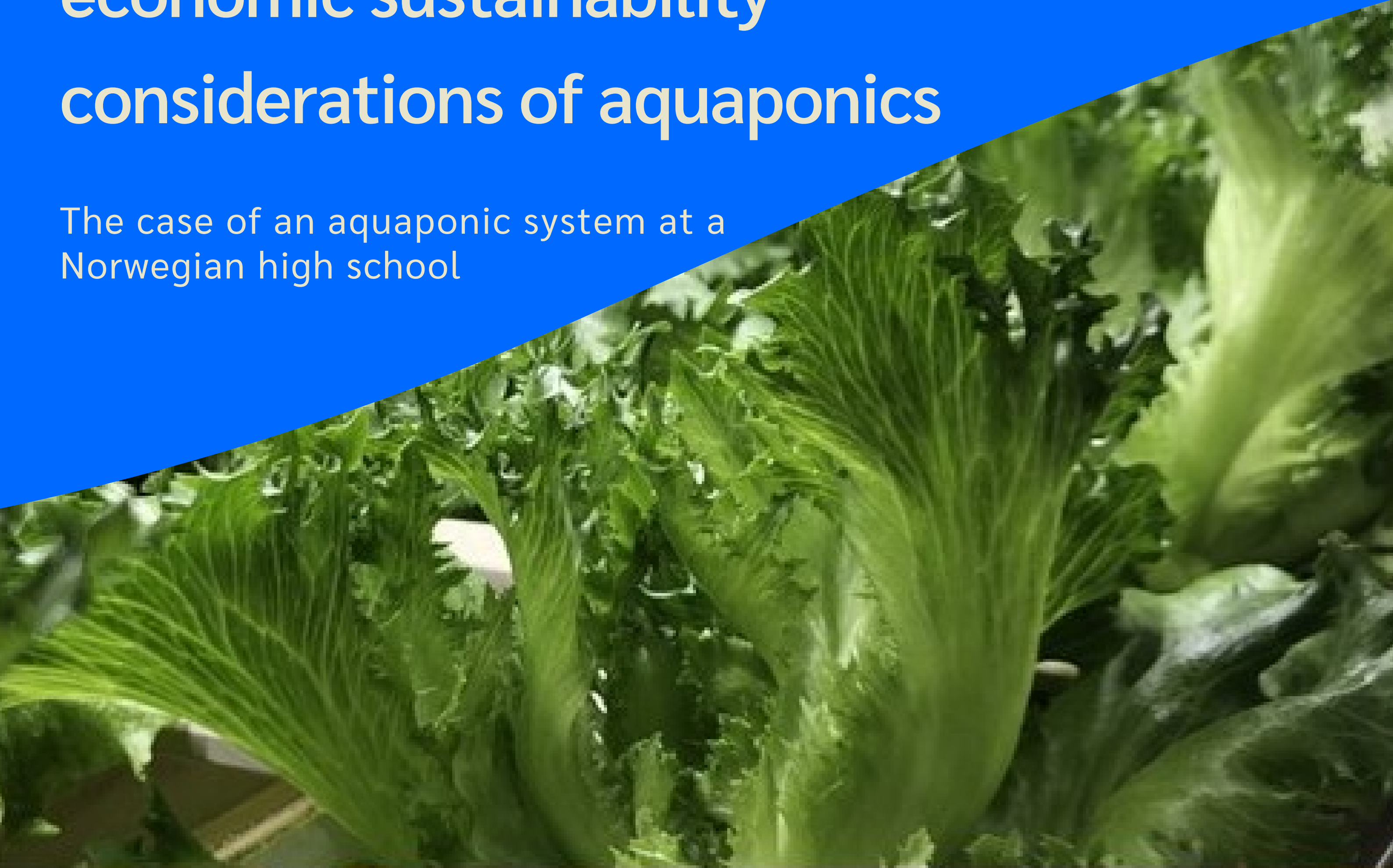
7980-2024

Norwegian institute for
water research

Environmental, social and economic sustainability considerations of aquaponics

The case of an aquaponic system at a Norwegian high school



Photos: Gabrielle Hairabedian

Report

Norwegian Institute for Water Research

Serial no: 7980-2024

ISBN 978-82-577-7717-3
NIVA report
ISSN 1894-7948

This report has been quality assured according to NIVA's quality system and has been approved by:

Gabrielle Hairabedian
Lead Author

Trine Dale
Quality Assurer

Sondre Meland
Research Manager

www.niva.no

Title
Environmental, social and economic sustainability considerations of aquaponics
Miljømessige, sosiale og økonomiske betraktninger av akvaponi

Pages
30

Date
06.05.2024

Author(s)
Gabrielle Hairabedian, Eléonore Maitre-Ekern, Ole-Kristian Hess-Erga, Anne Luise Ribiero, Sondre Meland

Topic group
Aquaculture

Distribution
Open

Client(s)
EEA/Norway Grants 2014-2021 through NCBR
NOR/IdeaLab/USAGE/0004/2020

Published by NIVA
210194

Abstract
This report covers how aquaponics contributes to the sustainability transition by discussing some of the main positive and negative environmental, social and economic aspects. It does this by taking a closer look into how aquaponics relates to different aspects of food systems, land and resource use, environmental pollution and material waste, and societal benefits. It considers how the scale and purpose of aquaponics might impact its economic viability and costs by demonstrating the actual work put into an aquaponic system in order to gain a better understanding of the inputs and outputs required to run such a system for non-commercial users. It also highlights some of the experiences learned through constructing and operating the Small-Scale Urban Pilot Installation (SUPI) aquaponic system developed within the USAGE (Urban Stormwater Aquaponics Garden Environment) project at the high school/upper secondary school Natur videregående skole (Natur VGS) in Oslo, Norway.

Keywords: aquaponics, sustainability, land use, resource use, costs, food systems, environmental pollution, societal benefits
Emneord: akvaponi, bærekraft, landbruk, ressursbruk, kostnader, matsystemer, miljøforurensing, samfunnsmessige fordeler

Table of contents

Preface

This report represents deliverables 5.2 and 5.3 or respectively the “Report on construction, instrumentation and operating costs of the aquaponic system” and “Report on re-use of side-streams and waste from the system” within the USAGE (Urban Stormwater Aquaponics Garden Environment) project. Financial support for the USAGE project comes from the EEA and Norway Grants 2014-2021 through the National Centre for Research and Development through the program "IdeaLab Cities for the future: services and solutions" with support also received from the Savings Bank Foundation DNB (Sparebankstiftelsen). The project is led by H2O-SCITECH, spanning from 2021-2024, where NIVA leads work package 5 “Participatory implementation of Small-Scale Urban Pilot Installation (SUPI) in Norway” and is involved in several of the other work packages relating to the use of stormwater, societal engagement, regulatory analysis, and plans for future development.

This combined deliverable highlights some of the experiences learned through constructing and operating the Small-Scale Urban Pilot Installation (SUPI) developed within the USAGE project in Norway at Natur videregående skole (Natur VGS), a high school/upper secondary school in Oslo.

Oslo, 29th April 2024

Summary

This report covers how aquaponics contributes to the sustainability transition by discussing some of the main positive and negative environmental, social and economic aspects. It does this by taking a closer look into how aquaponics relates to different aspects of food systems, land and resource use, environmental pollution and material waste, and societal benefits. It considers how the scale and purpose of aquaponics might impact its economic viability and costs by demonstrating the actual work put into an aquaponic system in order to gain a better understanding of the inputs and outputs required to run such a system for non-commercial users. It also highlights some of the experiences learned through constructing and operating the Small-Scale Urban Pilot Installation (SUPI) aquaponic system developed within the USAGE (Urban Stormwater Aquaponics Garden Environment) project at the high school/upper secondary school Natur videregående skole (Natur VGS) in Oslo, Norway.

Sammendrag

Denne rapporten tar for seg hvordan akvaponi kan bidra til en bærekraftig omstilling ved å diskutere noen av de viktigste positive og negative miljømessige, sosiale og økonomiske aspektene. Dette gjøres ved å belyse hvordan akvaponi kan knyttes til ulike aspekter ved matsystemer, land- og ressursbruk, miljøforurensning og materialavfall, samt samfunnsmessige fordeler. For å gi ikke-kommersielle brukere en bedre forståelse av hva som kreves for å drive et akvaponi system, diskuterer vi også hvordan omfanget av og formålet med akvaponi kan påvirke den økonomiske levedyktigheten og kostnadene ved å demonstrere det faktiske arbeidet som legges ned i et akvaponisystem for å få en bedre forståelse av hva som kreves for å drive et slikt system for ikke-kommersielle brukere. Den belyser også noen av erfaringene fra bygging og drift av SUPI-systemet (Small-Scale Urban Pilot Installation) som er utviklet i USAGE-prosjektet (Urban Stormwater Aquaponics Garden Environment) ved Natur videregående skole i Oslo.

List of abbreviations and acronyms	
AC	air conditioning
cm	centimetre
DWC	Deep Water Culture
g	gram
IBC	intermediate bulk container
IPDM	integrated pest and disease management
kg	kilogram
l	litre
m	metre
mm	millimetre
NFT	Nutrient Film Technique
NIVA	Norwegian Institute for Water Research
NOK	Norwegian krone
PVC	polyvinyl chloride
RAS	recirculating/recirculation aquaculture system
SDG	Sustainable Development Goal
SME	Small and Medium Enterprise
SSB	Statistisk sentralbyrå (Statistics Norway)
STEM	Science, Technology, Engineering, and Mathematics
SUPI	Small-Scale Urban Pilot Installation
USAGE	Urban Stormwater Aquaponics Garden Environment
UV	ultraviolet
VAT	value added tax
VGS	videregående skole (high school/upper secondary school in Norway)

1 Introduction

1.1 General considerations on sustainability and circularity

Human activities are exerting increasing pressure on the natural environment. In 2009, a group of Earth system scientists put forward the planetary boundaries framework that aimed to establish what many intuitively thought: that the Earth has limits and that exceeding those may cause grave harm on its natural balances and ultimately threaten the 'safe operating space for humanity' (Rockström et al., 2009; Steffen et al., 2015). The third and latest major update to the framework finds that we are currently transgressing six of the nine identified boundaries, i.e., climate change, biosphere integrity, land system change, freshwater change, biogeochemical flows and novel entities (Richardson et al., 2023). In addition, ocean acidification is approaching its planetary boundary. Figure 1 below shows the current status of the nine planetary boundaries.

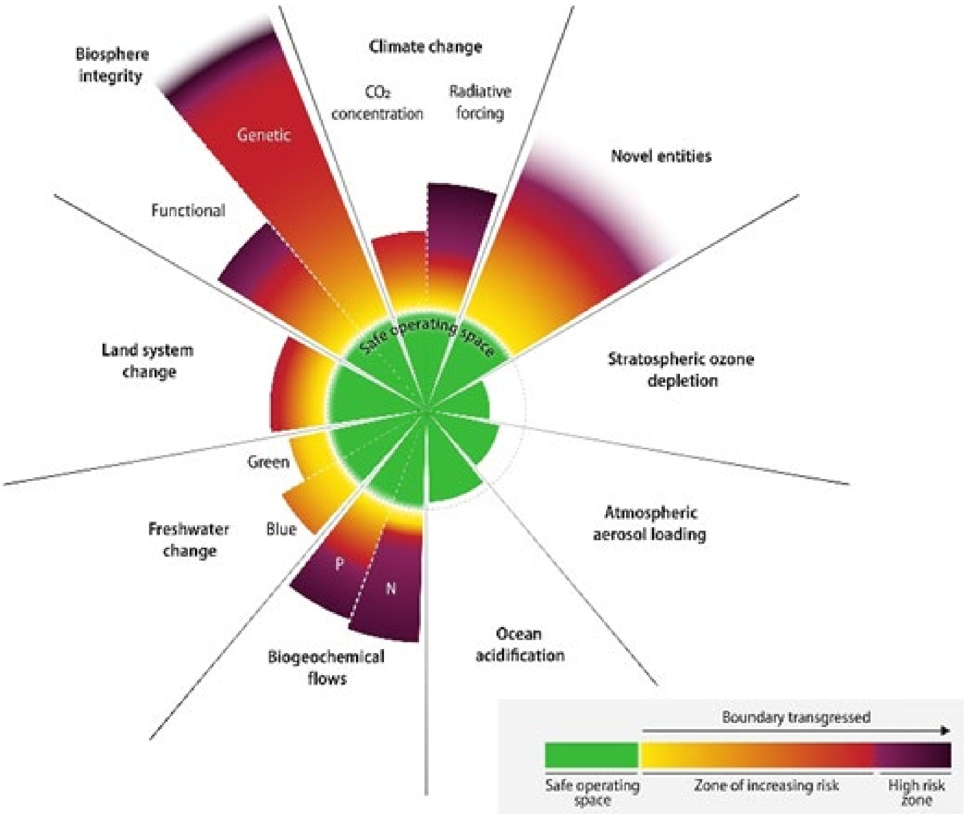


Figure 1. Current status of control variables for all nine planetary boundaries (Richardson et al., 2023).

Food systems are both a cause of harm to the planetary boundaries and a victim of the consequences of their transgression. Agriculture is notably responsible for deforestation, chemical pollution, soil and air pollution, and excessive water use. In one way or another, all these factors are affecting all the planetary boundaries (Campbell et al., 2017). At the same time, soil erosion, interference with the nitrogen and phosphorus cycles, intensification of weather events such as droughts and floods, threatened biodiversity, increased freshwater withdrawals, etc. that result from overstepping the planetary boundaries are exerting growing pressure on traditional food production systems. The deterioration of earth's environmental quality is threatening food systems and raising great challenges.

There is increasing pressure to produce more food to respond to the demand of a growing global population. Sustainability is not only an issue of environmental protection. Securing a safe and just operating space for humanity also requires ensuring the wellbeing of humans in addition to preserving the natural environment (Raworth, 2017). The UN Sustainable Development Goals (SDGs) have contributed to establishing what the social aspects of sustainability encompass. The most prominent here is SDG2, which aims to 'end hunger, achieve food security and improved nutrition and promote sustainable agriculture' and has interlinkages with the other SDGs, notably for promoting gender equality, ending rural poverty, ensuring healthy lifestyles, and tackling climate change.

In order to mitigate harm, food systems must change and become more sustainable. One of the tools for achieving more sustainability – not just for food systems – is circularity. The rise of the circular economy is driven by the recognition that most of our production processes are wasteful and resource intensive. The take-make-dispose model that characterises the linear economy is in contradiction with the reality of the natural environment and planetary boundaries. A circular economy, on the other hand, is meant to mimic nature in which nothing is lost.

Some argue that the concept of circularity can be extended to other disciplines. An example is circular pedagogy, which views education as a circular process rather than a linear one, where the student, teacher and researcher play interchangeable roles in technological and sustainable environments combining new and traditional practices (Morales et al., 2022; Pop et al., 2022).

1.2 The role of aquaponics in the sustainability transition

Aquaponics is a farming method that combines aquaculture (fish farming) and hydroponics (soil-less plant cultivation) in a symbiotic environment. Figure 2 shows an example of a closed-loop aquaponic system meant to mimic a natural ecosystem, utilising the natural processes of nutrient and water cycling. In aquaponics, waste produced by fish provides nutrients for plants, and the plants help to purify the water for the fish. The main inputs in aquaponics include system infrastructure, fish feed, and energy for lighting, heating and cooling, while the primary outputs are fish and plants (Goddek et al., 2019; Greenfeld et al., 2022).

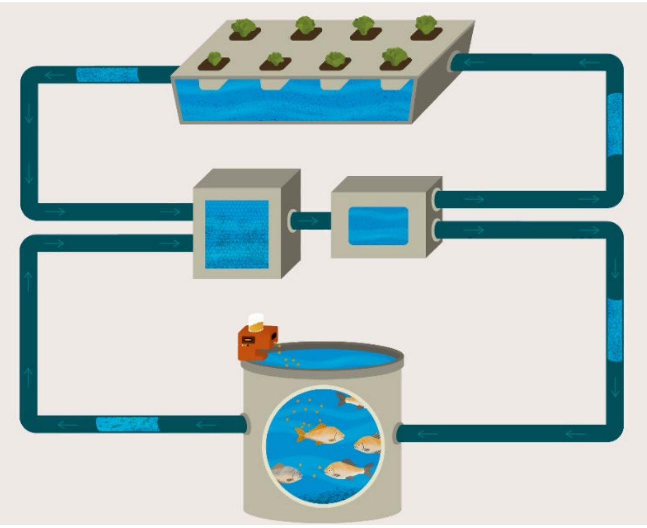


Figure 2. Aquaponic system where nutrients and water are recycled in a closed loop. Resources are cycled from the fish tank, through a recirculating/recirculation aquaculture system or RAS, to the hydroponic system before returning to the fish tank (illustrated by AVIA Produksjon, 2024).

Aquaponics is largely considered a quite sustainable form of agriculture, notably in comparison to aquaculture (on land and in water) and conventional agriculture (in soil or off-soil) (Greenfeld et al., 2022). Aquaponic systems can be established closer to the consumer due to their inherent self-sufficient and compact nature. Indeed, producing food in rural areas and transporting it to support cities has been reported as one of the key contributors to increased greenhouse gas emissions, biodiversity loss, water pollution, land-use exhaustion, and several other environmental impacts (David et al., 2022; Goldstein et al., 2016). Urban or peri-urban food production systems, on the other hand, offer the promise of more sustainable urban food consumption and reduction of environmental impacts (Armanda et al., 2019;

Schumacher, 2011). Some of the benefits are reduction in land use required to produce food, contribution to feeding a growing worldwide population and to ensuring food security.

Moreover, aquaponics is an example where circularity is used for improving the sustainability of human activity. The ‘waste’ (i.e., fish excrement) of one process serves as resource for another one, thus reducing both negative output to the environment and reliance of new products (in this case, plant fertilisers) that require raw resources for production and may also lead to increasing pollution (e.g., chemicals contained in fertilisers).

Finally, within the frame of circular pedagogy, aquaponics can provide a creative learning arena for students, teachers and researchers to interact, exchange knowledge and inspire change. In this way, aquaponics can contribute to improving the social aspects of sustainability.

1.3 Project USAGE and the Norwegian case study

The overarching objective for the USAGE (Urban Stormwater Aquaponics Garden Environment) project is to develop and build two small-scale aquaponic systems in Wrocław, Poland and Oslo, Norway for interdisciplinary use, linking topics such as food production and education in urban areas. The aquaponic systems also integrate rain and stormwater collection infrastructure to test the potential of additional water resources in food production.

The USAGE project utilises a Small-Scale Urban Pilot Installation (SUPI) built and installed at Natur videregående skole (Natur VGS), a high school/upper secondary school in Oslo, Norway. Natur VGS is a school for natural sciences, where students can take more specialised or general studies, acquire vocational skills through an internship/apprenticeship, and earn a vocational certificate. More information is available in Norwegian on their website: https://natur.vgs.no/om-skolen/. NIVA constructed the vertical SUPI by repurposing two shipping containers in a parking lot next to the school (see Figure 3). Figure 4 shows photos from inside the shipping containers where the SUPI aquaponic system is housed. NIVA employees have been operating the system and have trained teachers at Natur VGS to transfer this responsibility from NIVA to the teachers and eventually students at the school, a process still ongoing at the time of developing this report.

Through the USAGE project, an instructional tool available in both English and Norwegian has also been developed to support teachers in integrating aquaponics into the school’s curriculum planning. This tool can be adapted and customised as needed and utilises aquaponics as a learning arena to explore existing global challenges.

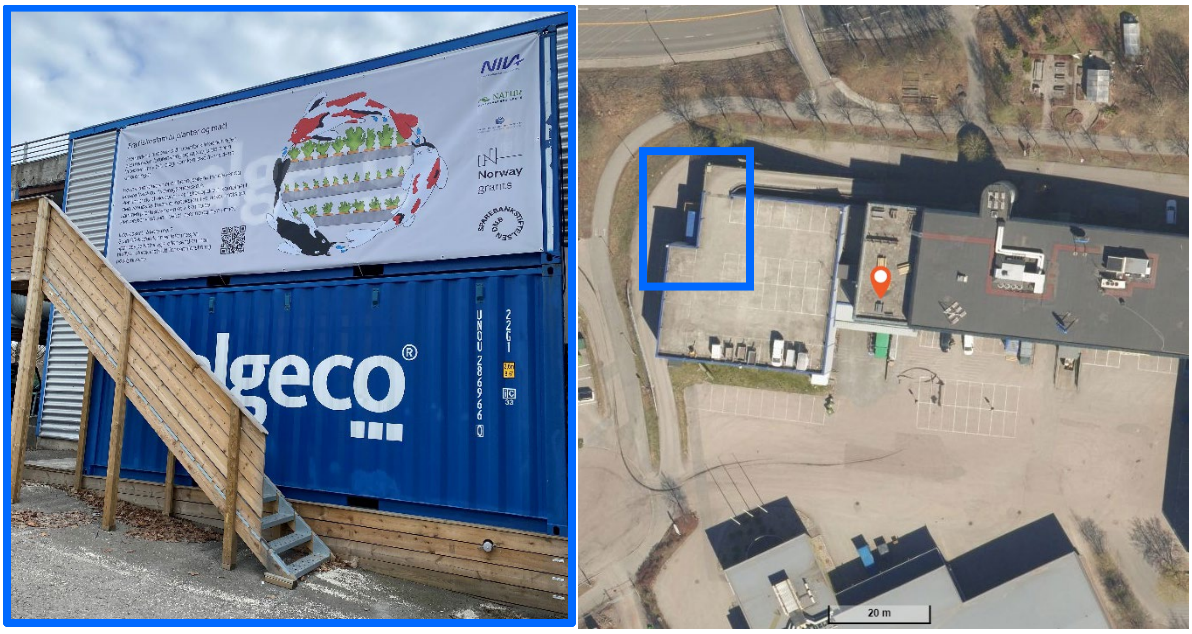


Figure 3. The two shipping containers housing the SUPI aquaponic system and their location at Natur VGS (photo taken by Anne Luise Ribeiro, 2024; Norgeskart, 2024).

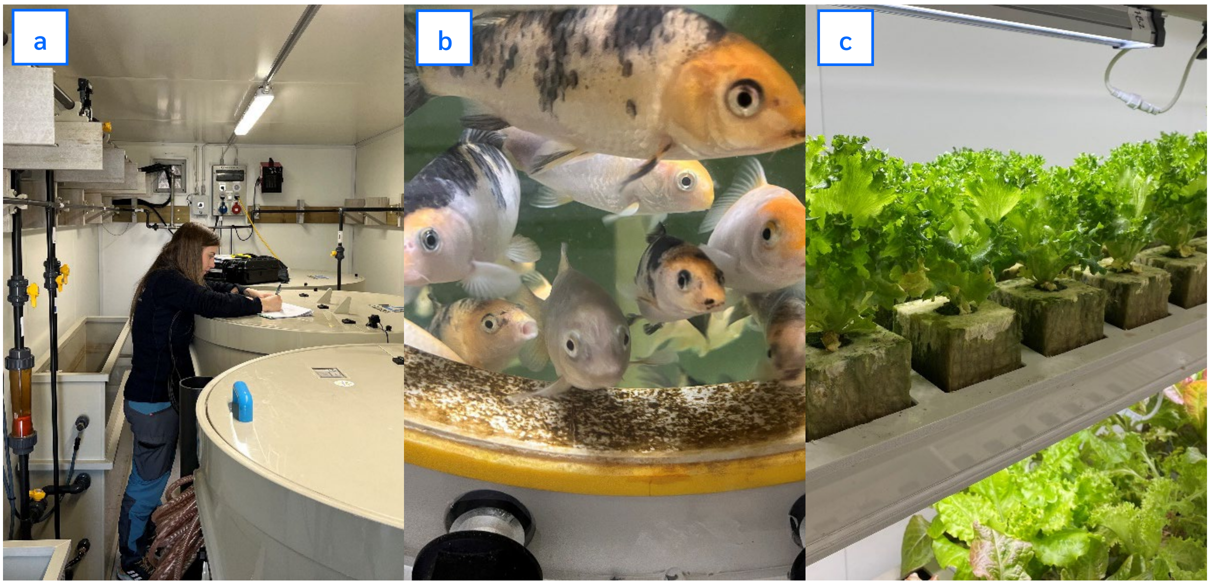


Figure 4. The SUPI aquaponic system at Natur VGS showing the a) aquaculture system setup within the lower container, b) koi fish, and c) hydroponic system setup with frillice lettuce in the upper container (photos taken by NIVA staff, 2023).

2 Results

Aquaponics aims to contribute to the sustainability transition, and it appears to be doing so in many areas. However, there are also challenges and uncertainties linked to this activity. In this section, we discuss the environmental and social aspects considering two different perspectives: positive contributions and the more contentious aspects of aquaponics based on selected literature and knowledge obtained through the USAGE project. We do not, however, claim to conduct an exhaustive review of all possible sustainability impacts of aquaponics, but rather raise some of the most important and relevant aspects.

We discuss these sustainability aspects both from a general standpoint and in light of the early findings from work with the SUPI aquaponic system at Natur VGS in Oslo, Norway. We also examine the issue of costs, discussing the sustainability of aquaponics in a school setting and from an economic perspective, including issues surrounding upfront investments, labour costs and scalability. In the last part of this section, we take a look at the capacity of production for the SUPI aquaponic system at Natur VGS in Norway.

2.1 Overview of environmental and social sustainability aspects of aquaponics

Aquaponics promises to bring about several sustainability benefits related notably, to food production and security, land use, use of resources and environmental impacts, as well as several societal contributions. However, aquaponic systems also require substantial energy to function, their set up is material intensive, and may lead to plastic pollution.

In this section, we discuss some of the main positive and negative environmental and social aspects that aquaponics likely contributes to, without claim to an exhaustive analysis of all aspects. The aim is to give a sense of where aquaponics is positioned in the transition to a more sustainable future, to point out its many benefits, but also to raise some concerns about some of the consequences. In addition, we include some findings from the USAGE project, and in particular, the SUPI aquaponic system at Natur VGS in Norway to illustrate and concretise some of these aspects that we discuss.

2.1.1. Food production and security

With a growing global population and uneven distribution of people, the demand for increased food production is rising, and the stress on global resources is rising with it, including land, water and nutrients, which are already under great pressure from climate change, biodiversity losses and other consequences of the environmental crisis (Goddek et al., 2015). Moreover, the rural labour force is shrinking with urbanisation (FAO, 2017). More than half of the global population currently resides in urban areas and most growth is expected to occur in cities (DESA, 2023). Aquaponics represents one method to partly combat some of these issues. It has great potential due to it requiring less resources and land, and because it can be set up in arid regions with non-arable soil and enough labour, such as cities.

In addition, the deployment of aquaponic systems could respond to food supply needs in a more localised manner such as canteens at schools and companies, restaurants, hotels, and the like. Staff could potentially be shared between the aquaponic facility and these varying arenas to improve overall knowledge, understanding and economy. Produce and crops that would otherwise be costly and long travelled from rural areas, could be replaced with greens bought through intermediaries providing locally grown produce.

In the USAGE project, the products from aquaponics could be sold by students through student-led enterprises (elevbedrift in Norwegian) as a part of their curriculum. This would give students an opportunity to reflect on food production and security issues, including where food comes from, what environmental, social and economic challenges the sector is facing and how policies and regulations frame this sector and what barriers stand in the way of more sustainable food production.

2.1.2. Land use

An important known benefit of aquaponics relates to land use, in terms of production, doubling the function of areas, and integration into existing infrastructure. Due to aquaponics' ability to be set up in urban, non-arable areas, it does not require fertile farmland. Aquaponics production can, for example, be located in otherwise unproductive and underutilised areas within cities such as parking lots and rooftops, thus doubling the function of certain areas. This can notably reduce land acquisition costs if those areas are deemed unsuitable for other purposes, such as housing (Joyce et al., 2019). In addition, production in aquaponics can also take pressure away from clearing ecologically valuable natural and semi-natural areas for conventional agriculture (Joyce et al., 2019).

Some forms of aquaponics can also take place in vacant lots, on existing rooftops, in underutilised warehouses or vertically, which means that it does not compete with other land uses or the uses of a building's interior (Buehler & Junge, 2016; Proksch et al., 2019; Specht et al., 2014). Integrating aquaponics into existing infrastructure has the potential to mitigate stormwater, provide shade, create an energy reservoir in terms of heat generation, and air purification.

Aquaponic systems are often compact and tightly contained in comparison to the equivalent open production area of vegetable and fruit crops of conventional soil-based farms (Joyce et al., 2019). Thus, the land footprint needed for production is smaller, despite other limitations surrounding the need for more artificial lighting and cooling/heating dependent on the local climate.

The use of vertical farming systems in urban areas is a viable alternative to conventional horizontal growth systems because growing space is optimised more efficiently, thereby producing more crop per unit area (Touliatos et al., 2016). This was demonstrated by the SUPI at Natur VGS in Norway, where the system was compactly built in two shipping containers in a parking lot on the side of a school.

2.1.3. Resource use

Most aquaponic systems are run in a closed-loop layout where water and nutrients are shared and recirculated between all compartments, i.e., fish tanks, mechanical and biological filters, and the plant production bed (Pinho et al., 2021). The fish excreta and excess nutrients from fish feed are converted by microorganisms and used as fertiliser for plant production. The production of fish feed is either fishmeal-based or plant-based and requires valuable resources and raw material which makeup the macro- and micronutrients and vitamins in the feed, therefore, wastage of the feed leads to wastage of resources.

Fish diets and feeding schedules should be designed carefully to provide nutrients at the right level and the right time to complement both fish and plants (Robaina et al., 2019). Further, fish feed needs to be produced in a sustainable manner, preferably with ingredients originating locally, using products and by-products from organic matter not suitable for other purposes (e.g., farmed insects and worms, macro- and microalgae, etc.), and from low trophic species or from species that are considered problematic (e.g., invasive) or exist in excess (Robaina et al., 2019). Feed should still fulfil nutritional requirements and not interfere with fish protein metabolism. The transformation of excess nutrients into plant fertilisers also has the potential to reduce the environmental impact of food production by fully utilising nutrients in the fish feed by minimising the use of non-renewable resources such as industrial fertilisers, and reducing the need for large volumes of water and land (David et al., 2022; Joyce et al., 2019).

The gains in resource use can be further increased through water reuse from different sources, for example from collected water from rooftop runoff instead of drinking water from the tap. This has been tested at the SUPI at Natur VGS by cycling water collected from three different green roofs (black reference/control, sedum and meadow) into the aquaponic system. Once this water was cycled into the system, NIVA was able to compare the growth and nutritional levels of frillice lettuce from a single supplier cultivated in four different setups, with analysis of these results still ongoing at the time of developing of this report.

In addition to growth and nutrition, NIVA tested the water quality over a period to evaluate the potential of reusing collected water from rooftop runoff for food production. Synthesis of the results from this study is also still ongoing.

2.1.4. Energy use

Aquaponic systems are energy intensive. Literature shows that, in northern latitudes, greenhouses have high energy consumption that is largely linked to heating during the winter months (Semple et al., 2017). This generally leads to both significant economic costs and environmental damage due to heavy reliance on fossil fuels for electricity and heat production. However, the use of renewable energy, notably with solar panels attached to an aquaponic system, is growing, as is the share of renewable sources of energy in Europe (Eurostat, 2023; Zainal Alam et al., 2022). Norway is an exception in the sense that most of the electricity production (98%) comes from renewable resources, mostly from hydropower and to a much smaller extent from thermal and wind power (Ministry of Energy, 2016).

Research and innovation driven by environmental regulation and cost reduction has led to energy savings. For example, dehumidification and heat recovery can decrease the need for indoor ventilation, which is energy intensive (Jansen & Keesman, 2022). Similarly, the development of LED horticultural lights that are extremely long lasting and energy efficient has increased competitiveness of indoor farming as well as production in northern latitudes (Joyce et al., 2019). However, seasonal variations affect the energy efficiency of aquaponic systems (Goddek & Körner, 2019).

There are nevertheless many factors that enter into account when considering energy use in food production, and comparing conventional agriculture to aquaponic systems is not straightforward. There are pros and cons for both, and often a significant difference in scale. For example, the use of machinery (such as tractors), production of fertilisers and fish feed, and transport of crops are energy intensive activities that are inherent to industrial farming, but are effectively absent in aquaponics due to smaller scale and in some cases, proximity to the market.

2.1.5. Chemical use

Aquaponics usually takes place in closed, contained units, which reduces the need for widespread application of pesticides (herbicides, insecticides, nematicides and fungicides) prevalent in soil-based agriculture (Joyce et al., 2019). Seed and transplant stocks in aquaponic units are carefully handled and monitored such that weeds, insect vectors, and algal, fungal, and bacterial contaminants can be controlled with targeted measures. Preventative measures against pathogens typical take place at the harvest and/or end of production by cleaning and disinfecting all components (e.g., pipes, valves, flowmeters) and other equipment (Yavuzcan Yildiz et al., 2019). Thus, the need for the use of chemicals for cleaning and disinfection is also reduced through these measures occurring between production rounds. In integrated pest and disease management (IPDM), pesticides should be used as a last resort due to detrimental effects on non-target organisms and persistence, while biological control measures or use of natural enemies of pests are mostly safe for any aquaponic design (Folorunso et al., 2021). The SUPI aquaponic system at Natur VGS has utilised potassium permanganate ($KMnO_4$) for treatment of parasites when needed.

Chemical use outside of pesticides involves the addition of buffers or chemicals that increase pH and are needed to enhance the nitrification process. Nitrification or the biological conversion of ammonia to nitrite and nitrite to nitrate, "consumes alkalinity" in aquaponic systems and additive buffers increase pH without causing negative effects on the fish and plants. The SUPI aquaponic system at Natur VGS in Norway demonstrates this by adding calcium carbonate ($CaCO_3$) and potassium bicarbonate ($KHCO_3$) to adjust the pH and enhance the nitrification process. Such buffers can also contribute with macronutrients (e.g., potassium and calcium) that normally are a limiting factor in aquaponics.

Tetra AquaSafe is also used in the SUPI aquaponic system at Natur VGS as a water conditioner to remove harmful substances during water changes. While this is not a general requirement for aquaponics, it was used due to the inability of circumventing copper pipes leading into the facility. Some hazardous wastes mixed with chemicals is also generated from the test kits when performing routine testing during supervision. Table 1 specifies the chemicals and their frequency of use in the SUPI aquaponic system at Natur VGS.

Table 1. Chemicals and their frequency of use at the SUPI aquaponic system at Natur VGS.

Chemical	Frequency of use
Ammonium Cell Test 0.20-8.00 mg/l NH_4-N, 0.26-10.30 mg/l NH_4	Weekly to monthly
Nitrite Cell Test 0.010-0.700 mg/l NO_2-N, 0.03-2.30 mg/l NO_2	Weekly to monthly
Nitrate Cell Test 0.5-18.0 mg/l NO_3-N, 2.2-79.7 mg/l NO_3	Weekly to monthly
Tetra AquaSafe*	Daily to weekly (during supervision)
Calcium carbonate ($CaCO_3$)	Weekly to bi-weekly
Potassium carbonate (K_2CO_3)	Weekly to bi-weekly
Potassium permanganate ($KMnO_4$)	If needed

*Use of Tetra AquaSafe is not required for aquaponics in general. It was used in the SUPI aquaponic system at Natur VGS as a water conditioner to remove harmful substances during water changes due to the inability of circumventing copper pipes leading into the facility.

2.1.6. Environmental pollution and waste

Controlled environment agriculture is a technology-based food production approach that also includes vertical farms, plant factories, and greenhouses among other manipulated year-round food production technologies. Aquaponics is one example of controlled environment agriculture that can minimise discharge to the environment by using and incorporating most of the water and nutrients into food production, thereby preventing environmental pollution. Impacts from aquaculture, such as unwanted effects on wild populations including genetic disturbance and disease transfer are largely avoided using aquaponics (Read et al., 2001; Read & Fernandes, 2003). Table 2 shows an overview of several of impacts specific to aquaculture that are minimised or prevented in aquaponics. Further, emissions are more localised in aquaponics and can be managed and controlled with minimal release to the surrounding environment.

Table 2. Overview of impacts specific to aquaculture that can be minimised or prevented in aquaponics (Samuel-Fitwi et al., 2012).

Impact specific to aquaculture	Description	Impact on environment
Nutrients	Release of effluents from fish farms	Potential eutrophication of recipient waters
Additives	Additives to feed and chemicals used for antifouling	Effects of some additives poorly known
Antimicrobial resistance	Emergence of antimicrobial resistance bacteria in treated animals and transfer of these resistant organisms to humans via the food chain	Lack of studies on impact assessment for antimicrobial use in aquaculture
Spread of disease	Spread of disease from farmed fish to wild stock	Difficult to trace disease identified in one population as having been spread from another
Escapees	The escapement of species from aquaculture to the wild has resulted in the introduction and establishment of these species in local ecosystems	Lack of evidence to ascertain the ecological impact of most escaped aquaculture stock
Destruction of coastal habitats	Coastal habitats (e.g., mangroves) are often destroyed for marine fish farming, resulting in losses of nursery and spawning grounds for marine animals	Affects the supply of wild stock replenishment (though difficult to quantify)
Overexploitation of wild species	Harvesting of wild seed (for which some species are outside the safe biological limit) to stock aquaculture ponds	Overexploitation of wild stocks

One potentially critical source of pollution from aquaponic systems is plastic. Plastic products have revolutionised the aquaculture industry, though studies have shown that long-term use of aquaculture products containing plastics (e.g., mesh netting, fibre rope, buoys, pipes, boxes) could leach microplastics and additives to the environment (Lin et al., 2023). While the amount of materials used may be less in aquaponics than in some aquaculture systems due to its more compact nature, the presence of plastic particles has been found in recirculating/recirculation aquaculture system or RAS (Lusher et al., 2024; Matias et al., 2023). Alternatively, for aquaponic systems that are located in schools or other settings where food is both produced and consumed, plastics pollution may decline from the reduced need for packaging.

The SUPI aquaponic system at Natur VGS produces organic wastes such as dead fish, leaves and other plant matter, excess fish feed, sludge from the biofilters, and inorganic wastes such as substrates for the soilless system, hazardous wastes mixed with chemicals (see Table 1), and plastic containers used in routine sampling. From our experience with system, certain consumables are also used with varying frequency. Table 3 specifies these consumables and their frequency of use in the SUPI aquaponic system at Natur VGS.

Table 3. Consumables and their frequency of use at the SUPI aquaponic system at Natur VGS.

Consumable	Frequency of use
0.5 litre sample bottles with lid	Weekly
1 millilitre single use plastic pipettes	Weekly to monthly
Nitrile gloves	Weekly

Consumable	Frequency of use
Waste bags	Weekly
Paper towels	Daily to weekly (during supervision)
Plastic bags (to collect dead fish for examination)	If needed
AA batteries for automated fish feeder	Monthly
Fish feed	Daily

2.1.7. Material durability

In line with circular economy objectives, the use of more durable products and materials contributes to increasing their lifetime. This is achieved through maintenance and repair, as well as ensuring a second life through activities related to reuse and remanufacturing. This helps to minimise the need for raw material extraction and resource-intensive production processes and reduces waste generation and release of other emissions from waste management.

Setting up an aquaponic system requires considerable infrastructure and equipment. However, establishing a small-scale aquaponic system does not necessarily require very specific nor costly materials. In fact, one may be able to find most of the required materials in shops for home builders or do-it-yourself enthusiasts and reuse equipment such as intermediate bulk containers (IBCs). This nonetheless requires those who intend to establish any system to have the specific competence and availability to set it up. Moreover, it is expected that such systems may not last as long as higher quality alternatives.

On the other hand, one can choose to invest in high-quality material specifically designed for aquaponics. Investment costs are higher than the abovementioned alternative, but the assembly and operation is usually simpler. Moreover, the durability should be increased, and long-term costs related to modifications and maintenance are expected to be lower. A systems expected lifetime is difficult to predict but should increase with increasing material quality and maintenance. However, material quality and investments should be balanced with sustainability and the potential production, giving a fair return of investments.

For the SUPI aquaponic system at Natur VGS, the choice was made to have recourse to high quality materials, due to easier operation of the system and that it could serve as an example of a small-scale commercial system. Given that the project was started in the end of 2021 and that the aquaponic system was established over the summer in 2023, it is too early to draw conclusions about the durability and long-term costs of the installation.

2.1.8. Societal benefits for urban residents

Aquaponics may contribute to improving social sustainability in various ways. With the increase of urban areas and the urbanisation of the population worldwide, people are increasingly disconnected from the natural environment and from the food that they eat. This is problematic considering changing lifestyles have made us think, feel and act as if we are not a part of a wider nature. It also contributes to increasing the consumption of ultra-processed foods, reducing the consumption of natural food, and lower perceptions of what nature means are diverging along with increasing ecological illiteracy (Beery et al., 2023). By bringing food production to urban areas and potentially involving citizens (e.g., students) in their operation, aquaponics can develop a link to nature that would otherwise be difficult to establish with urban residents.

Moreover, there are other potential social benefits from aquaponics surrounding community engagement and health and wellbeing. It is established that therapeutic horticulture programs improve the wellbeing of local communities, plant-person relationships promote people’s interaction with their environment and hence their health, functional level, and subjective wellbeing (Milliken & Stander, 2019).

Another important finding confirmed through the USAGE project is that aquaponics is well-equipped to serve as a platform for education because it can be deployed on the site of schools, universities and other educational facilities, and because it can be established on a small scale (Graber et al., 2014; Hairabedian et al., 2024; Junge et al., 2019). In urban areas, students may lack a relation to the natural environment and proper understanding of the functioning and importance of food production systems. Integrating aquaponics into school curriculums can therefore contribute to various educational objectives surrounding learning more about sustainability and life cycles, strengthening systems thinking skills, enriching interdisciplinary learning within STEM (Science, Technology, Engineering, and Mathematics) and humanities, and providing access to an aquatic ecosystem where there is otherwise limited access to the natural environment.

2.2 Economic sustainability considerations of aquaponics in the USAGE project

The previous sections have shown the benefits of aquaponics for both environmental and social sustainability, and that those seem to largely outweigh some of the more negative issues, such as energy use. However, an important consideration, and one that is often not addressed in the literature, is that of costs, for example of investment and establishing the system, operation and maintenance, labour, and so on. Neither the literature nor the findings from the USAGE project allows to draw general conclusions about the costs of aquaponics. However, we can report on some of the specific findings from the SUPI aquaponic system at Natur VGS in Oslo, Norway, and provide some broader remarks about the financial implications of establishing a small-scale aquaponic system in a school setting.

Following some general considerations regarding implications on costs from the decision of scale for the aquaponic system and purpose (i.e., pedagogical or commercial), we take a closer look at the SUPI aquaponic system at Natur VGS in Norway. We discuss the total personnel hours from NIVA's staff and costs of constructing and operating that system. The aim is for educators and users of aquaponics in general to obtain a better understanding of the inputs and outputs required to run such a system. However, it should be noted that the amount of research hours used in relation to the SUPI aquaponic system at Natur VGS is likely higher than the necessary work required to properly run a commercial system.

2.2.1. Some considerations of scale and purpose on costs

An important aspect about the costs of aquaponics is the scale of the system that is being put in place. The scale of different systems can greatly vary, more notably depending on the purpose, whether it is educational or commercial. Aquaponic systems for educational purposes with very small (5-50 m^2) or micro systems (<5 m^2) are usually the more suitable options (Junge et al., 2019; Maucieri et al., 2018). On the other hand, commercial systems could vary in size depending on the product, expected return of investment, profitability, and situation with personnel (e.g., part-time employment and sharing of staff).

One of the promises of small-scale, low-cost aquaponic systems is that they can contribute to the attainment of food security and sovereignty, and to socio-economic development in poor and resource-constrained communities (Adeleke et al., 2022). However, at least with recirculating aquaculture technology, reaching higher economies of scale is generally a way to reduce the cost of production, obtain access to markets, and the economic viability increases with the scale of the operation on commercial scales (Espinal & Matulić, 2019).

In addition, it is expected that commercial aquaponics would require a strict focus on profitability and less time to operate than what is presented here for the USAGE project under the section "Operating costs". Though it is anticipated that this would still require less intervention than traditional soil-based agriculture, which often requires significant manual labour for planting, weeding, and harvesting. Further, in cases where aquaponics is set up alongside a school, as in this case with the USAGE project, the system may be threatened by changing circumstances or priorities, whereas they would be more constant in commercial activities. In cases where education is the main objective in aquaponics, psychological ownership and stewardship behaviours in terms of responsibility for operating, monitoring and maintaining the system is especially vital for its success and continuation of outputs.

Establishing an aquaponic system with an aim to sell the produce requires a permission from the authorities in the form of an aquaculture license to farm and sell fish for human consumption, which may prove to be a complicated and lengthy process. In Norway, the relevant county municipality administration receives an aquaculture license application and coordinates with the relevant authorities (Fiskeridirektoratet, 2020). A prerequisite is to then follow the complex legislation on aquaculture and animal welfare, including having staff with the necessary knowledge, education, coursework and certifications. This is likely a greater barrier for schools and other small actors than it would be for larger commercial actors.

For the SUPI aquaponic system at Natur VGS, the Directorate of Fisheries (Fiskeridirektoratet) has determined that this activity does not fall under the concept of aquaculture and therefore does not require an aquaculture license. This is due to the aquaponics facility being on privately owned land, not having any negative impacts on the environment, that the scope and duration is minimal, and that the chosen fish species is ornamental and not meant for human consumption. Nevertheless, responsible personnel must have the sufficient competence and necessary training to operate the system, which again, can prove more burdensome and costly for small actors.

2.2.2. Construction and operational costs for the USAGE aquaponic system

The costs for the aquaponic system at Natur VGS include the costs of infrastructure, as well as phases within constructing and operating the system. Construction costs consist of the time spent designing, building, and installing the system, while operational costs involve the operation, monitoring and maintenance of the system. Other typical costs include the purchasing of equipment, instrumentation, gear, and spare parts. Laboratory expenses from sampling can also be included in costs, though are excluded here considering these costs in a research project are already anticipated to be higher than if used for other purposes.

To estimate the total amount of time spent constructing and operating an aquaponic system we calculated the total personnel hours worked by 11 different employees at NIVA from August 2021 through January 2024 in connection with the SUPI aquaponic system at Natur VGS. These hours amount to 114 consecutive days including weekends and assuming an eight-hour workday. The total personnel hours were estimated to calculate the percentage of hours worked on the system within one month or 31 days. To estimate further costs across varying earnings and occupations in Norway, average monthly earnings of selected occupations were gathered from Statistisk sentralbyrå (Statistics Norway or SSB). Table 4 shows the average monthly earnings for both sexes in 2023 for the occupations that have the greatest potential to involve aquaponics in work tasks. According to SSB, an occupation is made up of a set of jobs whose main tasks and duties are characterised by a high degree of similarity, which are classified based on tasks performed and on an individual's education, type of employment, contract, salary or industry (Statistisk sentralbyrå, 2024b). Figure 5 shows these average monthly earnings in 2023 multiplied with the percentage of hours worked on aquaponics within one month. From these estimates, it becomes clear that costs to construct and operate a system vary and are highly dependent on the specified earnings of any individual working the system.

Table 4. Average monthly earnings in 2023 given in Norwegian krone (NOK) for both sexes of varying occupations in Norway that have the potential to involve aquaponics in work tasks (Statistisk sentralbyrå, 2024a). Definitions for each occupational classification is determined by the work tasks and elaborated in the Norwegian document "Standard for yrkesklassifisering (STYRK-08)."

Occupation code	Occupation	Average monthly earnings (NOK)	Age (years)
2310	University and higher education teachers	58760	43
2320	Vocational education teachers	52090	44
2330	Secondary education teachers	57040	47
2341	Primary school teachers	53210	42
5153	Building caretakers	46270	49
5164	Pet groomers and animal care workers	35180	33
6113	Gardeners, horticultural and nursery growers	39130	40
6221	Aquaculture workers	53070	36
9214	Garden and horticultural labourers	38060	40

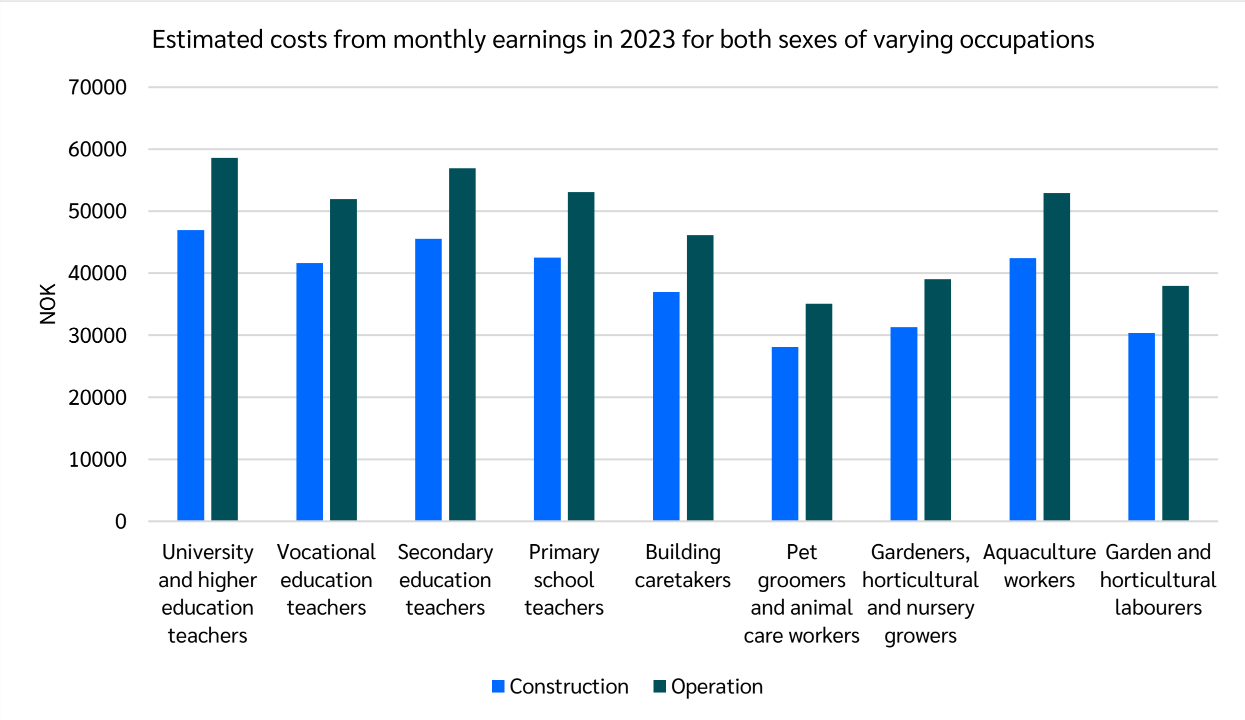


Figure 5. Estimated costs for construction and operation calculated from the average monthly earnings for both sexes of varying occupations in 2023 from SSB (Statistisk sentralbyrå, 2024a).

2.2.2.1. Construction costs

Construction costs consist of the time spent designing, building, and installing the system. System design concerned searching for an appropriate location at Natur VGS and the shipping containers to rent, choosing an appropriate aquaponic system supplier, creating technical drawings, and developing an operational manual.

The phase for designing the system took place from August 2021 through July 2022 (364 days), with 241 total personnel hours logged by NIVA's employees. These hours amount to 30 consecutive days including weekends and assuming an eight-hour workday. The phase for building and installing the system took place from August 2022 through March 2023 (242 days) with 335 total personnel hours logged by NIVA's employees. The hours amount to 42 consecutive days including weekends and assuming an eight-hour workday. The costs for infrastructure accumulated during the building and installing phase are outlined in Table 5.

Table 5. Infrastructure costs accumulated during the phase for building and installing the SUPI aquaponic system at Natur VGS in Norway. Note that most costs shown here exclude value added tax (VAT), though some may include VAT.

Item	Cost (NOK)
Customised SUPI aquaponic system*	619,108.44
Property fee to utilise parking lot at Natur VGS	103,367.00
Shipping container rental (monthly fee throughout project period)**	9,202.00
Aluminium rods and other materials	3,960.00
Wood and tools	3,791.00
PVC pipes	900.00
Building cleanup services	4,829.00

*Lighting, fish tanks, pumps, filters, biomedia, UV disinfection unit, probes (pH, temperature, dissolved oxygen), alarm system, flow meters, trays for plant cultivation, buffer tanks, and piping included
**Accumulated fee 148,926.00 NOK from September 2022 through January 2024

2.2.2.2. Operating costs

Operational costs involve the operation, monitoring and maintenance of the system, and daily routine care of the aquaponic system after the addition of fish in April 2023. A total of 718 personnel hours were spent by NIVA's employees from when the fish were added to the system through January 2024 (305 days). The hours amount to 90 consecutive days including weekends and assuming an eight-hour workday. Routine supervision takes approximately 2-3 hours three times per week within the first six months after the initial addition of fish. After these first six months, routine supervision could occur two times per week. However, this is pending the installation of cameras and sensors that provide warnings when key environmental parameters such as temperature, oxygen and pH are out of range considering live animals need to be checked daily otherwise. It is necessary that routine supervision also take place during vacation and holidays.

The purchasing of equipment, instrumentation and some consumables (shown in Table 6), as well as gear, and spare parts, and electricity to power the system and its parts is also relevant for operation. The operational phase for the SUPI aquaponic system is currently ongoing and will continue throughout the life cycle of the system and project. Note that some equipment and instrumentation might be missing from Table 6 considering that it might already be included within the purchase of the customised aquaponic system setup. Table 7 shows the specific costs connected to the addition of koi fish. Some of the items in both tables are single purchases (e.g., AC unit, probe, etc.), while other items are chemicals or consumables purchased more frequently or as required (e.g., test kit refills, pH buffer, fish feed).

Table 6. Equipment, instrumentation, and some chemical and consumable costs. Note that most costs shown here exclude value added tax (VAT), though some may include VAT.

Item	Cost (NOK)
Air conditioning (AC) unit	5,599.20
Aquaread multiparameter water monitoring probe	37,425.00
Spectroquant® Multy Colorimeter	~10,000.00
Ammonium Cell Test kit refill	1,115.00

Item	Cost (NOK)
Nitrite Cell Test kit refill	1,115.00
Nitrate Cell Test kit refill	1,390.00
Total acidity test kit refill	2,560.00
Emergency oxygen tank with diffusors	7,468.00
pH buffer	1,254.00
5 litres Tetra AquaSafe (water conditioner to remove harmful substances during water changes)	1,079.00

Table 7. Costs connected to the addition of koi fish to the SUPI aquaponic system at Natur VGS in Norway. The items in this table are listed as single units, and additional purchases were made in accordance with the number of fish tanks and the frequency of need. Note that most costs shown here exclude value added tax (VAT), though some may include VAT.

Item	Cost (NOK)
Automated fish feeder	1,079.00
Pond cleaner (fish tank vacuum)	3,352.00
Fish net	639.00
6 kilograms fish feed	1,505.00
125 koi fish (10-15 cm costing 128 NOK each)*	16,000.00

*A total of 125 koi fish was purchased, but due to some not surviving transport, 113 were added to the SUPI aquaponic system.

The aquaponic system at Natur VGS is supplied with electricity from the main building and has a separate electricity meter measuring energy use (Figure 6). An overview of all equipment requiring electricity includes the following:

Figure 6. Photo of the electricity meter measuring energy use in kWh for the SUPI aquaponic system at Natur VGS.

- Lamps for lighting (both general working light and light for the plants),
- Pumps to circulate water (both in the RAS unit and in the buffer tank),
- A blower to aerate and degas the water,
- Wall mounted heater (one in each container),
- Air conditioner (one in each container) to cool the air at elevated temperatures, and
- An electric ventilator to circulate air between the containers by removing air through a vent in the uppermost container.

Smaller electrical equipment and tools also require electricity occasionally (e.g., photometer, electronic cabinet for sending a live stream using Internet Protocol network cameras and sensor data from the fish). Table 8 shows the costs of components within or connected to the small electronic cabinet built to live stream the fish and to send sensor data to NIVA’s servers.

Table 8. Cost of components within or connected to the small electronic cabinet built to live stream the fish and send sensor data to NIVA's servers.

Amount	Item	Cost (NOK)
1	Wireless router	2,549.00
1	Wireless data for logging data from sensors (monthly cost throughout project period)*	239.00
1	Modbus air-temperature and air-humidity sensor**	656.00
1	4G Modem	2,437.60
1	POE Switch	938.00
3	POE CAM	1,216.00
1	POE switch accessories	450.00
1	ABS Fibox Box	1,234.97
4	10 CAT 5 Patch cable	355.96
1	12 Vdc AC/DC power supply	140.20

*Accumulated cost 2,531.00 NOK from March 2023 through January 2024.
**Fried or failure due to overvoltage from electrical surge and the replacement increased in price (983.00 NOK) due to inflation.

The total amount of electricity used since installation of the electric meter sums up to 32,549.92 kWh from the end of September 2022 to the end of January 2024 (488 days). The electricity price in this period has varied due to extreme fluctuations in the power market, but we estimate the price to be approximately 1 NOK per kWh on average in this period. This indicates a cost of 32,549.00 NOK for the whole period and 66.70 NOK per day.

2.3 Capacity of the SUPI aquaponic system

An important aspect about aquaponics is the capacity of any systems production. Aquaponics are capital intensive, highly technical and are affected by economies of scale, appropriate design of the components, reliance on market conditions and the expertise of operators, thus utilising a system to its full capacity is essential (Espinal & Matulić, 2019). In this section, we describe the capacity of production for the SUPI aquaponic system at Natur VGS.

The fish in any aquaponic system must be procured from an approved commercial operator. The SUPI aquaponic system is limited to a maximum of 25 kg/m^3 of fish as a precaution but might have the capacity to hold a larger biomass at a larger fish density. The fish biomass needs to be balanced with the plant biomass in the system, ensuring that most of the nutrients are used for plant growth.

In April 2023, a total of 113 koi (approximately 10-15 cm each) were added to a single fish tank (1 m^3). In the beginning of August 2023, the fish were weighed (average weight per fish 34.8 g) and separated into two tanks in accordance with observed fish size, as the larger koi were competing with the smaller koi for fish feed. The fish biomass was last measured in the end of January 2024 at 4.5 kg (average weight per fish 43 g). This increase indicates an average growth per individual of 23% in the period when accounting for dead fish accumulated throughout the project in each fish tank. Clear differences in fish growth were observed, showing that the larger fish acquired food more easily and had a higher survival rate. Considering these observations, individual fish growth may have been a more representative and interesting to measure, but individual measurements would have added substantial stress and was not deemed crucial to the project goals. Despite the demonstration of overall growth in koi, the SUPI aquaponic system at Natur VGS is nowhere near its estimated safe holding capacity of fish and estimated yearly production of fish.

Table 9 shows the dimensions and water volume in the different components of the SUPI aquaponic system at Natur VGS. While there are three fish tanks, only two have been utilised during the project.

Table 9. Dimensions and water volume in the different components of the SUPI aquaponic system at Natur VGS.

Equipment	Dimensions (mm)*	Volume (litres)	Amount	Total volume (litres)
Fish tank	1,250 (h) × 1,220 (w)	1,000	3	3,000
Sump (balance tank)	635 (h) × 646 (w) × 346 (l)	100	1	100
Buffer tank	985 (h) × 1468 (w) × 368 (l)	350	1	350
Rearing system	2,022 (h) × 1,079 (w) × 1,104 (l)	200	1	200
DWC system	1,867 (h) × 5,111 (w) × 470 (l)	638	2	1,276
NFT system		147	2	294
RAS unit + pipes		~200	-	200
			Total volume	**5420**

*h=height, w=width, l=length

From our experiences with the SUPI aquaponic system at Natur VGS, the maximum plant production using frillice (a cross between iceberg lettuce and curly endive) as an example could be 228 plants in the Deep Water Culture (DWC) and 756 plants in the Nutrient Film Technique (NFT). Considering that the frillice life cycle is six weeks until a fully grown head of lettuce at about 130 grams, 984 plants could potentially be available each cycle. If we assume a profit of 10 NOK per head of frillice lettuce, then the total potential profit over the course of one year would be approximately 85,280.00 NOK if the system maximised its full capacity.

3 Conclusion

Aquaponics as a farming method that combines aquaculture (fish farming) and hydroponics (soil-less plant cultivation) in a symbiotic environment appears globally positive from an environmental and social point of view. Based on our review of selected literature, we found aquaponics to support the objectives of increasing food production and security, lowering land, resources and chemical use, minimising pollution and waste, as well as bringing about social benefits to an urban population that is growing and living further remote from nature and raw food production. On the other hand, we have also specified some potential downsides and risks of aquaponics related to energy use or the need for materials for building the system.

However, none of the identified benefits and issues were necessarily completely positive or negative. For example, when it comes to resource use, there is always the risk of wastage of fish feed or excess nutrients from fish excreta if not properly balanced. Likewise, energy use and its negative impact on climate can be mitigated by utilising renewable energy resources to increase energy efficiency. In addition, as aquaponics continues to gain momentum, it is expected that the extent to which this farming method does contribute to the transition to a sustainable future, and the challenges it faces in doing so will be better and more researched and documented.

The findings from the SUPI aquaponic system at Natur VGS in Oslo, Norway, one of the test cases in the USAGE project, has confirmed the tendencies found in the literature. Some of the most interesting and promising insights from this case are:

- The project was established together with a high school in Norway, where teachers are utilising the *Classroom Model System for Aquaponics in Education*, an instructional tool developed for teachers to implement collaborative learning through topics relevant to aquaponics and existing global challenges. Through aquaponics, students are provided with the opportunity to reflect on food production and security issues, and other environmental, social and economic as well as the regulatory challenges the sector is facing, notably in the sustainability transition (Hairabedian et al., 2024).
- In terms of resource use, the quality of rooftop runoff water was tested in view of reusing it in the aquaponic system. Despite analysis and synthesis of these results still ongoing, we expect that the reuse of rooftop runoff water is a relevant avenue for future research, and will open the door for better, less wasteful resource use and management.
- Aquaponics as controlled units reduce the need for widespread application of pesticides and preventative measures further enable less pesticide use pending prolonged closure and containment of the system.
- The choice of high-quality, durable materials made it easier to start operation of the system and we expect it will extend its lifetime. It is however too early to conclude on the durability and lifetime of the system that at this stage.

Throughout the course of the project, we have identified some potential barriers to successful urban aquaponics, some of which are specific having been established in a pedagogical, non-commercial setting:

- The regulatory framework can prove particularly difficult to navigate, with some unclear or very demanding requirements in addition to lengthy and costly processes (i.e., education, coursework and certifications). This may prove particularly challenging if such a system is to be established by non-commercial actors for whom running an aquaponic system is not the main activity.

- An aquaponic-related activity must be well monitored to ensure fish welfare and minimise risk of food contamination This requires necessary training and ensuring the availability of those trained throughout the year. In a setting such as a school, the risk is that teachers and/or students will not have the capacity or willingness to take responsibility for operating, monitoring, and maintaining the system in addition to day-to-day work.
- If an aquaponic system is run in collaboration between two or more non-commercial partners, such as schools and private businesses, the risk is that some of them fall out due to changes in circumstances (e.g., management, ownership, bankruptcy).
- Costs represent another potential barrier to establishing and running an aquaponic system. There are few studies that truly conclude on the cost-benefit analysis of aquaponics, and it is thus difficult for actors interested in establishing such a system to know what to expect. Given that the aquaponic system was established over the summer in 2023, it is too early to draw conclusions about the long-term costs of the installation.

The findings from this report brings us to conclude that aquaponics should and shall play a role in the sustainability transition that is urgently needed. In spite of remaining uncertainties about the extent of the contribution and factors susceptible to impact it in one or another direction, it appears that the potential benefits of such systems are important. In this report, we highlight the fact that small-scale systems established in a non-commercial, pedagogical context can bring about a number of social benefits, in addition to ecological ones. More research is needed, however, to clarify both the extent and specification of the costs involved in the construction and operation of such a system, as well as the financial benefits that can be expected, notably from using or selling the production.

To our knowledge, there is no or very limited literature on how to mainstream aquaponics so that it becomes more broadly used by Small and Medium Enterprises (SMEs) and larger companies (such as catering businesses, canteens, restaurants, hotels). One suggestion to start developing the market could be that aquaponics be included in calls for tenders by public authorities for schools and other public institutions. Moreover, aquaponics as an alternative to purchasing greens and fish from a retailer remains largely unknown and there is limited information about general consumer acceptance of products sourced from aquaponics. One study found that willingness to pay when buying food is mainly based on price and whether products are free of antibiotics, pesticides and herbicides, and locally produced (Miličić et al., 2017). The same study also found that some consumers had never heard of aquaponics, were disgusted with fish excrements in connection with vegetables, were concerned with animal welfare in aquaponics, and distrusted the positive claims about aquaponics (Miličić et al., 2017). There is a need for increasing consumer knowledge about aquaponics and showcasing examples of existing good practices. Projects like USAGE that collaborate with schools and utilise aquaponics represent an excellent opportunity to demonstrate the benefits offered by aquaponics from an environmental and a social perspective and proving the practical and economic feasibility of such a system, as well as educating the next generation to such farming alternatives.

4 References

Adeleke, B., Cassim, S., & Taylor, S. (2022). Pathways to low-cost aquaponic systems for sustainable livelihoods and economic development in poor communities: defining critical success factors. *Aquaculture International*, *30*(3), 1575-1591. https://doi.org/10.1007/s10499-022-00865-z

Armanda, D. T., Guinée, J. B., & Tukker, A. (2019). The second green revolution: Innovative urban agriculture's contribution to food security and sustainability – A review. *Global Food Security*, *22*, 13-24. https://doi.org/https://doi.org/10.1016/j.gfs.2019.08.002

Beery, T., Stahl Olafsson, A., Gentin, S., Maurer, M., Stålhammar, S., Albert, C., Bieling, C., Buijs, A., Fagerholm, N., Garcia-Martin, M., Plieninger, T., & M. Raymond, C. (2023). Disconnection from nature: Expanding our understanding of human–nature relations. *People and Nature*, *5*(2), 470-488. https://doi.org/https://doi.org/10.1002/pan3.10451

Buehler, D., & Junge, R. (2016). Global Trends and Current Status of Commercial Urban Rooftop Farming. *Sustainability*, *8*(11), 1108. https://www.mdpi.com/2071-1050/8/11/1108

Campbell, B. M., Beare, D. J., Bennett, E. M., Hall-Spencer, J. M., Ingram, J. S. I., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J. A., & Shindell, D. (2017). Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecology and Society*, *22*(4). https://www.jstor.org/stable/26798991

David, L. H., Pinho, S. M., Agostinho, F., Costa, J. I., Portella, M. C., Keesman, K. J., & Garcia, F. (2022). Sustainability of urban aquaponics farms: An emergy point of view. *Journal of Cleaner Production*, *331*, 129896. https://doi.org/https://doi.org/10.1016/j.jclepro.2021.129896

DESA, U. (2023). *The Sustainable Development Goals Report 2023: Special Edition* (978-92-1-101460-0). U. Nations. https://unstats.un.org/sdgs/report/2023/

Energy, M. o. (2016). *Renewable energy production in Norway*. Regjeringen.no Retrieved from https://www.regjeringen.no/en/topics/energy/renewable-energy/renewable-energy-production-in-norway/id2343462/

Espinal, C. A., & Matulić, D. (2019). Recirculating Aquaculture Technologies. In S. Goddek, A. Joyce, B. Kotzen, & G. M. Burnell (Eds.), *Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future* (pp. 35-76). Springer International Publishing. https://doi.org/10.1007/978-3-030-15943-6_3

Eurostat. (2023). Renewable energy statistics. In: Statistics Explained.

FAO. (2017). *The State of Food and Agriculture 2017. Leveraging Food Systems for Inclusive Rural Transformation.* FAO. https://www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1046886/

Fiskeridirektoratet. (2020). *Akvakultursøknad*. Fiskeridirektoratet. https://www.fiskeridir.no/Akvakultur/Registre-og-skjema/Skjema/Akvakultursoeknad

Folorunso, E. A., Roy, K., Gebauer, R., Bohatá, A., & Mraz, J. (2021). Integrated pest and disease management in aquaponics: A metadata-based review. *Reviews in Aquaculture*, *13*(2), 971-995. https://doi.org/https://doi.org/10.1111/raq.12508

Goddek, S., Delaide, B., Mankasingh, U., Ragnarsdottir, K., Jijakli, H., & Thorarinsdottir, R. (2015). Challenges of Sustainable and Commercial Aquaponics. *Sustainability*, *7*(4), 4199-4224. https://doi.org/10.3390/su7044199

Goddek, S., Joyce, A., Kotzen, B., & Dos-Santos, M. (2019). Aquaponics and Global Food Challenges. In S. Goddek, A. Joyce, B. Kotzen, & G. M. Burnell (Eds.), *Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future* (pp. 3-17). Springer International Publishing. https://doi.org/10.1007/978-3-030-15943-6_1

Goddek, S., & Körner, O. (2019). A fully integrated simulation model of multi-loop aquaponics: A case study for system sizing in different environments. *Agricultural Systems*, *171*, 143-154. https://doi.org/https://doi.org/10.1016/j.agsy.2019.01.010

Goldstein, B., Hauschild, M., Fernández, J., & Birkved, M. (2016). Testing the environmental performance of urban agriculture as a food supply in northern climates. *Journal of Cleaner Production*, *135*, 984-994. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.07.004

Graber, A., Antenen, N., & Junge, R. (2014). *The multifunctional aquaponic system at ZHAW used as research and training lab* 3rd Conference VIVUS, Conference on Agriculture, Environmentalism, Horticulture, Floristics, Food Production and Processing, Strahinj, Slovenia, 14–15 November 2014, Strahinj. https://digitalcollection.zhaw.ch/handle/11475/2518

https://digitalcollection.zhaw.ch/bitstream/11475/2518/1/2014_Graber_The%20multifunctional%20aquaponic%20system_Prenos%20inovacij.pdf

Greenfeld, A., Becker, N., Bornman, J. F., Spatari, S., & Angel, D. L. (2022). Is aquaponics good for the environment?—evaluation of environmental impact through life cycle assessment studies on aquaponics systems. *Aquaculture International*, *30*(1), 305-322. https://doi.org/10.1007/s10499-021-00800-8

Hairabedian, G., Barkved, L. J., Hess-Erga, O.-K., Ribeiro, A. L., Meland, S., Maitre-Ekern, E., Øyen, H., Tronerud, T. T., Hovde, A. I., & Lindholt, J. G. (2024). *Classroom Model System for Aquaponics in Education* (978-82-577-7665-7). N. I. f. W. Research. https://niva.brage.unit.no/niva-xmlui/handle/11250/3115831

Jansen, L., & Keesman, K. J. (2022). Exploration of efficient water, energy and nutrient use in aquaponics systems in northern latitudes. *Cleaner and Circular Bioeconomy*, *2*, 100012. https://doi.org/https://doi.org/10.1016/j.clcb.2022.100012

Joyce, A., Goddek, S., Kotzen, B., & Wuertz, S. (2019). Aquaponics: Closing the Cycle on Limited Water, Land and Nutrient Resources. In S. Goddek, A. Joyce, B. Kotzen, & G. M. Burnell (Eds.), *Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future* (pp. 19-34). Springer International Publishing. https://doi.org/10.1007/978-3-030-15943-6_2

Junge, R., Bulc, T. G., Anseeuw, D., Yavuzcan Yildiz, H., & Milliken, S. (2019). Aquaponics as an Educational Tool. In S. Goddek, A. Joyce, B. Kotzen, & G. M. Burnell (Eds.), *Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future* (pp. 561-595). Springer International Publishing. https://doi.org/10.1007/978-3-030-15943-6_22

Lin, L., Huang, Y., Wang, P., Chen, C. C., Qian, W., Zhu, X., & Xu, X. (2023). Environmental occurrence and ecotoxicity of aquaculture-derived plastic leachates. *Journal of Hazardous Materials*, *458*, 132015. https://doi.org/https://doi.org/10.1016/j.jhazmat.2023.132015

Lusher, A. L., Allan, I., Rohler, L., Snekkevik, V. K., Collard, F., & Hjelset, S. (2024). *Interim report: Quantification of microplastic and plastic additives in water and fish in RAS (WP1)* (978-82-577-7698-5). N. I. f. W. Research.

Matias, R. S., Gomes, S., Barboza, L. G. A., Salazar-Gutierrez, D., Guilhermino, L., & Valente, L. M. P. (2023). Microplastics in water, feed and tissues of European seabass reared in a recirculation aquaculture system (RAS). *Chemosphere*, *335*, 139055. https://doi.org/https://doi.org/10.1016/j.chemosphere.2023.139055

Maucieri, C., Forchino, A. A., Nicoletto, C., Junge, R., Pastres, R., Sambo, P., & Borin, M. (2018). Life cycle assessment of a micro aquaponic system for educational purposes built using recovered material. *Journal of Cleaner Production*, *172*, 3119-3127. https://doi.org/https://doi.org/10.1016/j.jclepro.2017.11.097

Miličić, V., Thorarinsdottir, R., Santos, M. D., & Hančič, M. T. (2017). Commercial Aquaponics Approaching the European Market: To Consumers' Perceptions of Aquaponics Products in Europe. *Water*, *9*(2), 80. https://www.mdpi.com/2073-4441/9/2/80

Milliken, S., & Stander, H. (2019). Aquaponics and Social Enterprise. In S. Goddek, A. Joyce, B. Kotzen, & G. M. Burnell (Eds.), *Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future* (pp. 607-619). Springer International Publishing. https://doi.org/10.1007/978-3-030-15943-6_24

Morales, L., Coetzer, J.-H., Barkoczi, N., Pop, L., Marian, C., & Flynn, P. (2022). A Circular Pedagogy for Higher Education [Working Paper]. https://doi.org/https://doi.org/10.21427/74V5-DT69

Pinho, S. M., David, L. H., Garcia, F., Keesman, K. J., Portella, M. C., & Goddek, S. (2021). South American fish species suitable for aquaponics: a review. *Aquaculture International*, *29*(4), 1427-1449. https://doi.org/10.1007/s10499-021-00674-w

Pop, L., Barkoczi, N., Morales, L., Coetzer, J.-H., Marian, C., & Flynn, P. (2022). Circular Pedagogy for Smart, Inclusive and Sustainable Education [Working Paper]. https://doi.org/https://doi.org/10.21427/9AN6-3816

Proksch, G., Ianchenko, A., & Kotzen, B. (2019). Aquaponics in the Built Environment. In S. Goddek, A. Joyce, B. Kotzen, & G. M. Burnell (Eds.), *Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future* (pp. 523-558). Springer International Publishing. https://doi.org/10.1007/978-3-030-15943-6_21

Raworth, K. (2017). A Doughnut for the Anthropocene: humanity's compass in the 21st century. *Lancet Planet Health*, *1*(2), e48-e49. https://doi.org/10.1016/S2542-5196(17)30028-1

Read, Fernandes, & Miller. (2001). The derivation of scientific guidelines for best environmental practice for the monitoring and regulation of marine aquaculture in Europe. *Journal of Applied Ichthyology*, *17*(4), 146-152. https://doi.org/https://doi.org/10.1046/j.1439-0426.2001.00311.x

Read, P., & Fernandes, T. (2003). Management of environmental impacts of marine aquaculture in Europe. *Aquaculture*, *226*(1), 139-163. https://doi.org/https://doi.org/10.1016/S0044-8486(03)00474-5

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., . . . Rockström, J. (2023). Earth beyond six of nine planetary boundaries. *Science Advances*, *9*(37), eadh2458. https://doi.org/doi:10.1126/sciadv.adh2458

Robaina, L., Pirhonen, J., Mente, E., Sánchez, J., & Goosen, N. (2019). Fish Diets in Aquaponics. In S. Goddek, A. Joyce, B. Kotzen, & G. M. Burnell (Eds.), *Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future* (pp. 333-352). Springer International Publishing. https://doi.org/10.1007/978-3-030-15943-6_13

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., . . . Foley, J. (2009). Planetary Boundaries

Exploring the Safe Operating Space for Humanity. *Ecology and Society*, *14*(2). http://www.jstor.org/stable/26268316

Samuel-Fitwi, B., Wuertz, S., Schroeder, J. P., & Schulz, C. (2012). Sustainability assessment tools to support aquaculture development. *Journal of Cleaner Production*, *32*, 183-192. https://doi.org/https://doi.org/10.1016/j.jclepro.2012.03.037

Schumacher, E. F. (2011). *Small is beautiful: A study of economics as if people mattered*. Random House.

Semple, L., Carriveau, R., & Ting, D. S.-K. (2017). Assessing heating and cooling demands of closed greenhouse systems in a cold climate. *International Journal of Energy Research*, *41*(13), 1903-1913. https://doi.org/https://doi.org/10.1002/er.3752

sentralbyrå, S. (2024a). *11418: Monthly earnings, by occupation, sector, sex and working hours 2015 - 2023*. Statistisk sentralbyrå. https://www.ssb.no/en/statbank/table/11418/

sentralbyrå, S. (2024b). *Lønn*. Statistisk sentralbyrå. https://www.ssb.no/arbeid-og-lonn/lonn-og-arbeidskraftkostnader/statistikk/lonn

Specht, K., Siebert, R., Hartmann, I., Freisinger, U. B., Sawicka, M., Werner, A., Thomaier, S., Henckel, D., Walk, H., & Dierich, A. (2014). Urban agriculture of the future: an overview of sustainability aspects of food production in and on buildings. *Agriculture and Human Values*, *31*(1), 33-51. https://doi.org/10.1007/s10460-013-9448-4

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223), 1259855. https://doi.org/doi:10.1126/science.1259855

Touliatos, D., Dodd, I. C., & McAinsh, M. (2016). Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics. *Food and Energy Security*, *5*(3), 184-191. https://doi.org/https://doi.org/10.1002/fes3.83

Yavuzcan Yildiz, H., Radosavljevic, V., Parisi, G., & Cvetkovikj, A. (2019). Insight into Risks in Aquatic Animal Health in Aquaponics. In S. Goddek, A. Joyce, B. Kotzen, & G. M. Burnell (Eds.), *Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future* (pp. 435-452). Springer International Publishing. https://doi.org/10.1007/978-3-030-15943-6_17

Zainal Alam, M. N. H., Kamaruddin, M. J., Adzila, S., Nordin, N., & Othman, R. (2022). Solar-powered aquaponics prototype as sustainable approach for food production. *Materials Today: Proceedings*, *65*, 2953-2959. https://doi.org/https://doi.org/10.1016/j.matpr.2022.02.530

The Norwegian Institute for Water Research

We are Norway's premier research institute in the fields of water and the environment. We are experts on ecosystems in both freshwater and marine environments, from mountains, lakes and rivers, to fjords, coasts and oceans. We develop science-based knowledge and solutions to challenges related to the interaction between water and climate, the environment, nature, people, resources and society.