly losses at 1 l/h in the form of sludge discharge.

The fish production took place in a single RAS tank with a water volume maintained at 2200 l. The lettuces were produced on four separate DWC stations with 800 l of system volume per unit. The hydroponic subsystem was kept under artificial illumination supplied by a single LED panel per DWC unit. The measurement conducted by a certified laboratory proved the unit run by Flenexa plus s.r.o. was in a stable condition. The nitrogen present in the system was mainly in a form of nitrates, proving the nitrification process was working adequately. Overall, the measurements provided data for concentrations of total nitrogen, nitrates, total phosphorus, and total potassium. Based on the importance of these nutrients in both plant and fish management, the decision to implement them into the mathematical model was made.

After some consideration, it was decided to create two models. The first model referred to in the text as Model 1, implements a statistical approach towards the prediction of nutrient concentrations. The idea behind Model 1 stems from the need to bridge periods of dynamic development during the system start-up. In similar situations, the application of purely physics-based models can become problematic due to the high complexity of interactions taking place within the system. Model 1, therefore, implements an in-built database of nutrient concentrations which can help better predict the system behaviour. Additionally, the system builds a separate database purely from measurements conducted on the managed system. Algorithms then compare both databases and continuously improve the underlying regression models. The output of the system comes in two forms. Firstly, the system can visualize measured data, and secondly, it can predict future concentrations of nutrients. The prediction takes a form of a range of concentrations that are expected based on the provided data with the probability of 95 %. The model was created with future implementation of additional nutrients in mind.

The second model, Model 2, is a physics-based prediction tool that utilizes the mass balance of nutrients to predict their changes and consequently their future concentrations. The model also implements a simplified microalgal bioreactor. The tool was created with an emphasis on minimizing the requirements put on its user. Therefore, the system utilizes editable libraries of data, from which the user can select the required parameters of the managed aquaponic farm. The system is then able to predict future nutrient concentrations and make recommendations for the operator. The recommended actions are aimed to prevent an occurrence of nutrient concentrations incompatible with plant and fish wellbeing.

Generally, both systems have certain flaws and have not avoided simplifications. However, their underlying structure allows for an uncomplicated expansion and possible improvements. Both models would also benefit from their unification into a single working system. Such unification would solve many of these shortcomings and is discussed in detail in the respective chapter.

CONCLUSION

The expected growth in the human population is going to be accompanied by increased demand for food. Furthermore, the growth is expected to take place in underdeveloped areas with poor soil conditions. The agricultural industry producing most of our food today is already responsible for 70 % of fresh water and 30 % of worldwide energy consumption. It is reasonable to expect these figures to worsen without a shift towards more efficient methods of agricultural production. When considering an implementation of a technology with such wide-reaching consequences, emphasis must be placed on its sustainability, high productivity, and flexibility. Based on the findings and information gathered in the course of this work, it sensible to expect the aquaponics to be a part of the solution.

The discussion of whether the industry is going to implement a coupled or a decoupled aquaponics is still ongoing. The decoupled type offers more closely regulated conditions for both fish and plants resulting in higher productivity. The accompanied complexity and costs are however limiting its wider acceptance. With coupled aquaponics, on the other hand, certain compromises must be made during the management of the process conditions. However, the resulting productivity and environmental efficiency are still better compared to traditional agricultural production methods. It is reasonable to expect a future proliferation of both types of aquaponics.

Coupled aquaponic configurations differ mostly in the design of the hydroponic subsystem. The *Media Bed type* is most well suited for smaller applications where the need for heavy infrastructure is outweighed by its relative ease of maintenance and management. The *Nutrient Film Technique* is going to continue its development mainly in urban settings. There, the NFT's efficient use of space and ease of automation is going to offset its requirements for precise management. Finally, the *Deep Water Culture* can be expected to become the industry standard. DWC can be easily upscaled, has a high relatively stable productivity, and can be managed both using high and low-tech means. However, any aquaponic system is still highly dependent on biofilter for nitrification and on plants to facilitate water purification. To improve the resilience of the aquaponic design, the inclusion of a microalgal photobioreactor has been proposed.

In aquaponics, microalgal photobioreactor could help balance pH, increase dissolved oxygen levels, serve as a biofilter backup, and utilize otherwise discarded nutrients in an economically productive manner. Three basic types of the microalgal reactor could be envisioned for implementation into aquaponics. Open raceways are inexpensive and relatively simple to set up and manage. On the other hand, they require large areas, have low productivity and high risk of contamination. Closed systems are at the other end of the spectrum, with high productivity, high costs and complexity. The implementation of hybrid systems, therefore, seems the most probable. They offer high productivity, relative simplicity, and both low capital and operational costs. However, the economics of microalgal photobioreactor implementation into aquaponics is highly dependent on the type of illumination used. The design is probably not going to become profitable when artificial light sources are used.

Lastly, to manage any future aquaponic systems, with or without a photobioreactor, the ability to predict nutrient concentrations is going to be crucial. To lay foundations for future development, two mathematical models were developed. The first model is statistical, predicting nutrient concentrations based on regression of built-in and model-constructed databases. The second model is physics-based and implements a microalgal photobioreactor. To secure the relevance of both models, real-world nutrient concentration data acquired from measurements conducted by a certified laboratory were used during their development. The farm which served as a data source was operated by Flenexa plus s.r.o. as an experimental DWC unit under stable operating conditions.

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NOMENCLATURE

Abbreviation/symbol	Meaning
s.r.o.	s. r. o. is a marking of a company which is based in the Czech Republic and registered in accordance (and request) of Czech legislation. Its legal background and character is quite similar (though with some specific differences) to Ltd company in the United Kingdom or LLC in the United States of America
UN	United Nations
Fig.	Figure
Tab.	Table
Eq.	Equation
FAO	Food and Agriculture Organization
LC-PUFAs	Long-chain polyunsaturated fatty acids
RAS	Recirculating aquatic system
FCR	Feed conversion ratio
PR	Protein retention
CR	Calorie retention
$\boldsymbol{\omega_{edible\ part}}$	Weight ratio of total feed to eaten feed
$\boldsymbol{\omega_{protein\ in\ edible\ part}}$	Weight ratio of eaten protein to eaten feed
$\boldsymbol{\omega_{protein\ in\ feed}}$	Weight ratio of protein in total feed to total feed
$\boldsymbol{\rho_{calories\ in\ edible\ part}}$	Caloric density of eaten feed
$\boldsymbol{\rho_{calories\ in\ feed}}$	Caloric density of feed
UV	Ultraviolet
LDPE	Low-density polyethylene
US	United States
LECA	light expanded clay aggregate
NFT	Nutrient film technique
PVC	Polyvinyl chloride
NGS	New Growing System
DWC	Deepwater culture
DFT	Deep flow technique
FRC	Floating raft culture
DRFT	Dynamic root floating technique
DO	Dissolved oxygen
$\mathbf{NH_4^+}$	Ammonium ion
$\mathbf{NH_3}$	Uncharged ammonia molecule
ppm	Parts per million
$\boldsymbol{NO_2^-}$	Nitrite ion
$\boldsymbol{NO_3}$	Nitrate group
$\mathbf{H_2PO_4^-}$	Dihydrogen phosphate ion
$\mathbf{HPO_4^{2-}}$	Hydrogen phosphate ion
$\mathbf{PO_4^{3-}}$	Orthophosphate ion

$MgNH_4PO_4 \cdot 6H_2O$	Struvite
$Ca_5(OH)(PO_4)_3$	Hydroxyapatite

Abbreviation/symbol	Meaning
CO_2	Carbon dioxide
KOH	Potassium hydroxide
H_2O	Water
$C_6H_{12}O_6$	Glucose
O_2	Oxygen
LEA	Lipid extracted algae
TDS	Total dissolved solids
N	Nitrogen
P	Phosphorus
PBR	Photobioreactor
$FeCl_3$	Ferric chloride
$Al_2(SO_4)_3$	Aluminium sulfate
PHA	Polhydroxyalkonates
Ca	Calcium
K	Potassium
Mg	Magnesium
B	Boron
Cu	Copper
Fe	Iron
Mn	Manganese
Mo	Molybdenum
Zn	Zinc
Ag	Silver
Na	Sodium
VBA	Visual Basic for Applications
OLS	Ordinary least square
a	Coefficient resulting from OLS
b	Coefficient resulting from OLS
c	Coefficient resulting from OLS
d	Coefficient resulting from OLS
x_{index}	Model 1 regressor – dimensionless index
x_{feed}	Model 1 regressor – added feed weight in grams per litre of the system volume
$x_{fertilizer}$	Model 1 regressor – added fertilizer weight in grams per litre of the system volume
$y_{nutrient\ conc.}$	Model 1 – dependent variable – final concentration of respective nutrient in micrograms per litre of the system volume

$x_{maximum\ number\ of\ regressors}$	Maximum number of regressors – for Model 1 equal to 4
$y_{minimal\ dataset\ size}$	Minimal alternative dataset size – for Model 1 equal to 20

Abbreviation/symbol	**Meaning**
$m_{fish\ feed\ added}$	Weight of fish feed in grams added into an aquaponic system
$V_{process\ water}$	The volume of total process water in litres
$m_{fertilizer\ added}$	Weight of fertilizer in grams added into an aquaponic system
e_1	Coefficient resulting from SOLVER minimization
e_2	Coefficient resulting from SOLVER minimization
e_3	Coefficient resulting from SOLVER minimization
R^2	Coefficient of determination
$\overline{R^2}$	Corrected coefficient of determination
n	Total number of observation sets
k	Number of regressors
RMSE	Standard error of the estimate
CV	Coefficients of variation – definition 1
CV*	Coefficients of variation – definition 2
y_i	i-th dependent variable
$\hat{y}_i$	i-th dependent variable predicted by the regression model
$\bar{y}$	Mean value of the dependent variable
MAD	Mean absolute deviation
F.INV.RT	VBA function
T_0	Student t-statistic
$\widehat{\beta_1}$	Original hypothesis
$\beta_{1,0}$	Alternative hypothesis
$se(\widehat{\beta_1})$	Standard error value for the respective coefficient
T.INV.2T	VBA function
URB	Upper range boundary of predicted conc.
LRB	Lower range boundary of predicted conc.
$y_{pred.nutrient\ conc.}$	Concentration value predicted by the final model
t_{crit}	The critical value of t-statistic for given conditions
$\sqrt{Var(\tilde{e})}$	Standard error of the forecast
σ^2	Unbiased estimator of the mean square error of error model terms
$\tilde{X}$	Vector of specific values for which the conc. Should be evaluated
X^T	Transposed matrix of data for independent variables
X	Matrix of data for independent variables
$\tilde{X}^T$	Transposed vector of specific values for which the conc. Should be evaluated
$c_{i,j}$	i-th nutrient concentration for j-the time period in milligrams per litre of system water volume

$\boldsymbol{m_{i,j-1}}$	Weight of i-th nutrient in time j-1 in the system in milligrams

Abbreviation/symbol	Meaning
$\boldsymbol{\Delta m_{i,j}}$	Weight of the i-th nutrient lost in the event of process water discharge in milligrams
$\boldsymbol{m_{alg,i}}$	Weight of the i-th nutrient lost to algal photobioreactor uptake in milligrams
$\boldsymbol{m_{plnt,i}}$	Weight of the i-th nutrient lost to plant uptake in milligrams
$\boldsymbol{m_{fert,i}}$	Weight of the i-th nutrient added in the form of fertilizer in milligrams
$\boldsymbol{m_{feed,i}}$	Weight of the i-th nutrient added in the form of a fish feed in milligrams
$\boldsymbol{V_{sys,j}}$	Total system volume for j-th time period in litres
$\boldsymbol{c_{i,j-1}}$	i-th nutrient concentration for j-1 time period in milligrams per litre of system water volume
$\boldsymbol{V_{sys,j-1}}$	Total system volume for j-1 time period in litres
$\boldsymbol{V_{PBR,j-1}}$	Algal photobioreactor volume in the j-1 time period
$\boldsymbol{\eta_{j-1}}$	Effectivity of the algal photobioreactor in j-1 time period
$\boldsymbol{\rho_{alg,i}}$	Uptake of i-th nutrient in milligrams per litre of reactor volume
$\boldsymbol{n_{plnt,j-1}}$	Number of plants present in the hydroponic component in the j-1 time period
$\boldsymbol{\rho_{plnt,i}}$	Uptake of i-th nutrient in milligrams per plant and day
$\boldsymbol{m_{feed}}$	Weight of the added fish feed
$\boldsymbol{\eta_{ret}}$	Retention of nutrients – a coefficient multiplying ratio of consumed feed with the ratio of retained nutrients in the event of consumption
$\boldsymbol{c_{feed,i}}$	The weight concentration of i-th nutrient in the fish feed
$\boldsymbol{\Delta V_{fresh}}$	The volume of fresh water in litres to be added to the system
$\boldsymbol{c_{i,critical\ high}}$	The upper boundary of recommended weight concentrations for i-th nutrient
$\boldsymbol{m_{fert}}$	Weight of the fertilizer in grams to be added to the system
$\boldsymbol{c_{i,critical\ low}}$	The lower boundary of recommended weight concentrations for i-th nutrient
$\boldsymbol{c_{fert,critical}}$	The concentration of the critical nutrient in the fertilizer

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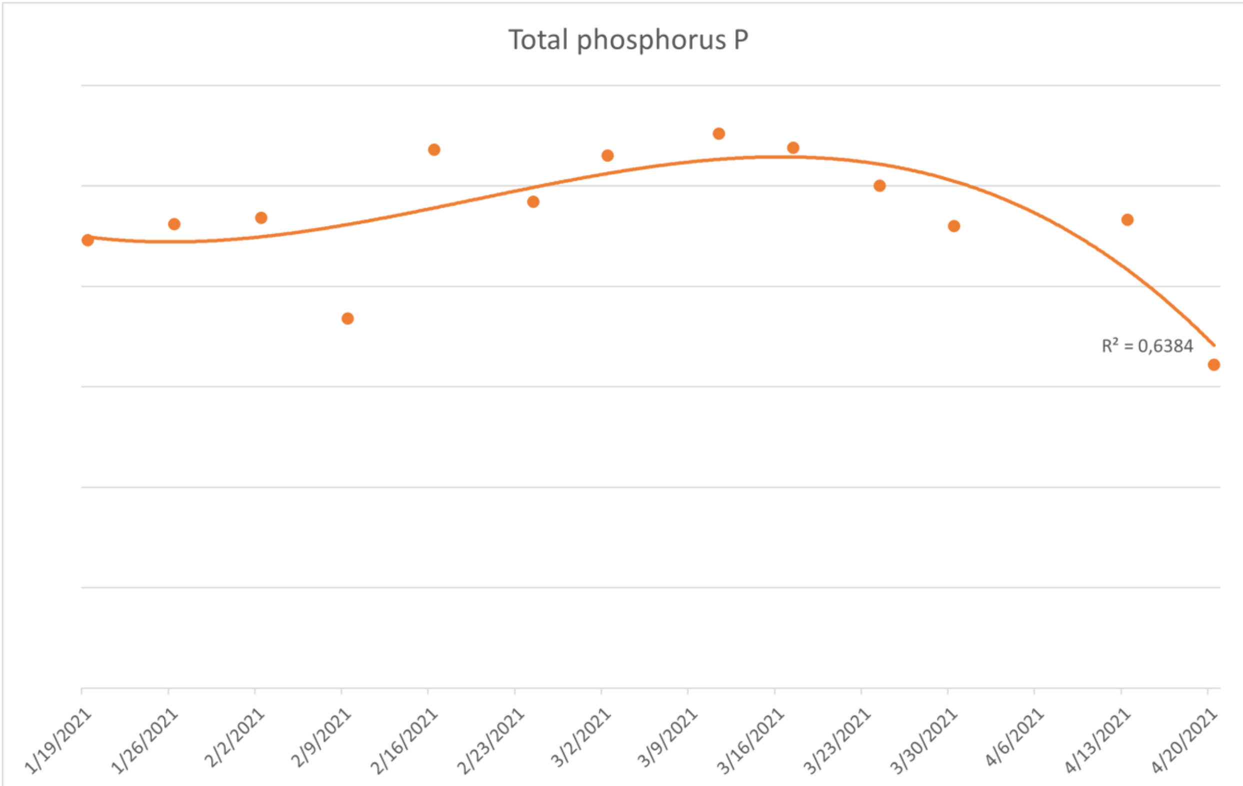
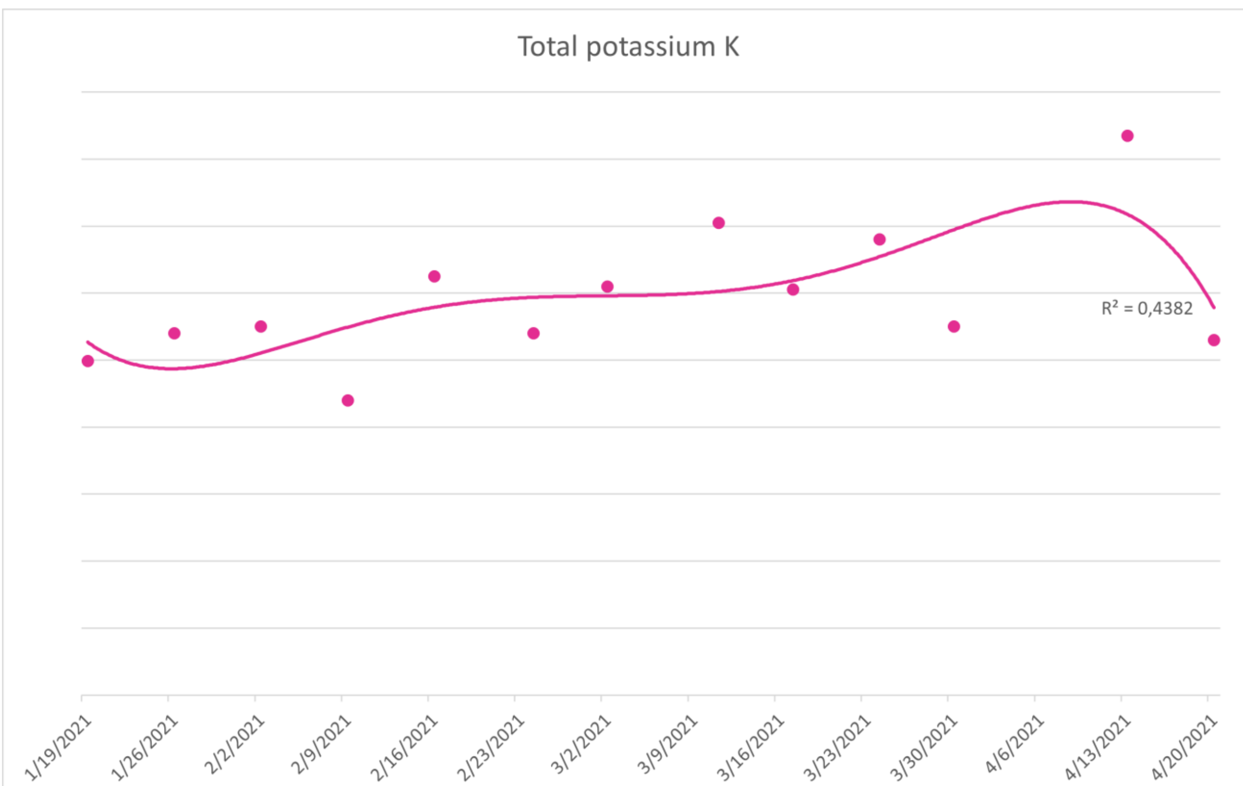
Appendix A – total phosphorus and potassium concentrations development





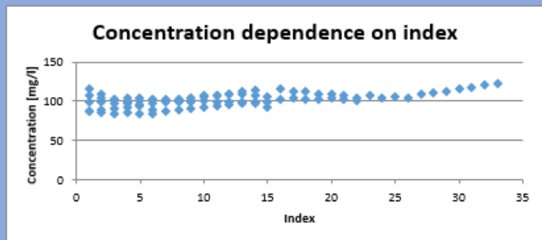
Appendix B – Continuously improving model for general aquaponic cycle, the interface

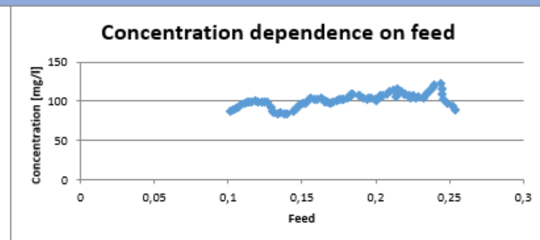
Additional stat. data for original models

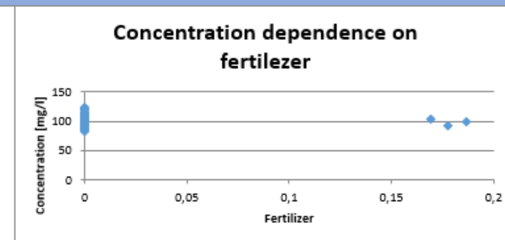
Refresh data visualization

Nitrogen - linear model

R^2	$\bar{R}^2$	RMSE	CV	CV*	MBE	NMBE	MAD	F-stat	F-crit	t-test for index	t-crit for index	t-test for feed	t-crit for feed	t-test for fertilizer	t-crit for fertilizer	t-test for intercept	t-crit for intercept
	$\bar{R}^2p$	RMSEp	CVp	CV*p			MADp										

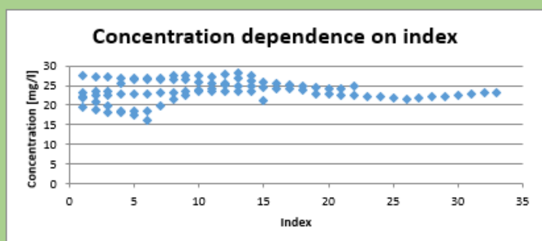


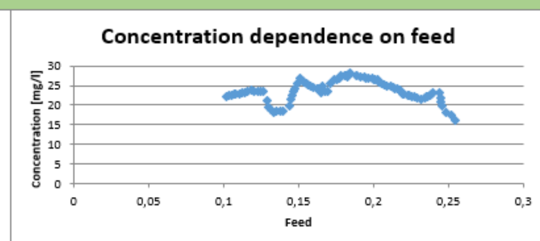


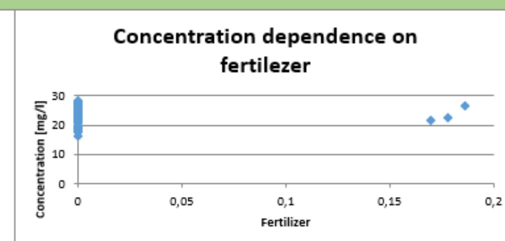


Phosphorus - linear model

R^2	$\bar{R}^2$	RMSE	CV	CV*	MBE	NMBE	MAD	F-stat	F-crit	t-test for index	t-crit for index	t-test for feed	t-crit for feed	t-test for fertilizer	t-crit for fertilizer	t-test for intercept	t-crit for intercept
	$\bar{R}^2p$	RMSEp	CVp	CV*p			MADp										

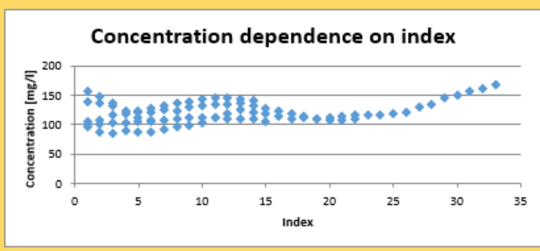


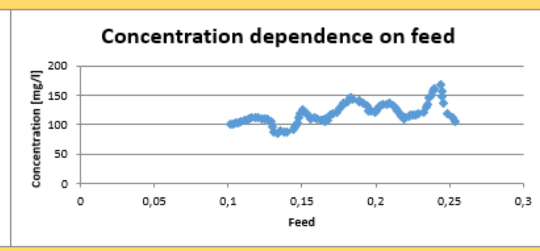


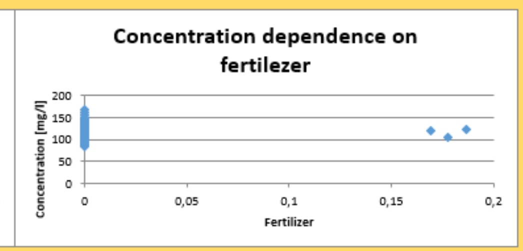


Potassium - linear model

R^2	$\bar{R}^2$	RMSE	CV	CV*	MBE	NMBE	MAD	F-stat	F-crit	t-test for index	t-crit for index	t-test for feed	t-crit for feed	t-test for fertilizer	t-crit for fertilizer	t-test for intercept	t-crit for intercept
	$\bar{R}^2p$	RMSEp	CVp	CV*p			MADp			7,006394097		12,78403361		-0,572048365			







Additional stat. data for alternative models

Refresh data visualization

Nitrogen - final model

R^2	$\bar{R}^2$	RMSE	CV	CV*	MBE	NMBE	MAD	F-stat	F-crit	t-test for index	t-crit for index	t-test for feed	t-crit for feed	t-test for fertilizer	t-crit for fertilizer	t-test for intercept	t-crit for intercept

Final model

Phosphorus - best model

R^2	$\bar{R}^2$	RMSE	CV	CV*	MBE	NMBE	MAD	F-stat	F-crit	t-test for index	t-crit for index	t-test for feed	t-crit for feed	t-test for fertilizer	t-crit for fertilizer	t-test for intercept	t-crit for intercept

Final model

Potassium - best model

R^2	$\bar{R}^2$	RMSE	CV	CV*	MBE	NMBE	MAD	F-stat	F-crit	t-test for index	t-crit for index	t-test for feed	t-crit for feed	t-test for fertilizer	t-crit for fertilizer	t-test for intercept	t-crit for intercept

Final model

Additional info on all sub-best models

Appendix C – Model of an aquaponic cycle with nutrient removal by algae, the interface