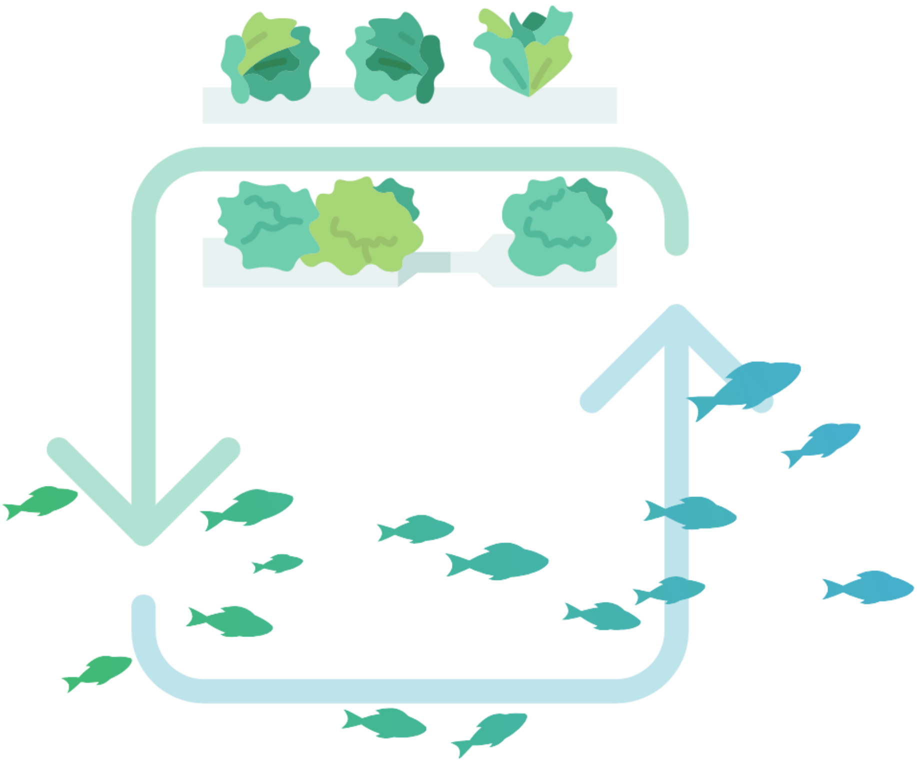
Central Baltic Programme

TransFarm

DEMONSTRATION UNIT TESTING AND MONITORING IN LATVIA



UNIVERSITY OF LATVIA

D.2.4.1. – Short report - Demo testing & monitoring in Latvia

Abstract

This study presents a comprehensive monitoring-based assessment of a small-scale aquaponics system during start-up and early operational phases, with a focus on water quality dynamics, fish welfare, and plant productivity. The system consisted of a recirculating fish tank, multi-stage mechanical and biological filtration, floating and media-based plant cultivation units, and a compartmentalized sump, with a total system volume of approximately 3.2 m^3. Monitoring was conducted over one month without fish followed by nearly two months with fish. Following the introduction of 60 sturgeon (average initial mass ~100 g), the system exhibited characteristic nitrogen cycle dynamics associated with biofilter establishment. An initial ammonium spike (up to 8.34 mg L^{-1}) was observed, followed by a prolonged nitrite accumulation phase peaking at 12.1 mg L^{-1}. Targeted management interventions, including feed reduction, temporary feed withdrawal, enhanced aeration, and salt addition, effectively mitigated toxicity risks and maintained fish welfare during this critical period. Subsequent stabilization of ammonium and nitrite concentrations confirmed successful establishment of nitrifying microbial communities. Chemical and physical water quality parameters remained stable throughout the monitoring period, with pH maintained between 7.2 and 7.4, dissolved oxygen levels above 10 mg L^{-1}, and low turbidity. Plant growth was closely linked to nitrogen availability, with temporary growth cessation observed during periods of elevated nitrite and reduced nitrate availability. Estimated plant biomass production reached approximately 6.2 kg, supported by fish-derived nutrients across a cultivation area of ~5 m^2. A simplified economic assessment indicated that fish production costs were approximately 8.5–9.3 EUR kg^{-1}, while optimized use of the 5 m^2 plant growing area under an intensive cultivation scenario could reduce romaine lettuce production costs from approximately 18 EUR kg^{-1} to about 3–5 EUR kg^{-1}, primarily through improved space utilization. Visual assessments revealed mild nutrient deficiencies, including nitrogen, iron, and calcium limitations, which were addressed through foliar micronutrient application. The results demonstrate that feeding rate was the dominant driver of system stability, influencing nitrogen loading, water quality, fish behaviour, and plant productivity. Once biological filtration was established, the system showed strong resilience and capacity for stable operation. The findings highlight the importance of adaptive feed management, targeted nutrient supplementation, and integrated monitoring in achieving balanced and sustainable aquaponics system performance.

Keywords: *TransFarm, aquaponics, parameters, growth systems, monitoring*

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Contents

1. Introduction

1.1. TransFarm project

There are several environmental and social challenges that the food sector has to face: Agriculture is a sector particularly affected by climate change, our seas are overfished, and the world population is estimated to continue growing, being about 9.7[1] billion people by 2050. Countries in the Baltic Sea Region are strongly dependent on food import, especially for vegetables, fruit and fish; in recent years the pandemics and the war in Ukraine have exposed the need for more self-sufficient food systems. Moreover, agriculture and aquaculture are among the main contributors to the eutrophication of the Baltic Sea.

To answer these challenges TransFarm project wants to bring food production closer to consumers by promoting soil-less farming methods that can be implemented even indoors and allow it to grow all year round. Examples of these methods are hydroponics, where plants are grown in water, and aquaponics, which combines hydroponics with aquaculture.

Aquaponics is a circular, closed-loop system, where water from the fish culture is used to grow plants. The fish waste within the water is microbiologically transformed by a biofilter, absorbed by plants and then cleaner water returned to the fish. The system has a completely circular water flow allowing nutrient reuse without emissions of nutrients in the environment. Since the fish, plants and microorganisms in an aquaponics system function in close symbiotic relationships, antibiotics or pesticides are not used, which in turn provides cleaner, healthier produce.

TransFarm will demonstrate aquaponics in Sweden, Estonia and Latvia as well as test alternative water sources such as rainwater and reclaimed greywater: Partners from these countries will build demonstration facilities with different characteristics and aims. The experiences exchanged from the different demos will contribute to knowledge co-creation and the facilities will be the opportunity to inspire and educate future aquaponics farmers. The knowledge gathered from the construction and monitoring of the demos will result in education material available for all the actors interested in aquaponics.

The project will also investigate business models, run activities to inform consumers about the quality of the aquaponics produced, educate entrepreneurs who want to start an aquaponics system as well as inform civil servants and policy makers about the reduced environmental impact of circular soil-less farming methods.

TransFarm project duration is three years (2023-2026), and it is coordinated by **Turku School of Economics** at the University of Turku (Turku, Finland). Project partners are the **Estonian University of Life Sciences** (Tartu, Estonia), **University of Latvia** (Riga, Latvia), **Norrtälje Vatten och Avfall** and **Coompanion** (Norrtälje, Sweden).

TransFarm project is funded by the EU's Interreg Central Baltic program, the total budget of the project is 1.87 million euros, EU financing covers 1.5 million euros.

[1] UN DESA publications – World population prospects 2022

2. Monitoring of an aquaponics system

2.1. Purpose of monitoring in aquaponics systems

Monitoring is a fundamental aspect of aquaponics system management, as it ensures the stable integration of aquaculture (fish production) and hydroponics (plant cultivation). Aquaponics systems rely on complex biological, chemical, and physical interactions, particularly the transformation of fish waste into plant-available nutrients through microbial processes. Continuous or regular monitoring allows early detection of imbalances that could negatively affect fish health, plant growth, or system performance. One of the primary purposes of monitoring is to maintain optimal water quality conditions for fish, plants, and beneficial microorganisms. Parameters such as temperature, pH, dissolved oxygen, and nitrogen compounds must remain within suitable ranges to prevent stress, toxicity, or reduced productivity. Monitoring also supports the control of the nitrogen cycle, which is central to aquaponics systems, as excessive ammonia or nitrite concentrations can be harmful to fish, while insufficient nitrate levels may limit plant growth.

In addition, monitoring contributes to animal welfare and sustainable production. Observations of fish behavior, growth, and survival provide insight into stress levels and system suitability. Similarly, monitoring plant growth and health helps identify nutrient deficiencies, toxicities, or environmental stressors. By systematically collecting and analysing data, operators can make informed management decisions, improve resource efficiency, and enhance the long-term stability and sustainability of the aquaponics system.

2.2. Overview of system components

An aquaponics system consists of three closely interconnected components: fish, plants, and water. Each component plays a critical role, and the functionality of the system depends on their balanced interaction.

Fish serve as the primary nutrient source in aquaponics systems. Through feeding and metabolic processes, fish release waste products, mainly in the form of ammonia, into the water. While ammonia is toxic to fish at high concentrations, it becomes a valuable nutrient after being converted by nitrifying bacteria into nitrite and subsequently nitrate. The choice of fish species depends on system design, water temperature, and production goals, with commonly used species including tilapia, carp, and trout.

Plants utilize the nutrients dissolved in the water, particularly nitrate, for growth and biomass production. By absorbing these nutrients, plants contribute to water purification and help prevent the accumulation of harmful compounds. A wide range of leafy greens, herbs, and fruiting plants can be cultivated in aquaponics systems, depending on nutrient availability and environmental conditions.

Water acts as the connecting medium that links fish, plants, and microorganisms. It transports nutrients, oxygen, and metabolic by-products throughout the system. Water quality directly influences biological processes and organism health, making it the central element that integrates all system components. Proper water management is therefore essential for maintaining system balance and productivity.

3. Description of the Aquaponics System

3.1. System type (e.g., media bed, NFT, DWC)

The aquaponics system built In Latvia is a recirculating system that combines multiple treatment and cultivation units to ensure efficient nutrient utilization and high water quality. The system consists of a fish tank, a biofilter with an integrated mechanical filter, a floating bed, a media bed filled with expanded clay, and a multi-compartment sump that also contributes to filtration (Figure 1).

Water originates from the fish tank, where fish are stocked and fed. From the fish tank, water flows by gravity into the sump system, allowing continuous passive transfer without additional energy input. Prior to reaching the plant cultivation units, water passes through a biofilter equipped with an integrated mechanical filter. This unit serves a dual function: the mechanical component removes suspended solids and particulate matter, while the biological component supports nitrifying bacteria responsible for converting ammonia into nitrite and nitrate.

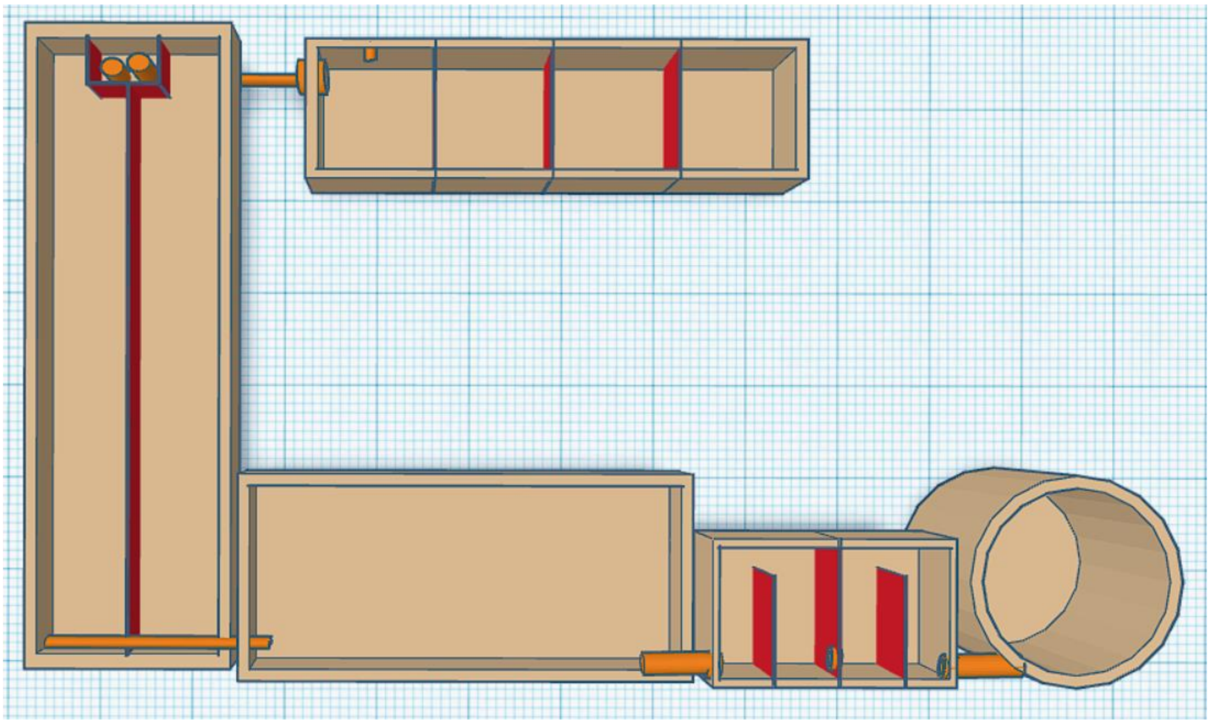

Figure 1. Visual sketch of the demonstration unit built in Latvia.

Plant cultivation is carried out using two different methods. The floating bed provides a shallow, continuously flowing nutrient-rich water layer suitable for fast-growing plants with relatively low nutrient demands. In parallel, a media bed filled with expanded clay pellets (4–8 mm) supports plant growth while also contributing to additional mechanical and biological filtration. The media bed provides a large surface area for microbial colonization and enhances nutrient transformation processes (Figure 1).

The sump consists of four separate sections, each divided by filter materials that further removes fine particles from the water. One of the sump sections functions as an additional biofilter, increasing the total biological filtration capacity of the system. This multi-stage filtration ensures that water returning to the fish tank is largely free of suspended solids, thereby reducing stress on fish and preventing the accumulation of organic matter. Water is pumped from the final sump compartment back to the fish tank using an 1300 W water pump equipped with frequency converter (to adjust water flow), completing the recirculation loop. This system design integrates mechanical filtration, biological treatment, and plant-based nutrient uptake to maintain stable water quality and support the health and productivity of fish and plants.

3.2. Fish species and plant species cultivated

The aquaponics system is currently stocked with sturgeon originating from the recirculating aquaculture system (RAS) facility BIOR in Tome, Latvia. Sturgeon were selected due to their high economic value, adaptability to controlled aquaculture environments, and suitability for recirculating systems. As a benthic species, sturgeon exhibit specific requirements regarding water quality, oxygen availability, and feeding practices, which makes consistent monitoring of system parameters particularly important. Their inclusion in the system also provides a realistic model for evaluating aquaponics performance under demanding aquaculture conditions. Plant production within the system focuses primarily on leafy greens and herbs, which are well suited to aquaponics due to their moderate nutrient requirements and relatively fast growth cycles. Cultivated plant species include various salad types, basil, mixed culinary herbs, cucumbers, and Swiss chard. These crops efficiently utilize dissolved nutrients, particularly nitrates, derived from fish metabolism, thereby contributing to water purification and system balance. The current selection of plant species allows for assessment of system performance across different growth habits and nutrient demands, from fast-growing leafy vegetables to fruiting crops such as cucumbers. This diversity supports evaluation of nutrient availability and uptake efficiency within the system. Future plans include expanding the range of cultivated plant species to further optimize nutrient use, increase system resilience, and explore the suitability of additional crops for aquaponics production under local conditions.

3.3. Basic system layout and operation

The aquaponics system is designed as a closed-loop, recirculating system that integrates fish production, water treatment, and plant cultivation. The system layout follows a gravity-assisted flow wherever possible to minimize energy consumption and ensure stable hydraulic operation. Water circulation begins in the fish tank, where fish are stocked and fed. Fish metabolism generates waste products, primarily ammonia, which are released directly into the water. From the fish tank, water flows by gravity through the filtration units and into the sump system. Mechanical filtration removes suspended solids and uneaten feed, reducing organic load and preventing particle accumulation. Biological filtration takes place in dedicated biofilters, the media bed filled with expanded clay, and one of the sump compartments, where nitrifying bacteria convert ammonia into nitrite and subsequently into nitrate. Plant cultivation is currently carried out in a floating bed (deep water culture) system, where plant roots are continuously submerged in nutrient-rich water. This cultivation method provides stable access to nutrients and allows efficient uptake of dissolved nitrogen compounds. In addition, a media bed containing expanded clay contributes to plant growth while also providing supplementary mechanical and biological filtration due to its high surface area for microbial colonization. The sump represents the lowest point of the system and consists of four separate compartments divided by filter materials. These divisions allow further removal of fine particles and promote water clarification before recirculation. One sump compartment functions as an additional biofilter, increasing the nitrification capacity of the system. Water from the final sump section is pumped back to the fish tank using an 80 W pond pump, completing the recirculation loop.

Future system development includes the planned installation of a vertical nutrient film technique (NFT) unit positioned above the sump. This expansion is intended to increase plant production capacity while making efficient use of space and existing water flow, further enhancing nutrient utilization within the system.

4. Water Quality Monitoring

4.1. Physical Parameters (e.g., temperature, turbidity)

Physical water quality parameters were monitored to assess the stability of the aquaponics system and to ensure suitable conditions for fish, plants, and microbial processes. The system was filled with tap water, with a total operational water volume of approximately 3.2 m^3. Water temperature was monitored throughout the system start-up and operation period. At the time of system filling, the initial water temperature was approximately 8 °C, reflecting the temperature of the supplied tap water. Over a period of around 1.5 weeks, the water temperature gradually increased and stabilized at the ambient room temperature of approximately 20 °C. This gradual temperature adjustment allowed for acclimation of system components and supported the establishment of biological processes. During the subsequent monitoring period, water temperature remained stable, indicating consistent environmental conditions and reliable system operation.

Turbidity was monitored as an indicator of suspended solids and the effectiveness of mechanical filtration. Despite the presence of fish, turbidity levels remained low, with measured values averaging approximately 3–4 NTU. These values indicate good water clarity and effective removal of particulate matter by the integrated mechanical filtration units and sump filtration sections. Low turbidity levels reduce stress on fish, minimize gill irritation, and support system health. Throughout the monitoring period, both temperature and turbidity remained relatively constant, demonstrating stable physical water quality conditions. This stability is essential for maintaining efficient nitrification, supporting fish welfare, and enabling consistent plant nutrient uptake within the aquaponics system.

4.2. Chemical Parameters (e.g., pH, dissolved oxygen, electrical conductivity)

Chemical water quality parameters were monitored to evaluate system stability, fish welfare, and nutrient availability for plant growth. Key parameters assessed during the monitoring period included pH, dissolved oxygen, and electrical conductivity. pH, DO, EC were measurd using HACH portable measuring device with the corresponding electrodes.

The pH of the system remained stable throughout the three-month monitoring period, with measured values ranging between 7.2 and 7.4. No significant acidification trends were observed, indicating a well-balanced system and effective buffering capacity. The stability of pH suggests sufficient alkalinity in the water to counteract acidifying processes associated with nitrification, which is particularly important for maintaining optimal conditions for fish, plants, and nitrifying bacteria.

Dissolved oxygen (DO) concentrations were maintained at consistently high levels through active aeration in the fish tank, biofilter, floating bed, and sump compartments. Measured DO values ranged from approximately 8.0 to 10.3 mg L^{-1}, corresponding to oxygen saturation levels of 85–106%. These elevated oxygen levels support fish respiration, enhance nitrification efficiency, and reduce the risk of anaerobic conditions within the system.

Electrical conductivity (EC) was monitored as an indicator of total dissolved ions in the water. Initially, EC values were approximately 450 µS cm^{-1}. During system operation, conductivity was gradually increased to around 1600 µS cm^{-1} through controlled salt addition. This adjustment was implemented to protect fish from potential negative effects associated with elevated nitrate concentrations. The increased salinity also contributes to osmotic balance and stress reduction in fish. It is planned to gradually reduce the salt concentration over the following month to restore lower conductivity levels more suitable for plant growth. The monitored chemical parameters remained within suitable ranges throughout the observation period, indicating stable system operation and effective water quality management.

4.3. Nutrient and Nitrogen Cycle Parameters (e.g., ammonia, nitrite, nitrate)

Monitoring of nitrogen cycle parameters was conducted to evaluate the establishment and performance of biological filtration within the aquaponics system. Concentrations of ammonium (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-) were monitored throughout the system start-up and operation period. Immediately after fish introduction, despite previously set up biofilter functionality, ammonium concentrations increased rapidly, reaching a peak value of 8.34 mg L^{-1} within one day. At this stage, nitrifying microorganisms, particularly ammonia-oxidizing bacteria (AOB), were not yet established, resulting in the accumulation of ammonium in the system. During this initial phase, both nitrite and nitrate concentrations remained at minimal level, indicating the absence of active nitrification.

Over the following 1.5 weeks, ammonium concentrations gradually decreased to 0.12–0.15 mg L^{-1} and remained stable at this level for the remainder of the monitoring period. This decline in ammonium, accompanied by stable low concentrations, indicates successful colonization and activity of AOB within the biofilter, media bed, and sump biofiltration compartments (Figure 2).

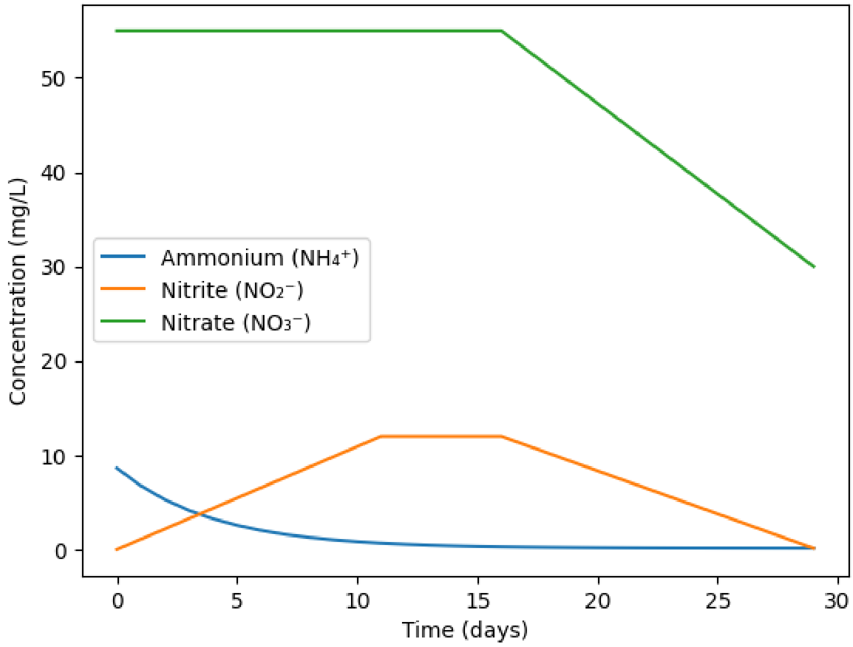

Figure 2. Ammonium, nitrite and nitrate changes within the system of demonstration unit built in Latvia during biofilter establishing over the first 30 days post fish introduction to the system.

Subsequently, nitrite concentrations began to increase, reflecting the conversion of ammonium to nitrite. Nitrite levels rose progressively from 1 mg L^{-1} to a maximum of 12.1 mg L^{-1}, where they remained elevated for approximately four days. This accumulation phase is characteristic of systems in which ammonia oxidation is established but nitrite-oxidizing bacteria (NOB) are not yet fully active. Due to the potential toxicity of nitrite to fish, salt was added to the system at this stage to mitigate nitrite uptake and reduce physiological stress. Following this intervention, a gradual decline in nitrite concentrations was observed, decreasing from peak values to 0.128 mg L^{-1} (Figure 2). This decrease clearly indicates the establishment and activation of NOB populations, completing the nitrification process. The combined stabilization of low ammonium and nitrite concentrations confirms the successful maturation of the biological filtration system. Nitrate concentrations remained relatively stable throughout most of the monitoring period, fluctuating between 50 and 60 mg L^{-1}. As nitrite concentrations began to decline, nitrate levels also decreased to approximately 30 mg L^{-1}, likely reflecting increased plant uptake and system stabilization. Together, these trends demonstrate the development of a functional nitrogen cycle and effective integration of biological filtration and plant nutrient utilization within the aquaponics system.

4.4. Monitoring Frequency and Methods

Monitoring frequency and analytical methods were selected to accurately capture water quality dynamics during both the system start-up phase and subsequent stable operation. Particular emphasis was placed on nitrogen cycle parameters due to their critical importance for fish health and biofilter establishment.

Concentrations of inorganic nitrogen compounds were determined using commercially available HACH water quality analysis reagents. Nitrate concentrations were measured using the NitriVer® 5 method, nitrite concentrations using the NitriVer® 3 method, and ammonium concentrations using LCK305 cuvette test kits (Figure 3). These colorimetric methods provide reliable and reproducible measurements and are widely used in aquaculture and environmental monitoring applications. During the initial system start-up and biofilter establishment phase, ammonium, nitrite, and nitrate concentrations were measured daily.

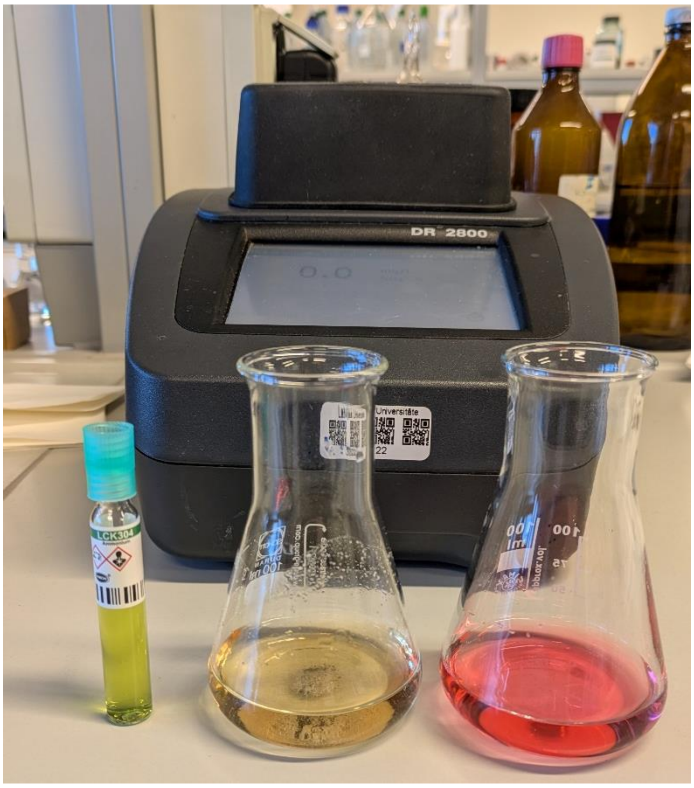

Figure 3. Measurements done for the monitoring of (from the left) ammonium, nitrates and nitrites using Hach DR2800 spectrophotometer.

This high-frequency monitoring allowed for close tracking of rapid changes in nitrogen compound concentrations, early detection of potentially harmful conditions, and timely implementation of management measures, such as salt addition during periods of elevated nitrite levels. Once the biofilter was considered established, based on stable low ammonium and nitrite concentrations, the monitoring frequency was adjusted. Nitrogen parameters will be measured every two to three days for an additional one-month period to confirm long-term stability and identify potential emerging trends. Following this observation phase, routine monitoring is planned to be conducted on a weekly basis, which is considered sufficient for stable aquaponics system operation.

In addition to routine nitrogen monitoring, micronutrient concentrations will be assessed on a monthly basis. These analyses will be performed using atomic absorption spectroscopy (AAS) and inductively coupled plasma optical emission spectrometry (ICP-OES). Periodic micronutrient analysis provides insight into nutrient availability for plants and helps identify potential deficiencies or imbalances that may not be detectable through standard water quality measurements. Together, the selected methods and monitoring schedule provide a comprehensive framework for assessing system performance, ensuring fish welfare, and supporting sustainable aquaponics operation.

5. Fish Health and Welfare Monitoring

5.1. Physiological and Behavioral Indicators (e.g., feeding behavior, swimming activity)

Fish physiological condition and behaviour were continuously observed as key indicators of health, welfare, and system suitability. Particular attention was given to feeding behaviour, swimming activity, and general responsiveness, as these parameters provide rapid, non-invasive insight into stress levels and water quality conditions. During the initial phase of system operation, fish were fed a total of 100 g of feed per day, divided into three feeding events to reduce waste accumulation and improve feed utilization. Following the observed spike in ammonium concentration, the daily feed ration was reduced to 30 g in order to limit nitrogen input and prevent further deterioration of water quality. This reduction was implemented as a precautionary management measure during biofilter establishment. As nitrite concentrations continued to rise and reached approximately 9 mg L^{-1}, feeding was completely suspended for a period of approximately 1.5 weeks. Temporary feed withdrawal is a commonly applied strategy in recirculating aquaculture systems to reduce metabolic waste production during critical water quality events. Feeding was resumed once a consistent decrease in nitrite concentrations was observed, indicating improving biological filtration performance. After confirmation of biofilter establishment, feeding was reintroduced at 30 g per day and subsequently increased back to 100 g per day, again split into three meals, once it was evident that this feeding level did not overwhelm the system's nitrification capacity. Future feeding adjustments will be implemented gradually, with planned increases of approximately 20 g per day as fish biomass and system capacity increase.

Figure 4. Sturgeon released into the demonstration unit fish tank.

Throughout the entire monitoring period, fish remained active and displayed normal swimming behaviour. No abnormal movements, loss of equilibrium, or signs of distress were observed. During the period of feed withdrawal, fish exhibited increased surface-oriented swimming behaviour, likely reflecting anticipatory feeding responses, but otherwise maintained normal activity levels. The absence of behavioural abnormalities despite elevated nitrite concentrations suggests that timely management interventions, including feeding adjustments and salinity increase, effectively mitigated stress and supported fish welfare.

5.2. Growth and Survival Rates

Fish survival and general condition were monitored throughout the observation period as part of routine welfare assessment. At system start-up, a total of 60 fish (Figure 4) with an average individual weight of approximately 100 g were stocked in the system. During the monitoring period, one fish mortality was recorded approximately two weeks after introduction. The affected individual displayed abnormal behaviour upon arrival to the facility, suggesting that the mortality was likely associated with transport-related stress or pre-existing trauma rather than system conditions. No additional mortalities were observed during or after periods of elevated ammonium or nitrite concentrations, indicating that water quality management measures were effective in protecting fish welfare.

Fish were inspected regularly for external signs of stress, injury, or disease, including abnormal swimming behaviour, changes in posture, discoloration, or visible lesions. No systematic signs of compromised welfare were detected. Survival rate during the monitoring period was therefore 98.3%. Growth performance was not quantitatively assessed during the initial monitoring phase, as system establishment and stabilization were prioritized. However, visual observations indicated variation in fish size, with some individuals appearing larger than others. This size heterogeneity may be related to differences in feeding competitiveness or dominance behaviour, which is commonly observed in cultured fish populations, particularly during early growth stages. To support optimized feeding strategies and reduce size variability, fish biomass monitoring is planned at three-month intervals. Periodic weight measurements will enable adjustment of feeding rates according to actual biomass and growth performance, improving feed efficiency and supporting uniform development. Continued monitoring of growth and survival will provide valuable data for long-term system optimization and fish welfare assessment.

In aquaponics and recirculating aquaculture systems, the primary source of nitrogen entering the system is fish feed. Estimating potential nitrate production based on feed composition provides a useful tool for predicting nitrogen loading and adjusting feeding rates to match biofilter capacity and plant nutrient demand. Protein is the main nitrogen-containing component of fish feed. On average, protein contains approximately 16% nitrogen by mass. Therefore, the nitrogen input from feed can be estimated based on protein content, assuming that most of the ingested nitrogen is excreted by fish as ammonia and subsequently converted to nitrate through nitrification.

For example, when 100 g of feed with a protein content of 45% is supplied to the system:

<u>Protein input:</u>

100 g × 0.45 = 45 g protein

<u>Nitrogen input from protein:</u>

45 g × 0.16 = 7.2 g nitrogen

In aquaculture systems, approximately 70–80% of dietary nitrogen is typically excreted by fish, while the remainder is retained in biomass. Assuming a conservative excretion rate of 75%, the amount of nitrogen released into the water is:

Excreted nitrogen:

7.2 g × 0.75 = 5.4 g nitrogen

During complete nitrification, ammonium nitrogen is converted to nitrate nitrogen. To express this nitrogen load as nitrate (NO_3^-), a molecular weight conversion is applied:

Molecular weight of nitrogen (N): 14 g mol^{-1}

Molecular weight of nitrate (NO_3^-): 62 g mol^{-1}

Thus, the conversion factor from nitrogen to nitrate is 62 / 14 ≈ 4.43.

Estimated nitrate production:

5.4 g N × 4.43 ≈ 24 g NO_3^-

This example demonstrates that feeding 100 g of feed containing 45% protein can theoretically result in the production of approximately 24 g of nitrate, assuming efficient nitrification and minimal nitrogen losses. Such calculations provide a valuable framework for understanding nitrogen dynamics, planning feeding strategies, and balancing fish stocking density with plant nutrient uptake capacity in aquaponics systems.

5.3. Stress and Disease Indicators

Fish were routinely observed for indicators of stress and disease throughout the monitoring period as part of standard welfare assessment procedures. Visual inspections focused on behavioral changes, external physical condition, and general responsiveness to environmental stimuli. Common stress indicators, including abnormal swimming patterns, loss of equilibrium, reduced activity, surface gasping, or isolation from the group, were not observed. Fish maintained normal posture and swimming behaviour under both routine operating conditions and during periods of water quality fluctuation associated with biofilter establishment. Similarly, no visible signs of disease were detected during the monitoring period. Fish showed no external lesions, fin erosion, abnormal discoloration, excessive mucus production, or other symptoms commonly associated with bacterial, parasitic, or fungal infections. Feeding responses, when feeding was active, remained consistent with healthy fish behaviour. The absence of observable stress and disease symptoms indicates that the applied water quality management strategies, including feeding adjustments, aeration, and salinity control during elevated nitrite concentrations, were effective in maintaining fish welfare. Continued routine observation and preventive monitoring are planned as part of long-term system management to ensure early detection of potential health issues.

5.4. Stocking Density and Welfare Considerations

At system start-up, 60 sturgeons with an average individual mass of ~100 g were stocked in a fish tank with a working volume of 1.8 m^3. The initial biomass was therefore ~6 kg, corresponding to an initial stocking density of ~3.3 kg m^{-3}. This is a conservative stocking density for a recirculating setup and is generally favourable from a welfare perspective, as it provides adequate space, reduces competition for feed, and lowers the immediate risk of water quality deterioration.

As fish grow, biomass and feeding demand will increase, which directly increases nitrogen loading to the system. If biomass increases without compensatory measures (greater plant uptake area, higher biofiltration capacity, or biomass removal), the system may experience elevated ammonium and nitrite during peak feeding periods and progressively rising nitrate concentrations. In addition to water chemistry effects, higher densities may increase social stress and feeding competition, potentially amplifying size differences (dominant individuals feeding more aggressively and growing faster). To illustrate the potential future load, a simple nitrate production estimate can be made from feed input. Using the earlier assumption that 100 g of feed with 45% protein may generate ~24 g of NO_3^- (based on protein nitrogen content and an assumed fraction excreted and nitrified), the expected nitrate production is approximately 0.24 g NO_3^- per gram of feed (theoretical maximum, before plant uptake and other losses).

If the fish biomass increases and the daily feeding rate scales accordingly, nitrate loading can rise quickly. For example, assuming a moderate feeding rate of ~1% of standing biomass per day:

- If average fish mass reaches 300 g (total biomass ~18 kg), stocking density becomes ~10 kg m^{-3} and daily feed might be ~180 g day^{-1}. Theoretical nitrate production would be ~43 g NO_3^- day^{-1}, equivalent to roughly 13 mg L^{-1} day^{-1} in a 3.2 m^3 (~3200 L) total system volume if there were no plant uptake or water exchange.
- If average fish mass reaches 500 g (total biomass ~30 kg), stocking density becomes ~16.7 kg m^{-3} and daily feed might be ~300 g day^{-1}. Theoretical nitrate production would be ~72 g NO_3^- day^{-1}, or about 23 mg L^{-1} day^{-1} (without uptake).
- If fish approach 1 kg average mass (total biomass ~60 kg), stocking density becomes ~33.3 kg m^{-3} and daily feed might be ~600 g day^{-1}, producing ~144 g NO_3^- day^{-1}, or about 45 mg L^{-1} day^{-1} (without uptake).

In practice, these increases are partially offset by plant nitrate uptake and routine management (solids removal, biofiltration performance, and potential water replacement). However, the calculations demonstrate how rapidly nitrate can accumulate if fish biomass and feeding increase faster than plant capacity or filtration. For this reason, a conservative operational approach is recommended: maintaining stocking density in a "low-to-moderate" range during growth (for example, aiming to remain below ~15–20 kg m^{-3} unless filtration and oxygenation capacity are clearly sufficient), while using water quality trends (TAN, nitrite, and nitrate) as decision points for scaling feeding, adding plant capacity, or reducing fish biomass.

A planned biomass management strategy will therefore be applied during the next year by removing fish once they reach predefined weight thresholds. This approach allows regulation of nutrient production (especially nitrate), helps keep stocking density within welfare-friendly limits, and reduces feeding competition that can lead to size inequality. Feeding will continue to be adjusted gradually (e.g., in ~20 g increments) based on water quality response and observed feeding behavior, ensuring that increased production does not compromise fish welfare or system stability.

6. Plant Growth and Health Monitoring

6.1. Growth Parameters (e.g., plant height, leaf number, biomass)

Plant growth performance was assessed using qualitative observations and approximate biomass estimates, as systematic quantitative measurements (e.g., plant height, leaf number, and individual biomass) were not yet implemented during the monitoring period. The primary focus during this phase was system establishment and stabilization, with plant production serving as an indicator of nutrient availability and system functionality. Based on harvest counts and visual assessment, total aboveground plant biomass produced during the monitoring period is estimated to be approximately 6.2 kg. Individual salad heads reached an estimated fresh weight of approximately 200–300 g per plant, which is consistent with typical aquaponics-grown leafy vegetable yields. Basil plants produced an estimated biomass of approximately 100 g per plant, while other herbs contributed smaller but consistent amounts to the total biomass. Although plant height, leaf number, and biomass were not measured systematically, plants exhibited uniform growth, adequate leaf development, and normal morphology. No signs of severe nutrient deficiency, growth inhibition, or physiological stress were observed. The estimated biomass production indicates that nutrient availability, particularly nitrate concentrations maintained during system operation, was sufficient to support plant growth. Future monitoring will incorporate standardized growth measurements, including periodic assessment of plant height, leaf number, and fresh and dry biomass at harvest. Implementation of quantitative plant growth metrics will allow improved evaluation of nutrient use efficiency, system productivity, and the relationship between fish-derived nutrient inputs and plant biomass production.

6.2. Visual Health Indicators and Nutrient Deficiency or Toxicity Symptoms

Plant health was evaluated through regular visual inspection, focusing on leaf color, morphology, growth uniformity, and the presence of physiological disorders or pest damage. Visual assessment provides a rapid and practical method for identifying nutrient deficiencies or toxic effects in aquaponics systems, particularly during periods of system stabilization.Plants exhibited satisfactory growth and morphology, with no widespread symptoms of severe stress or growth failure. However, several nutrient-related symptoms were observed, reflecting changes in nutrient availability during different phases of system operation. Mild signs of nitrogen deficiency were noted, particularly following the temporary cessation of fish feeding during the period of elevated nitrite concentrations. As nitrate production declined during this phase, reduced nitrogen availability was reflected in lighter green foliage and slower growth rates in some plants.

Symptoms consistent with iron deficiency were observed in salad plants grown in the floating bed system. These symptoms included interveinal chlorosis in younger leaves, which is typical for iron limitation under neutral to slightly alkaline pH conditions common in aquaponics systems. Iron availability is often restricted due to precipitation at higher pH, making deficiency a frequent challenge in soilless cultivation systems. In addition, signs consistent with nitrite-related toxicity were observed in basil plants cultivated in the floating bed during the period of elevated nitrite concentrations. These symptoms included leaf discoloration and localized tissue stress, likely caused by nitrite uptake through plant roots. Although plants are generally more tolerant to nitrite than fish, elevated concentrations can interfere with nutrient uptake and physiological processes, particularly in sensitive species. Salad plants grown in the media bed exhibited symptoms indicative of calcium uptake limitation, including marginal leaf deformation and localized necrosis in younger tissues. Calcium deficiency in aquaponics systems is often associated with limited translocation of calcium within plants, especially under conditions of rapid growth or fluctuating water availability at the root zone (Figure 5).

Figure 5. Calcium deficiency in romaine salad grown in media bed and nitrite toxicity in basil grown in floating bed.

As a preventive and corrective measure, plants were treated with foliar applications of micronutrient fertilizer to alleviate observed deficiencies without immediately altering system water chemistry. Foliar feeding provides rapid nutrient availability while minimizing potential impacts on fish and microbial communities. Once long-term system stability is confirmed, chelated micronutrients will be added directly to the system water as needed to ensure consistent nutrient availability. No pest infestations or disease symptoms were observed during the monitoring period. Preventive biosecurity measures were implemented, including the use of sterile tools and equipment and the avoidance of introducing externally grown plants. All seedlings were produced within the same controlled environment, reducing the risk of pest introduction and supporting overall plant health.

6.3. Yield and Productivity Indicators

Yield and productivity in aquaponics systems are closely linked to nutrient input from fish feed and the efficiency with which these nutrients are converted into plant biomass. In this system, plant productivity was evaluated by relating estimated nitrogen input from feed to observed and potential plant biomass production within the available cultivation area. As demonstrated in previous sections, feeding 100 g of fish feed with a protein content of 45% introduces approximately 7.2 g of nitrogen into the system, of which an estimated 75% (≈5.4 g nitrogen) is excreted and becomes available for nitrification. Following complete nitrification, this nitrogen corresponds to approximately 24 g of nitrate (NO_3^-). This nitrogen pool represents the primary nutrient source for plant growth in the aquaponics system.

Figure 6. Growth of plants in floating and media bed during the 28 days of monitoring.

Plant biomass production can be approximated by considering the nitrogen content of leafy vegetables and herbs. Fresh leafy biomass typically contains approximately 2.5–4.0% nitrogen on a dry matter basis, with dry matter accounting for roughly 8–12% of fresh biomass. Using a conservative assumption of 3% nitrogen in dry matter and 10% dry matter content, approximately 3 g of nitrogen are required to produce 1 kg of fresh leafy plant biomass (Figure 6).

Figure 7. Conceptual nutrient flow in the aquaponics system illustrating the conversion of fish feed protein nitrogen into plant biomass. Feeding 100 g of feed with 45% protein introduces approximately 7.2 g of nitrogen, of which an estimated 5.4 g is excreted and nitrified, supporting the production of approximately 1.5–2.0 kg of fresh plant biomass under efficient uptake conditions.

Based on this assumption, the 5.4 g of plant-available nitrogen derived from 100 g of feed could theoretically support the production of approximately 1.5–2.0 kg of fresh plant biomass, assuming efficient nutrient uptake and minimal losses (Figure 7). This estimate aligns well with the observed system performance, where approximately 6.2 kg of plant biomass was produced during the monitoring period under variable feeding and system stabilization conditions. The current plant cultivation area is approximately 5 m^2, corresponding to an estimated productivity potential of roughly 0.3–0.4 kg m^{-2} per 100 g of feed input under stable operating conditions. Actual productivity is influenced by crop type, growth stage, environmental conditions, and nutrient availability, and is expected to increase once feeding rates, biofilter performance, and micronutrient supplementation are fully optimized. These calculations demonstrate that the system is capable of effectively converting fish-derived nutrients into plant biomass. Continued refinement of feeding strategies, plant species selection, and nutrient supplementation is expected to improve yield efficiency and support higher productivity per unit of cultivation area as the system matures.

7. Monitoring of environmental parameters

In addition to water quality monitoring, key environmental parameters within the aquaponics system room were continuously monitored to assess their influence on plant growth, fish welfare, and system performance. Environmental conditions were measured using Aranet monitoring sensors connected to a base station with data synchronization to the Aranet Cloud platform, allowing remote access and continuous evaluation of room conditions (Figure 8).

Light intensity was monitored at plant canopy level in both cultivation units. In the floating bed system, photosynthetic photon flux density (PPFD) was maintained at approximately 420–450 µmol m^{-2} s^{-1}, while the media bed received slightly lower light intensities of approximately 350–400 µmol m^{-2} s^{-1}. These light levels are suitable for leafy greens, herbs, and basil, supporting active photosynthesis without excessive energy input. The difference in light intensity between the two cultivation areas may contribute to observed variation in plant growth rates and nutrient demand.

Carbon dioxide (CO_2) concentration in the room air was also monitored as an indicator of ventilation efficiency and photosynthetic potential. Baseline CO_2 concentrations were approximately 450 ppm during periods without human presence, increasing to around 650 ppm when people were present in the room. These concentrations fall within a range considered non-limiting for plant growth and may provide a modest enhancement of photosynthesis compared to ambient outdoor levels, while remaining well below thresholds associated with negative effects on plant physiology or human comfort.

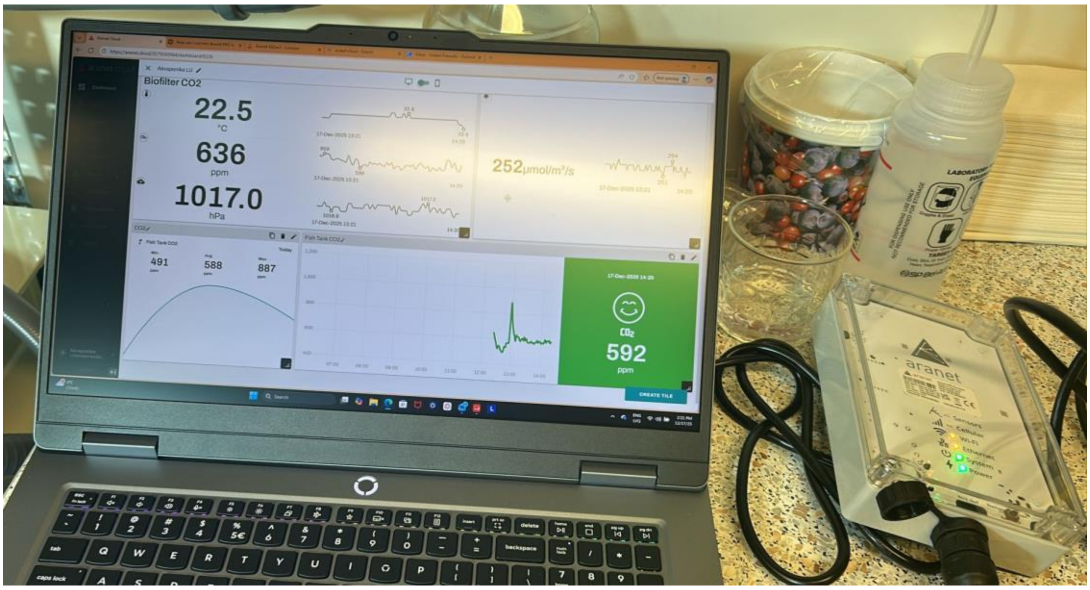

Figure 8. Monitoring system set up at the demo unit to monitor room abiotic factors.

Relative air humidity was strongly influenced by the building's central ventilation system and remained relatively low, at approximately 30–35% throughout the monitoring period. Such low humidity levels can increase plant transpiration rates and may contribute to reduced calcium transport within plants, potentially explaining the calcium-related deficiency symptoms observed in media bed-grown salad plants. While low humidity reduces the risk of fungal diseases, careful monitoring is required to balance transpiration-driven nutrient uptake with plant stress.

Room air temperature exhibited a predictable diurnal pattern. During nighttime and periods without artificial lighting, temperatures remained at approximately 19.5 °C. Following light activation, room temperature increased to approximately 22–23 °C due to heat generated by lighting equipment. This temperature range is suitable for both plant growth and maintaining stable water temperature conditions for fish, contributing to system stability. Together, continuous monitoring of environmental parameters provided essential context for interpreting plant growth responses and nutrient-related symptoms and supported informed management decisions throughout the monitoring period.

Figure 9. Real-time water monitoring to control demo system functionality and fish welfare.

Water quality monitoring in the aquaponics system is ensured through continuous in situ measurements and complementary laboratory analyses. Real-time monitoring is performed using the SC1000 Multi-parameter Universal Controller and Display Module (Figure 9), equipped with four electrochemical probes measuring electrical conductivity (EC), pH, oxidation–reduction potential (ORP), and dissolved oxygen (O_2) and it’s saturation together with water temperature. These parameters provide immediate insight into system stability, conditions for fish welfare as well as nutrient availability for plants and biofilter redox capacity. In addition to online monitoring, key water quality indicators—including nutrients (e.g., nitrogen and phosphorus species), chemical oxygen demand (COD), biochemical oxygen demand (BOD), and trace metals—are periodically analyzed in the laboratory to ensure comprehensive assessment of system performance, nutrient cycling efficiency, and microelement content for plant development. This combined approach enables both high-resolution process control and detailed evaluation of water quality dynamics within the aquaponics system.

8. System Performance and Interactions

8.1. Relationship between water quality, fish health, and plant growth

The monitoring period, which consisted of approximately one month of system operation without fish followed by nearly two months with fish, provided valuable insight into the dynamic relationship between water quality, fish health, and plant growth in the aquaponics system. The results demonstrate that feeding rate and associated nitrogen loading were the dominant drivers influencing system stability and biological performance. Water quality dynamics during biofilter establishment had a direct and observable impact on both fish behaviour and plant growth. The initial ammonium spike following fish introduction and the subsequent prolonged nitrite accumulation phase reflected the gradual establishment of nitrifying microbial communities. During the period when nitrite concentrations peaked, plant growth in both the floating bed and media bed systems temporarily ceased, indicating a disruption in nutrient availability and root-zone functioning. This growth stagnation highlights the sensitivity of plants to rapid changes in nitrogen speciation and system stability. As nitrite concentrations declined and nitrates stabilized, plant growth resumed; however, when nitrate concentrations later decreased from approximately 50–60 mg L^{-1} to around 30 mg L^{-1} following feed withdrawal, visible plant responses were observed. Leaves became paler green and growth rates slowed slightly, consistent with nitrogen limitation. These observations confirm a close coupling between fish feeding intensity, nitrate availability, and plant productivity.

Fish behaviour closely reflected changes in water quality but remained within acceptable welfare limits throughout the monitoring period. During the nitrite peak, fish exhibited increased surface-oriented swimming behaviour and were frequently observed swimming within aeration bubbles. This behaviour is commonly associated with physiological stress or increased oxygen demand and was likely exacerbated by elevated nitrite concentrations. However, high dissolved oxygen levels and timely salt addition effectively mitigated nitrite toxicity, as evidenced by the absence of mass mortality or severe stress symptoms. Following the establishment of the biofilter, ammonium and nitrite concentrations remained consistently low even after feeding was gradually returned to the initial rate of 100 g day^{-1}. This demonstrated that the biological filtration capacity had become sufficient to handle the nitrogen load, marking a clear transition from system instability to functional equilibrium. Differences in plant responses between cultivation units further illustrate system complexity. Floating bed plants exhibited more pronounced nitrogen and iron deficiency symptoms, while media bed plants showed signs of calcium uptake limitation. These differences likely reflect variation in root-zone conditions, nutrient availability, and water–root contact dynamics between the two systems, despite shared water chemistry. The observed interactions confirm that feeding rate was the primary control parameter governing water quality, fish welfare, and plant growth. Feed withdrawal and salt addition were identified as the most effective stabilizing interventions during critical periods, emphasizing the importance of adaptive management during aquaponics system start-up. Once biological filtration was established, the system demonstrated resilience, with stable water quality supporting both healthy fish and renewed plant growth.

8.2. Indicators of system balance and stability

System balance and stability in aquaponics can be assessed through the consistency of key water quality parameters, biological performance, and the system's ability to recover from disturbances. In this study, several indicators collectively demonstrated the transition of the system from an initial start-up phase to a stable operational state. A primary indicator of system stabilization was the sustained reduction and subsequent stability of ammonium and nitrite concentrations following biofilter establishment. After the initial fluctuations associated with microbial colonization, both parameters remained consistently low, even when feeding rates were returned to 100 g day^{-1}. This indicates that the biological filtration capacity had become sufficiently robust to handle the nitrogen input generated by fish metabolism. Stability was further reflected in the consistency of physical and chemical water quality parameters. Water temperature and turbidity remained constant throughout the monitoring period, while pH showed minimal variation (7.2–7.4), indicating adequate buffering capacity and resilience against acidification associated with nitrification. Dissolved oxygen concentrations remained high across all system compartments, supporting fish respiration and efficient microbial activity. From a biological perspective, fish health and behaviour served as reliable indicators of system balance. Following the stabilization phase, fish exhibited normal swimming patterns, consistent feeding responses, and no signs of chronic stress or disease. The absence of additional mortalities and the maintenance of active behaviour during normal feeding conditions further support the conclusion that the system reached a stable equilibrium.

Plant performance also reflected improving system balance. Although growth was temporarily halted during periods of elevated nitrite and reduced nitrate availability, plant growth resumed once nitrogen cycling stabilized. The continued presence of mild nutrient deficiencies suggests that while macronutrient cycling was largely balanced, fine-scale micronutrient management remains an area for optimization rather than an indicator of system instability. Operational responsiveness represents an additional indicator of stability. The system demonstrated predictable responses to management interventions, particularly feed withdrawal and salt addition, which effectively mitigated water quality stress without causing secondary disturbances. Such controllability and recoverability are characteristic of balanced aquaponics systems.

The convergence of stable water quality parameters, consistent fish welfare, resumed plant growth, and predictable system responses indicates that the aquaponics system reached a functional and resilient steady state. Continued monitoring and gradual scaling of feeding and biomass are expected to further reinforce long-term stability and productivity.

8.3. Cost synthesis – economic assessment of the aquaponic system

A simplified economic assessment was conducted to estimate the operational costs of the aquaponics system and to evaluate the approximate production cost per kilogram of fish and salad. The assessment is based on measured system parameters, observed production data, and clearly defined assumptions. The objective was not to calculate full commercial profitability, but to provide a transparent cost-based evaluation of system performance. Note that this is an estimate!

Assumptions

The system was assumed to operate continuously for one year under stable conditions. A total of 60 sturgeon were stocked, with an initial average weight of approximately 0.1 kg and a projected harvest weight of 1.5 kg per fish after one year, resulting in a total harvest biomass of 90 kg. Fish growth was assumed to require a feed conversion ratio (FCR) between 1.2 and 1.5. Plant production was assumed to consist entirely of romaine lettuce, with an estimated annual yield of approximately 37.2 kg based on observed biomass production rates.

The price of sturgeon feed was 69 EUR per 25 kg (2.76 EUR kg^{-1}). Electricity price was assumed to be 0.21 EUR kWh^{-1}, representing an average residential electricity cost in Latvia. Water consumption included an initial system fill of 3.2 m^3 and weekly top-up of 30 L. Micronutrient supplementation costs were estimated at 1 EUR per month.

Energy consumption and costs

Daily electricity consumption of the system was calculated based on installed equipment:

LED grow lights: 3 × 200 W, operating 14 h day^{-1}

Water pump: 80 W, operating 24 h day^{-1}

Air blowers: 3 × 60 W, operating 24 h day^{-1}

Total electricity demand was approximately 14.64 kWh day^{-1}, corresponding to 5344 kWh $year^{-1}$. This resulted in an estimated annual electricity cost of approximately 1120 EUR. Lighting accounted for the largest share of electricity use (~57%), followed by aeration and pumping.

Water and consumable costs

Total annual water use was approximately 4.76 m³, resulting in a water cost of roughly 13 EUR per year. Micronutrient supplementation added an additional cost of approximately 12 EUR per year. Water and consumables therefore represented a minor fraction of total operating costs compared with electricity and feed.

Feed costs

To achieve a biomass gain of approximately 84 kg fish per year, feed requirements were estimated to range between 101 and 126 kg, depending on assumed FCR. This resulted in an annual feed cost of approximately 280–350 EUR.

Cost per kilogram of fish

Fish-related operating costs were allocated to pumping, aeration, feed, and water. Total annual fish-related costs were estimated at approximately 770–840 EUR. Based on a projected harvest of 90 kg fish per year, the estimated production cost was:

8.5–9.3 EUR per kg fish

Cost per kilogram of salad

Plant-related operating costs were dominated by electricity for lighting, with minor contributions from water and micronutrients. Total annual plant-related costs were estimated at approximately 670 EUR. Based on an estimated annual lettuce production of 37.2 kg, the resulting production cost was:

approximately 18 EUR per kg salad

Table 1. Estimated production output and cost per unit

Product	Annual output (assumed)	Cost allocation basis	Estimated cost (EUR kg^{-1})
Fish (sturgeon)	90 kg (60 fish × 1.5 kg)	Feed + aeration + pumping	**8.5–9.3**
Salad (romaine)	37.2 kg	Lighting + water + micronutrients	**~18.0**

Nitrogen-based yield interpretation

Based on nitrogen mass-balance calculations, 100 g of fish feed containing 45% protein can theoretically generate sufficient plant-available nitrogen to support approximately 1.5–2.0 kg of fresh leafy biomass. This corresponds to a feed-derived nutrient cost of only 0.14–0.18 EUR per kg salad. The substantially higher observed production cost is therefore primarily attributable to energy consumption, particularly artificial lighting, rather than nutrient limitations.

Improving the cost efficiency of the romaine salad production in demo unit

Another issue with the current system is the underutilisation of the space allocated for plant growth. By optimising the grow bed and floating bed we can signifficantly increase the production of the salad. Under an intensified production scenario with full utilization of the available 5 m² growing area, romaine lettuce is assumed to be cultivated at a spacing of approximately 20 × 20 cm, corresponding to a planting density of about 25 plants per m². Average harvest mass is assumed to be approximately 0.25 kg per head, consistent with observed yields in the system. A crop cycle length of approximately seven weeks from transplant to harvest is assumed, allowing for roughly 7–8 production cycles per year. To account for minor losses, empty planting positions, and scheduling inefficiencies, an utilization factor of 0.9 is applied. Under these assumptions, annual romaine lettuce production is estimated at approximately 200 kg (compared to 37.2 kg currently). Operating costs are assumed to remain unchanged, as lighting, pumping, aeration, and general system operation are already in place. This scenario represents a realistic upper-bound estimate for plant productivity under optimized space use and continuous crop succession, provided that nutrient availability and system stability are maintained. This would allow to produce the salad at 3.2 EUR per kg. So, optimisation of the system plant spacing part could signifficantly increase the profitability of salad production.

9. Conclusions and Recommendations

9.1. Summary of key monitoring outcomes

This study demonstrated the successful establishment and stabilization of a small-scale aquaponics system through systematic monitoring of water quality, fish welfare, and plant performance. The monitoring period captured critical system dynamics during start-up, including the establishment of biological filtration and the progression of the nitrogen cycle from ammonium accumulation to stable nitrification.

The results clearly showed that fish feeding rate was the dominant driver of system behaviour, influencing nitrogen loading, water quality, fish health, and plant growth. Initial ammonium and nitrite spikes following fish introduction reflected the absence of established nitrifying microbial communities. However, through adaptive management measures, including feed reduction, temporary feed withdrawal, and salt addition, water quality was stabilized and fish welfare maintained during critical phases. Once the biofilter was fully established, ammonium and nitrite concentrations remained consistently low, even after feeding rates were restored to initial levels. This stability confirmed the successful maturation of the biological filtration system and the system's capacity to process nitrogen inputs effectively. High dissolved oxygen levels and stable pH further supported biological processes and contributed to system resilience. Plant growth responded directly to changes in nitrogen availability, with growth cessation observed during periods of elevated nitrite and reduced nitrate availability, followed by recovery once nitrogen cycling stabilized. Differences in nutrient deficiency symptoms between floating bed and media bed cultivation highlighted the importance of root-zone conditions and micronutrient availability in aquaponics systems.

The system demonstrated a clear transition from an unstable start-up phase to a balanced and resilient operational state. The integrated monitoring approach provided valuable insight into system interactions and confirmed that careful feed management and targeted interventions are critical for maintaining aquaponics system stability.

9.2. Recommendations for system optimization and management

Based on the findings of this study, several recommendations can be made to support continued system stability, productivity, and fish welfare. First, feeding rate should remain the primary control parameter for managing nitrogen loading. Gradual adjustments to feeding, particularly during periods of biomass increase, are recommended to prevent overloading the biofilter and to maintain stable ammonium and nitrite concentrations. Regular monitoring of nitrogen cycle parameters should be continued, with increased measurement frequency during periods of system change, such as biomass increase, seasonal temperature variation, or system expansion. Periodic verification of biofilter performance is particularly important as fish grow and feeding rates increase. To improve plant productivity and nutrient balance, targeted micronutrient management is recommended. While foliar fertilization proved effective as a short-term corrective measure, the controlled addition of chelated micronutrients to system water should be implemented once long-term stability is confirmed. This approach will help prevent recurring deficiencies, particularly of iron and calcium, without compromising fish welfare. Stocking density should be actively managed as fish biomass increases. Planned removal of fish at predefined weight thresholds is recommended to regulate nitrate production, maintain welfare-friendly densities, and align nutrient output with plant uptake capacity. Expansion of plant growing area, including the planned vertical NFT system, is expected to further improve nutrient utilization efficiency.

Finally, continued documentation of system performance, including quantitative plant growth measurements and periodic fish biomass assessments, is recommended. Thse data will support improved system optimization, enable more precise nutrient balancing, and provide a robust foundation for future scaling or research applications.