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Classroom Model System for Aquaponics in Education

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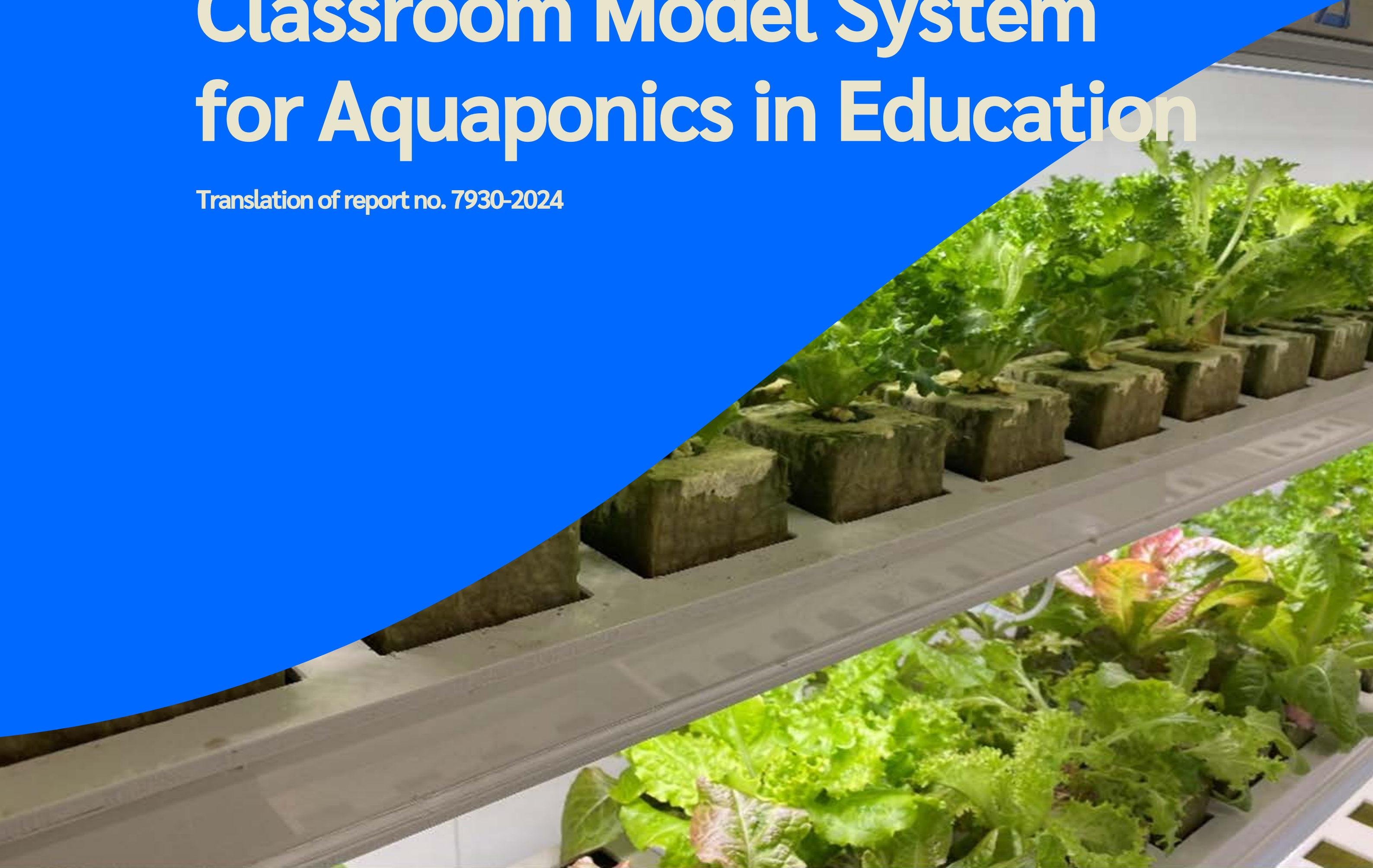

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Abstract
This represents a classroom model system (CMS) or instructional tool for teachers to implement collaborative learning through different modules relevant to aquaponics. It can be adapted and customized as needed and utilizes aquaponics as a learning arena to explore existing global challenges. It links with the Small-Scale Urban Pilot Installation developed within the USAGE project in Norway at Natur videregående skole (Natur VGS), a high school/upper secondary school in Oslo. The Norwegian National Curriculum has provided an overall point of departure for this work along with specified subjects and curriculum at Natur VGS. The varying subject curricula selected include: Agriculture, fishing and forestry; Natural science; English; Mathematics; Agriculture and horticulture; Chemistry; and Biology. Six topical teaching and learning modules provide background information and examples of activities and discussion topics that connect to aquaponics. The modules include: Sustainability; Plant growth, health and development; Animal welfare; Water chemistry and quality; Urban farming; and Economy and business operations. Aquaponics provides an opportunity for interdisciplinary learning across many subjects and through aquaponics, there is the potential to enrich classes in Science, Technology, Engineering, and Mathematics (STEM). This CMS aims to provide standard methods for the implementation of aquaponics in teaching or as a learning arena for high school/upper secondary school classrooms in Norway.

Keywords: aquaponics, educational resources, sustainability, plant growth, plant health, animal welfare, water chemistry, water quality, urban farming, economy, business operations
Emneord: akvaponi, utdanningsressurser, bærekraft, plantevekst, plantehelse, dyrevelferd, vannkjemi, vannkvalitet, urban dirking, økonomi, forretningsdrift

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Preface

This document/report represents deliverable 5.4 or the “Report on SUPI used as a classroom model system for teaching and learning” within the USAGE (Urban Stormwater Aquaponics Garden Environment) project. It exists in both English and Norwegian, with the Norwegian translation having been performed by Totaltekst. The research leading to this project deliverable was generated with financial support 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 Sparebankstiftelsen.

This deliverable represents a classroom model system (CMS) for teaching and learning using 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. The specified subjects in this document aim to reflect the curriculum at Natur VGS and the National Curriculum (called "Kunnskapsløftet 2020"), and were co-selected by teachers at Natur VGS and researchers at NIVA.

Thanks must be given to all the colleagues at NIVA that contributed to this work, as well as the design, building and development of the aquaponic system at the school. Special thanks to the teachers at Natur VGS for contributing to this work and stepping outside of their respective comfort zones into new learning arenas to meet the demands of an ever-changing world for future generations.

Oslo, 23rd January 2024

Summary

This document/report represents a classroom model system (CMS) or instructional tool for teachers to implement collaborative learning through different modules relevant to aquaponics. This CMS can be adapted and customized as needed and utilizes aquaponics as a learning arena to explore existing global challenges. This CMS links specifically with 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.

The Norwegian National Curriculum (called "Kunnskapsløftet 2020") has provided an overall point of departure for this work along with specified subjects and curriculum at Natur VGS. The varying subject curricula selected include: Agriculture, fishing and forestry; Natural science; English; Mathematics; Agriculture and horticulture; Chemistry; and Biology. The CMS is divided into six topical teaching and learning modules that provide background information, examples of activities and discussion topics that connect to aquaponics, and further resources such as a glossary. The teaching and learning modules include: Sustainability; Plant growth, health and development; Animal welfare; Water chemistry and quality; Urban farming; and Economy and business operations.

Aquaponics provides an opportunity for interdisciplinary learning across many subjects and through aquaponics, there is the potential to enrich classes in Science, Technology, Engineering, and Mathematics (STEM). This CMS aims to provide standard methods for the implementation of aquaponics in teaching or as a learning arena for high school/upper secondary school classrooms in Norway.

Sammendrag

Dette dokumentet / denne rapporten representerer et klasseromsmodellsystem (KMS) eller undervisningsverktøy som kan brukes av lærere til å sikre kollektiv læring gjennom formidling av moduler knyttet til akvaponi. Dette KMS kan tilpasses og tilrettelegges ut fra behov og bruker akvaponi som læringsarena for å utforske aktuelle globale utfordringer. Dette KMS knytter seg spesifikt til en småskala urban pilotinstallasjon (Small-Scale Urban Pilot Installation eller SUPI på engelsk) som er utviklet i prosjektet USAGE ved Natur videregående skole (Natur vgs.) i Oslo.

Kunnskapsløftet 2020 har gitt et generelt utgangspunkt for dette arbeidet sammen med spesifikke fag og læreplaner for Natur vgs. Læreplanene som ble valgt, var bl.a.: Naturbruk, Naturfag, Engelsk, Matematikk, Landbruk og gartnernæring, Kjemi og Biologi. KMS består av seks tematiske undervisnings- og læringsmoduler der det presenterer bakgrunnsinformasjon, gir eksempler på aktiviteter og diskusjonsemner knyttet til akvaponi og i tillegg til andre nyttige ressurser som en ordliste. De undervisnings- og læringsmodulene er: Bærekraft; Plantevekst, -helse og -utvikling; Dyrevelferd; Vannkjemi og -kvalitet; Urban dyrking; og Økonomi- og forretningsdrift.

Akvaponi gir mulighet for læring på tvers av mange fag og kan spesielt berike undervisningen i STEM-fagene (Science, Technology, Engineering, and Mathematics på engelsk). Dette KMS har som mål å gi standardmetoder for å bruke akvaponi i undervisningen eller som læringsarena i klasserommene på videregående skoler i Norge.

List of acronyms and chemical symbols	
ATP	adenosine triphosphate
C	carbon
Ca	calcium
$CaCO_3$	calcium carbonate
CMS	classroom model system
CO_2	carbon dioxide
CO_3	carbon trioxide
Cu	copper
DFT	Deep Flow Technique
DO	dissolved oxygen
DWC	Deep Water Culture
EU	European Union
FAO	Food and Agriculture Organization
GHG	greenhouse gas
GSA	Guidelines for Sustainable Aquaculture
H	hydrogen
H_2O	water
HPO_4^{2-}	hydrogen phosphate
$H_2PO_4^-$	dihydrogen phosphate
IAA	integrated agriculture-aquaculture
ISO	International Organization for Standardization
K	potassium
K_2CO_3	potassium carbonate
LCA	Life Cycle Assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
Mg	magnesium
N	nitrogen
N_2	nitrogen gas
$NaHCO_3$	sodium bicarbonate
NFT	Nutrient Film Technique
NH_3	ammonia
NH_4^+	ammonium
Ni	nickel
NO_2^-	nitrite
NO_3^-	nitrate
O	oxygen
O_2	oxygen gas
P	phosphorus
PE	polyethylene
PESTLE	political, economic, social, technological, legal, and environmental
PVC	polyvinyl chloride
RAS	recirculating/recirculation aquaculture system
S	sulphur
SDG	Sustainable Development Goal
SO_4^{2-}	sulphate
STEM	Science, Technology, Engineering, and Mathematics
SUPI	Small-Scale Urban Pilot Installation
SWOT	Strengths, Weaknesses, Opportunities, Threats
TAN	Total Ammonia Nitrogen
TSS	total suspended solids
UN	United Nations

1 Introduction

This document/report represents a *classroom model system (CMS)* for teaching and learning using an aquaponic system, specifically 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. This CMS links to the Norwegian curriculum, provides background information from articles, books and reports, examples of activities and discussion topics that connect to aquaponics, as well as further resources including a glossary of relevant terms.

A *classroom model system (CMS)*, as defined in this document, is an instructional tool for teachers to implement collaborative learning through topics relevant to aquaponics and existing global challenges that can be adopted and customized as needed.

Having an aquaponic system at a school (or other accessible space for teaching and learning) involves two key steps i) establishing and building/installing an aquaponics system and ii) operating, monitoring and maintaining the aquaponic system. This document does not go into the technical details for establishing a system nor the regulatory details for the permits needed, as this is contextual for each site/country. However, there can be teaching and learning activities from the initial idea and planning phase, and some of this information is available to connect to the activities and discussion topics in the modules. If access to a well-established aquaponic system is available, then routines for operation, monitoring and maintenance are key and templates for routine care are provided. Though, many of the activities are broad enough to use where aquaponic systems are otherwise inaccessible.

1.1 How to use the CMS and this document

The CMS presented emphasizes learning by doing and experiential learning and aims to enable an educational philosophy of curiosity and nature-based learning. The CMS is divided into six topical teaching and learning modules: Sustainability; Plant growth, health and development; Animal welfare; Water chemistry and quality; Urban farming; and Economy and business operations. The text under each module is meant to be an added resource for teachers, especially when working in an interdisciplinary way. Suggestions for individual and group work, as well as topics for discussion to use in the classroom related to aquaponics for each of the modules are also provided.

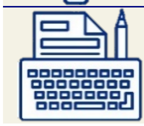
While the topical modules are designed to stand alone, the "Introduction to aquaponics" should always be covered prior to any module as a foundation. Table 1 shows the suggested order of the modules in a learning and teaching context. Table 2 clarifies the types of learning utilized in the CMS and this document under each module. The icons in this table are repeated throughout this document and under each module in separate tables with the activities suggested. The learning types aim to integrate the Norwegian National Curriculum's five basic skills: reading, writing, numeracy, oral skills and digital skills.

Table 1. Suggested order of the modules.

When the module should be completed	Module
Obligatory *before* any hands-on or practical work related to aquaponics	• Introduction to aquaponics • Plant growth, health and development • Animal welfare • Water chemistry and quality
During any hands-on or practical work related to aquaponics	• Plant growth, health and development • Animal welfare • Water chemistry and quality
At any time	• Introduction to aquaponics • Sustainability

When the module should be completed	Module
	• Urban farming • Economy and business operations

Table 2. Types of learning utilized in the CMS and this document (adapted from Junge et al., 2020). The icons in this table are used under the suggested activities in each module.

Icon*	Learning type	Description	With aquaponic system	Without aquaponic system
	Create	Draw or depict systems and/or anatomical features of organisms	X	X
	Discuss	Ask questions and deliberate in groups and/or plenum	X	X
	Explore	Search and discover using online and/or external resources	X	X
	Grow	Hands-on, practical experience with aquaponics	X	
	Inquire	Conduct research and cite references	X	X
	Observe and gather data	Make observations and gather data in aquaponics using the templates for routine care of aquaponic systems	X	
	Present	Show and explain work in groups and/or plenum	X	X
	Problem solve	Find solutions to complex issues	X	X
	Write	Produce written material and cite references	X	X

*Icons from the Noun Project (CC BY 3.0) respectively by Bestdesignmarket, businessicons13, Creative Stall, Tri H, 주희 김, Agung Pamuji, riyan adi sena, Yogi Aprelliyanto, and Edwin PM

1.2 What is aquaponics?

Aquaponics is the combination of two different technologies, *hydroponics* or plant cultivation in water without soil and *aquaculture* or the cultivation of aquatic organisms. The two technologies are connected in a closed loop system where plants use the waste produced by the fish and continuously clean the water together with nitrifying bacteria (Junge et al., 2017). See Figure 1 for the main components in the aquaponic system at Natur VGS.

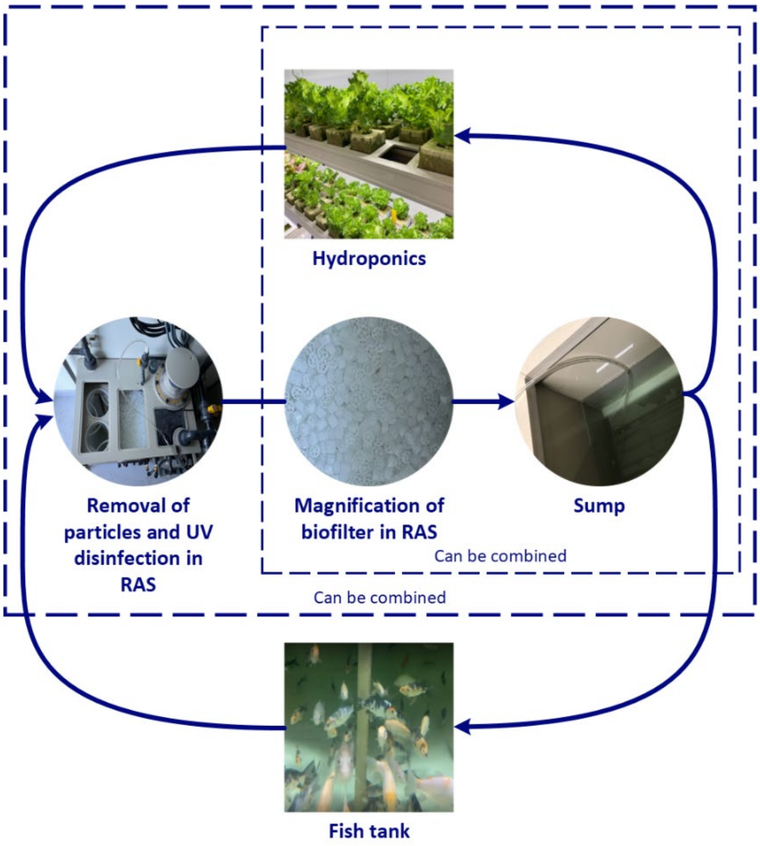


Figure 1. Main components of the aquaponic system at Natur VGS (layout adapted from Junge et al., 2020). "RAS" stands for recirculating/recirculation aquaculture system.

1.3 Aquaponics in education

Through aquaponics, there is the potential to enrich classes in Science, Technology, Engineering, and Mathematics (STEM) (Junge et al., 2019). Aquaponics provides an opportunity for interdisciplinary learning across many subjects, not only to demonstrate basic biological and ecological principles through observation of plant and animal cycles, but also chemistry by analyzing water quality, physics and mathematical skills by calculating water flow rates, and to practice financial skills by selling harvested products (Junge et al., 2017; Maucieri et al., 2018). Considering that this CMS is found in both Norwegian and English, aquaponics can provide a unique opportunity for Norwegian students to learn vocational English through hands-on practical work and is an example of interdisciplinary learning across STEM and humanities. Table 3 shows the potential benefits and challenges of using aquaponics in education.

Authentic interactions with the natural world are important for students to experience nature firsthand and gain practical skills, which are in line with experiential learning and the essential role it plays in the learning process (Hart et al., 2014). Further, aquaponics can be an effective tool in the classroom to model natural aquatic systems where access to the natural environment is otherwise limited in urban areas (Hart et al., 2014). Ecosystems are usually presented through abstract figures in textbooks, while aquaponics provides students with the opportunity to deepen their understanding of the varying parts of an ecosystem, and the roles of producers, consumers and decomposers (Hess-Erga et al., 2018).

Aquaponics also promotes systems thinking competences by thinking in relations instead of focusing on the single elements (Junge et al., 2014). Systems thinking is defined by an ability to identify and describe a system of interest, and reason about the system its processes (J.Wilson et al., 2020).

Table 3. Potential benefits and challenges of aquaponics in education to aid educators manage their expectations (Hart et al., 2014).

Potential benefits	Potential challenges
• Connect with nature, systems thinking, life cycle approach to learning • Hands-on, active teaching and learning, production and product based • Multidisciplinary, including science, technology, engineering, and mathematics; business administration; sustainability • Building community connections • Growing trend in aquaponics as a food production	• Time commitment spanning from planning, fundraising, construction, implementation to maintenance • Technical difficulties, including plumbing, electronics, water chemistry • Space and resource limitations • Weekend/holiday/summer care, adequate training of support staff and/or commitment from students • Lack of readily available/accessible information

2 Methodology

The specified subjects in the CMS and this document aim to reflect the curriculum at Natur VGS and the Norwegian National Curriculum (called "Kunnskapsløftet 2020"), and were co-selected by teachers at Natur VGS and researchers at NIVA. The varying subject curricula selected include: Agriculture, fishing and forestry; Natural science; English; Mathematics; Agriculture and horticulture; Chemistry; and Biology.

The competence objectives for the following subjects were first provided by a teacher instructing them in March 2023: Agriculture, fishing and forestry, Natural science, and Agriculture and horticulture. A researcher at NIVA cross-checked this with the subject curricula from the Norwegian Directorate for Education and Training in May 2023 to ensure that the most up-to-date competence objectives are provided in this CMS. Competence objectives for the remaining subjects were discussed and selected via email and during joint workshops between teachers at Natur VGS and a researcher at NIVA. The first workshop took place Tuesday, 6th June 2023 at Natur VGS, where competence objectives were selected apart from Biology 1 and 2, which a NIVA researcher added while working on the module on "Plant growth, health and development". The competence objectives for the subject English were provided outside of the workshops by a teacher instructing the subject via email on 25th August 2023. The competence objectives for Biology 1 and 2 were cross-checked by a teacher at Natur VGS teaching Chemistry on 18th October 2023 via email, as this subject is not a part of the curriculum at Natur VGS. A second workshop took place on 24th October 2023 at Natur VGS. The purpose was to encourage further involvement from additional teachers and to improve the existing content through discussions about how aquaponics can be better implemented for the specified subject areas. Through a similar process, the teaching and learning modules were co-selected by researchers at NIVA with endorsement from teachers at Natur VGS.

The setup for the suggested order of the modules and types of learning utilized in the CMS and this document are inspired by the Aquaponics Textbook for Higher Education Curriculum for Teachers. The learning types also aim to integrate the National Curriculum's five basic skills: reading, writing, numeracy, oral skills and digital skills. Further learning types were established to classify the activities across all modules.

A qualitative approach was taken to analyze documents and provide information and resources in this CMS. An initial search using several online databases (e.g., Science Direct, Springer Link, Wiley Online Library, etc.) was performed using keywords based upon the teaching and learning modules. As information was gathered, knowledge gaps naturally developed, and secondary and tertiary searches were performed to fill these gaps.

3 Integration into the Norwegian National Curriculum

While there is a great deal of information and resources on aquaponics, to our knowledge, there are no standard methods for the use of aquaponics in teaching or as a learning arena for high school/upper secondary school classrooms in Norway.

Norway has a National Curriculum for primary, lower secondary and upper secondary education. For this CMS we focus on activities targeting upper secondary education. The National Curriculum is called "Kunnskapsløftet 2020" and is valid for different years and subjects, and has provided an overall point of departure for this work along with the specified subjects and curriculum at Natur VGS (Utdanningsdirektoratet, 2022). The interdisciplinary topic "Sustainable development" under the National Curriculum is at the core of this CMS, enabling students to develop competence in how to make responsible choices and act ethically with environmental awareness. All competence objectives were jointly selected by teachers at Natur VGS and researchers at NIVA from varying subject curricula from the Norwegian Directorate for Education and Training. The subject curricula selected include: Agriculture, fishing and forestry; Natural science; English; Mathematics; Agriculture and horticulture; Chemistry; and Biology.

For each of the six different/topical teaching and learning modules, there are respective tables including all selected competence objectives for the varying subject curricula. The information and resources provided in this CMS for aquaponics in education aims to link with these competence objectives to align with the Norwegian core curricula for all subjects indicated.

4 Introduction to aquaponics

4.1 Building/installing an aquaponic system

Before installing an aquaponics system, educators should review these questions as a guide for planning (Hart et al., 2014; Junge et al., 2020):

1. Why do we want to use aquaponics in our classroom or school? What is the purpose and what are our learning objectives for the system? An answer to this question will help identify the goals, timelines, and curriculum planning.
2. What does success look like for using aquaponics (e.g., high number of students reached, a learning experience for all involved, systems used for a certain amount of time, fish fry lunch, self-sustaining business)?
3. How does our vision of success translate into tangible goals for the system? What happens if our goals are not met or if they change in the process?
4. How can we get all stakeholders (e.g., schools, teachers, administrators, students, parents) on the same page about the vision and goals? How will we clearly communicate at every stage of the project?
5. What is a realistic project timeline, given our goals, funding, personnel, school year constraints, and any legislative or regulatory hurdles? Is this a temporary or long-term project, and if permanent, how will resources and energy be maintained and refreshed? Keep in mind that biological filters take about six weeks to cycle and get established.
6. Given our goals for the system, our vision for success, and our realistic constraints, what is an ideal size for our system (e.g., tabletop aquarium versus small- to medium-scale versus commercial system)?
7. Is there space available properly equipped to meet our vision for success and accommodate the size of system chosen? Things to think about include climate and the need for heating and/or cooling, access outside of normal school hours, the availability of water and electricity, the structural integrity of the building and the weight of the water, drainage and the probability of large water spills.
8. Who will be building the system? Will they have prior knowledge and training? Who else will be involved in building the system so that multiple individuals understand its functioning?
9. Who will be caring for the system on a daily basis? What training and support will they have or need? Will the system require care over breaks (e.g., weekends and holidays)? How will system care be delegated?
10. Will the system require care over extended breaks (e.g., summer and winter)? If so, who will care for it? If it will be shut down, what happens to the plants and/or fish? Will they be moved or harvested and how?

The technical paper “Small scale aquaponic food production: Integrated fish and plant farming” developed by the Food and Agriculture Organization (FAO) provides more detailed information on how to build a small simple aquaponic system.

4.2 Basics of aquaponics

Aquaponic systems combine *hydroponics* and *aquaculture* and share common resources such as water and nutrients in a closed loop, where no less than 50% of the nutrients provided to the plants are derived from fish waste (Lennard & Goddek, 2019). Figure 2 shows an example of an aquaponic system. The inputs in any aquaponic system includes fish feed and/or additional fertilizer, energy for lighting, oxygen, heating and pumping, carbon dioxide dosing and biocontrols, while the outputs include fish and plants (Goddek et al., 2019). The bacterial community in aquaponic systems are complex and serve a variety of functions including converting ammonia to nitrate, determining fish health, and influencing the consumption of oxygen, as well as producing waste products such as carbon dioxide and ammonia under degradation of organic matter and particles (Fjellheim et al., 2017).

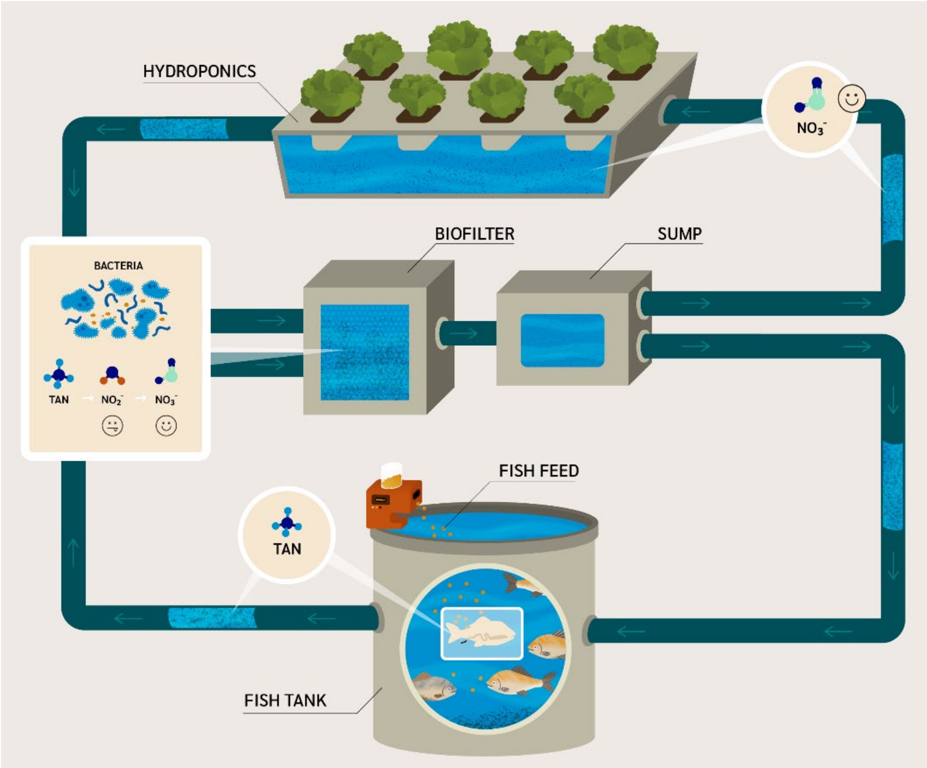


Figure 2. Example of an aquaponic system (illustrated by AVIA Produksjon, 2024).

Hydroponics involve plant production in soilless conditions where the supply of water and minerals is carried out in nutrient solutions with or without a growing medium such as stone wool, peat, perlite, pumice, coconut fibre, etc. (Maucieri et al., 2019). See Figure 3 for examples of common materials used as a growing medium or substrate.

Different types of hydroponic systems used in aquaponics include the following (Junge et al., 2020; Maucieri et al., 2019):

- Nutrient Film Technique (NFT) or a classic hydroponic system where nutrient solution flows in troughs.
- Media bed technique that uses space efficiently and where medium is used to support the roots of plants and functions as both a mechanical and biological filter.
- Deep Flow Technique (DFT) or Deep Water Culture (DWC) where plants are cultivated on floating rafts with holes to grow plants in net pots such that their roots are immersed in water or hanging supports in containers with a nutrient solution.

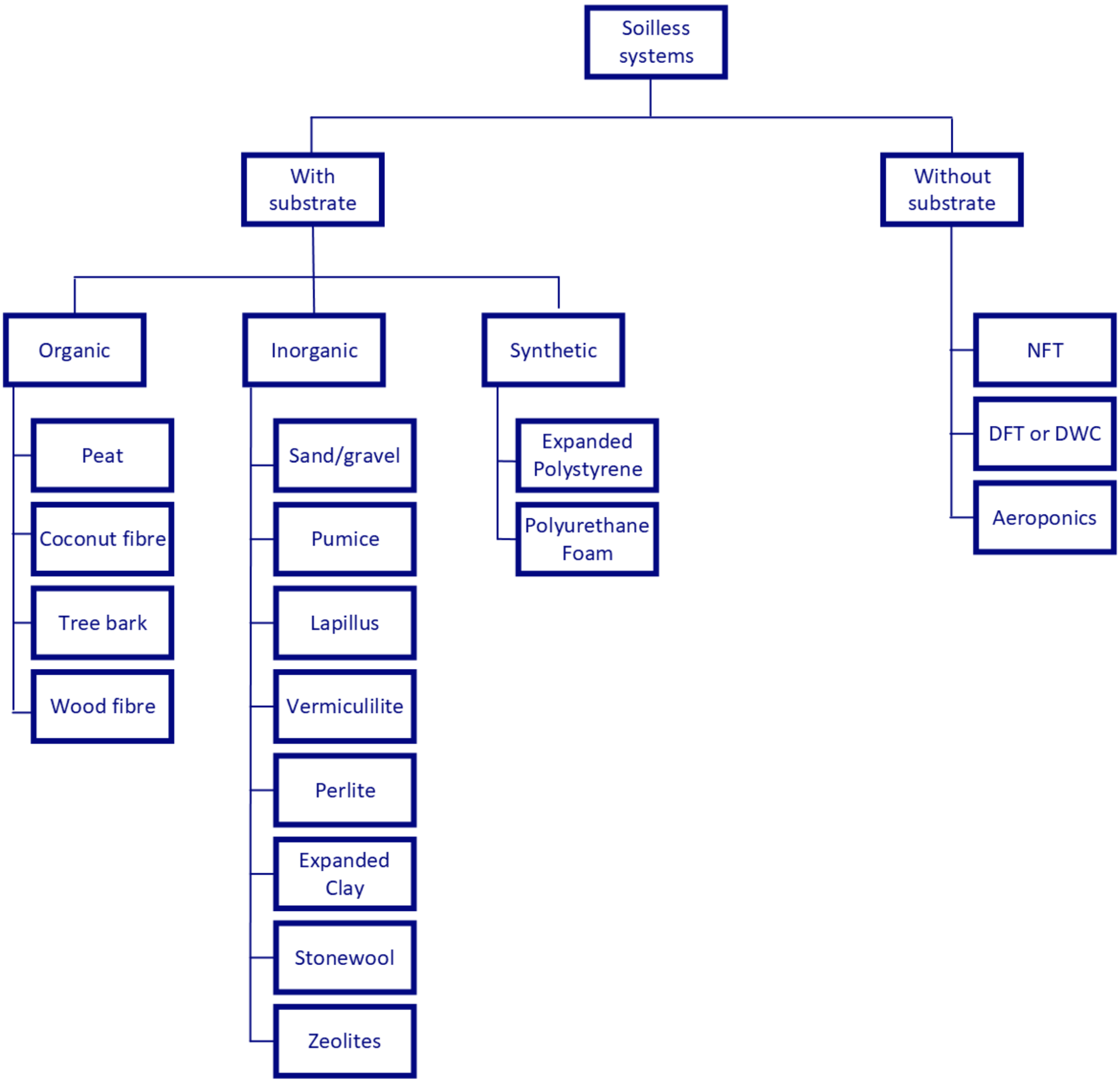


Figure 3. Materials usable as substrates in soilless systems (adapted from Junge et al., 2020; Maucieri et al., 2019).

Figure 4. Frillice is a cross between iceberg lettuce and curly endive and is a very popular and widespread variety in Norway ideal for plant production in aquaponic systems (Hess-Erga et al., 2013).

Plant species commonly grown in aquaponic systems include leafy greens, herbs and fruiting crops. Recommended plants for production include lettuce, as vast variety is available, it is widely used, has a short culture time, and there is much information on its expected growth and development (Hess-Erga et al., 2013). Figure 4 shows a very popular and widespread variety of lettuce available in Norway. It is important to keep in mind that different species respond differently in hydroponic systems, for example, lettuce grows best during the day at 15-25 °C (with a day length of 16 hours) and during the night at 10-15 °C (Hess-Erga et al., 2013).

Aquaculture is the breeding, rearing, and harvesting of aquatic plants and animals in all types of water environments. Types of aquaculture can be further defined: commercial, conservation, restorative, and regenerative. Further definitions of these terms are shown in Table 4. Clear definitions of the type of aquaculture is important in the sector to avoid misinterpretation between the terms used in different regulatory contexts (Mizuta et al., 2023). When aquaculture is integrated into aquaponics, it is restricted to aquatic animals because only the heterotrophic animal *metabolism* creates usable emissions as a nutrient base for autotrophic plants (Baganz et al., 2022).

Table 4. Definitions for aquaculture-related terms and connected concepts (Mizuta et al., 2023).

Term	Definition	Connected concepts
Commercial Aquaculture	The cultivation of an aquatic organism for enhanced production and improvement of stocks of final product ownership.	Production, selection, commodity
Conservation Aquaculture	The use of human cultivation of an aquatic organism for the planned management and protection of a natural resource.	Biodiversity, environmental protection, conservation hatchery
Restorative Aquaculture	Commercial or subsistence aquaculture that supports initiatives to provide/or directly provides ecological benefits to the environment, leading to improved environmental sustainability and ecosystem services, in addition to the supply of seafood or other commercial products and opportunities for livelihood.	Ecosystem services, biogenic habitats, production improvement
Regenerative Aquaculture	Commercial or subsistence aquaculture performed with focus on social, economic, and ecological responsibility and stability, with minimal external input and impact to the environment.	Policy, social wellbeing, environmentally friendly, holistic production and thinking, polyculture

In **recirculating aquaculture systems (RAS)**, wastewater from the fish is treated and reused within a system that is controlled and largely independent of local conditions (Junge et al., 2020). The RAS unit in the aquaponic system at Natur VGS is responsible for water treatment by removing particles using two bag filters, foaming and removal of particles in a protein skimmer, *nitrification* in the biofilter, and disinfection using a UV lamp. RAS are defined by the degree of recycling and reduce the need for freshwater, as well as the energy requirement for heating the production water, though they do require expertise, dependence on alarm systems and back-up solutions that are operational and immediate (Fjellheim et al., 2017).

The very nature of defining aquaponic systems involves the coupling of two subsystems, nonetheless aquaponics can either be in a closed loop (coupled) or in an open loop (decoupled) (Baganz et al., 2022). Aquaponics is a more recent form of integrated agriculture-aquaculture (IAA), where two or more aquaculture and agricultural activities take place concurrently or sequentially (FAO, 2022). While an aquaponic system can simultaneously fulfill several objectives, if the primary goal is education, evident options emerge as suitable from the range of categories (see Table 5).

Table 5. Classification of aquaponics according to different design principles and the suitability of different design options for educational purposes (Junge et al., 2019; Maucieri et al., 2018). Green text indicates the most suitable options, orange options are less suitable, and red options are not suitable.

Design goal	Categories
Objective or main stakeholder	Commercial crop production Household sufficiency Education Social enterprise Greening and decoration
Size	L large (>1000 m^2) M medium (200-1000 m^2) S small (50-200 m^2)

Design goal	Categories
	XS very small (5-50 m^2) XXS micro systems (<5 m^2)
Operational mode of the aquaculture compartment	Extensive (fish density is mostly under 10 kg/m^3 and allows for integrated sludge usage in grow beds) Intensive (obligatory sludge separation)
Water cycle management	Closed loop ('coupled' systems): after the hydroponic component, the water is recycled to aquaculture Open loop or end-of pipe ('decoupled' systems): after the hydroponic component, the water is either not or only partially recycled to the aquaculture component
Water type	Freshwater Rainwater Saltwater
Type of hydroponic system	Grow beds with different media Ebb-and-flow system Grow bags Drip irrigation Deep water cultivation (floating raft culture) Nutrient film technique (NFT)
Use of space	Horizontal Vertical

At harvest and/or the end of production, it is important to clean and disinfect all valves, flowmeters and other equipment as a measure against pathogens. Common measures against pathogens involve the following (Stouvenakers et al., 2019; Yavuzcan Yildiz et al., 2019):

1. Avoiding entry into the system by using a clean water supply, certified pathogen-free fish stocks, performing a fallow period, sanitizing the space (e.g., remove plant debris and disinfect surfaces), using specific clothing, certified seeds, a specific room for plant germination and physical barriers against insect vectors.
2. Limiting infection of plants and/or fish and spread of pathogens while growing.
    a. Reducing instances of plant infection can be achieved by using resistant plant varieties, disinfecting tools, avoiding plant *abiotic* stress, good plant spacing, and avoidance of algae development.
    b. Reducing incidents of fish infection can be achieved by using strains of fish resistant to pathogens, administering commercial vaccines, preventing stress by avoiding high stock density, removing contaminants (e.g., uneaten feed, excreta, dead or dying fish), and disinfecting tools.
    c. Limiting spread of pathogens during a growing period by monitoring environmental conditions such as air temperature, humidity, ventilation, nutrient solutions, etc.

4.3 Troubleshooting and maintenance for routine care of aquaponic systems

Aquaponic systems are complex, and several things can go wrong. Table 6 shows an overview of different things to think about when operating, monitoring, maintaining and troubleshooting the aquaponic system. Table 7 shows a checklist for everything to remember when monitoring and maintaining the system.

Establishment of routine care for aquaponics is important, and templates ready to print and use in the classroom are found in the "Appendix" of this CMS: contact list, daily monitoring of species growth and health, as well as water chemistry and quality. These templates are relevant both for a dedicated person responsible for operations and/or daily care and monitoring of the system, and for the students themselves when they are recording data and conducting group work activities. Collecting consistent data on the aquaponic system is also important for year-to-year comparison and finding trends and more data provides ample opportunities for learning activities.

Table 6. What can go wrong in a RAS or aquaponic system (Junge et al., 2020).

Type/System	Causes
Beyond control	Floods, tornadoes, hurricanes, wind, snow, ice, storms, electrical outages, vandalism/theft
Staff errors	Operator errors, overlooked maintenance causing failure of backup systems or systems components, alarms deactivated
Tank water level	Drain valve left open, standpipe fallen or removed, leak in system, broken drain line, overflowing tank
Water flow	Valve shut or opened too far, pump failure, loss of suction head, intake screen blocked, pipe blocked, return pipe ruptures/breaks/glue failure
Water quality	Low dissolved oxygen, high CO_2, supersaturated water supply, high or low temperature, high ammonia, nitrite or nitrate, low alkalinity
Filters	Channeling/clogged filters, excessive head loss
Aeration system	Blower motor overheating because of excessive back pressure, drive belt loose or broken, diffusers blocked or disconnected, leaks in supply lines

Table 7. Aquaponic system maintenance checklist.

Task	Daily	Weekly	Monthly	Harvest*	Yearly
Fish tanks					
Check water supply to fish	X				
Check air supply	X				
Check fish behavior (e.g., swimming calmly, belly not towards surface)	X				
Monitor water quality for temperature, pH, O_2, conductivity	X				
Remove any dead fish	X				
Monitor water quality for NH_4^+, NO_2^-, NO_3^-		X			
Feed fish (if NO_2^- values within range)	X	X			
Plant system					
Check water supply to plants	X				
Observe the plants and remove leaves with signs of pests and diseases and dead leaves	X				
General system check					
Check alarm and display	X				
Check the function of all valves and pumps	X				
Check that the water level is over all sensors, filter, biobodies, etc.	X				
Wash sensors and filter		X		X	
Check for sediments/unwanted biofilm and clean		X			
Wash surfaces (floors, equipment, etc.)		X		X	
Check and count inventory and order supplies		X			
Check and calibrate sensors			X		
Check, clean and disinfect all valves, flowmeters and other equipment				X	
Check and overhaul equipment					X

*Harvest or end of production

5 Classroom Model System (CMS) for teaching and learning using an aquaponic system

The six teaching and learning modules were defined by researchers at NIVA with endorsement from teachers at Natur VGS: Sustainability; Plant growth, health and development; Animal welfare; Water chemistry and quality; Urban farming; and Economy and business operations (see Figure 5). The text under each module is meant to be an added resource for teachers, especially for those working interdisciplinary, with suggestions for activities to use in the classroom related to aquaponics. The modules aim to connect to relevant topics surrounding aquaponics to ensure interdisciplinary and experiential learning, and for students to think more holistically and in line with systems thinking by thinking in relations.

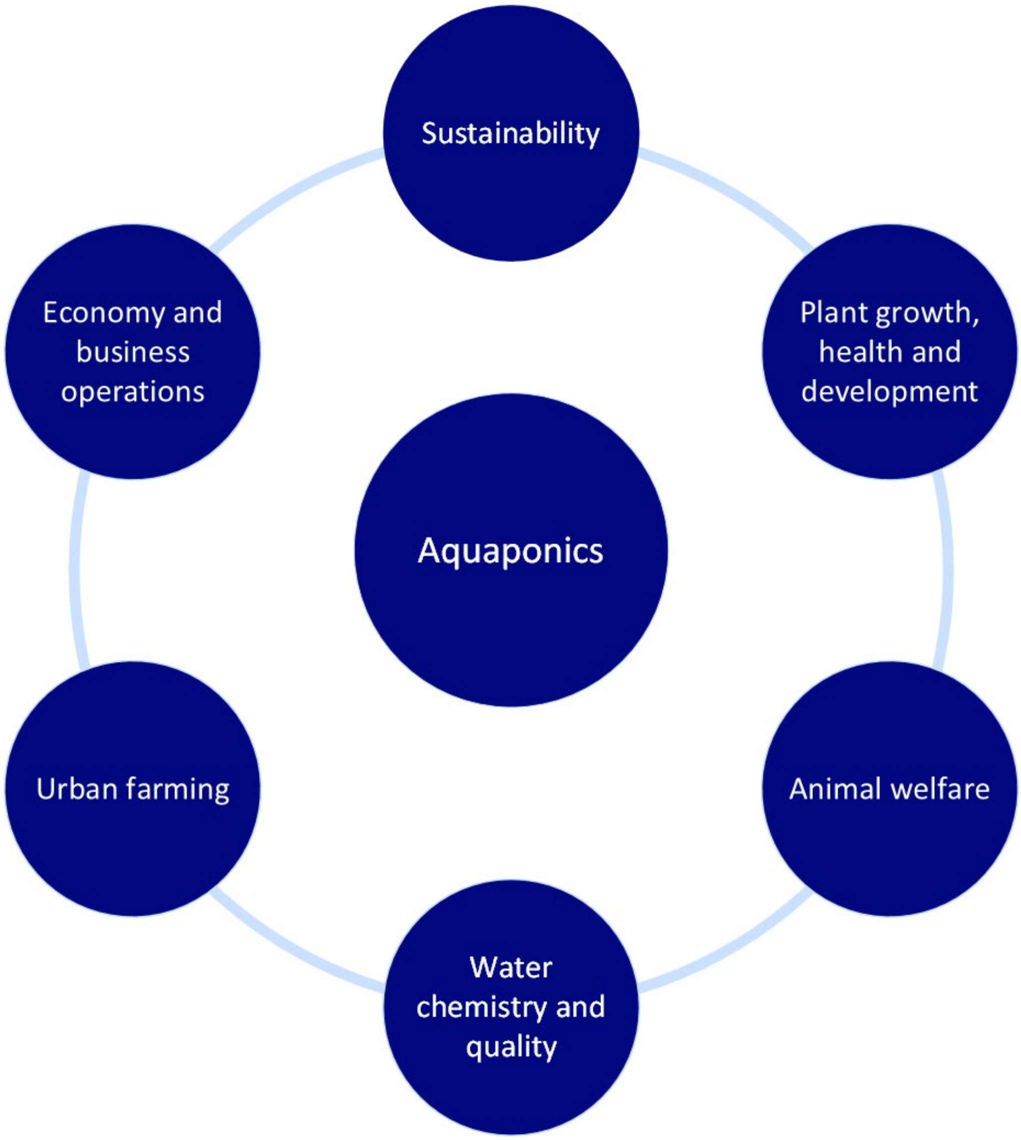


Figure 5. The teaching and learning modules in this CMS.

5.1 Sustainability

Aquaponic systems share common resources such as water and nutrients in a closed loop where resources are recirculated and reused in a self-sustaining system, making aquaponics an ideal arena to teach and learn about sustainability. Table 8 shows the competence objectives from varying subject curricula from the Norwegian Directorate for Education and Training for this module on Sustainability. Table 9 shows examples of activities and discussion topics that connect aquaponics to sustainability.

Table 8. Competence objectives from varying subject curricula from the Norwegian Directorate for Education and Training for the teaching and learning module on sustainability.

Subject	Subject code	Title	Competence objectives
VG1			
Agriculture, fishing and forestry	NAB01-03	nature-based business activities	• discuss how nature-based products and services can be developed within the framework of sustainable development and resource management
Natural science	NAT01-04	Vg1 SF	• explore a self-chosen natural-science research question, present findings and argue for the choice of methods
Natural science	NAT01-04	Vg1 BA	• explore a self-chosen research question relating to one's own education program, present findings and argue for the choice of methods
Natural science	NAT01-04	Vg1 NA	• explore a self-chosen research question relating to one's own education program, present findings and argue for the choice of methods • explore and present technology relating to one's own education program and assess it in a sustainability perspective
English	ENG01-04	Vg1 Vocational	• read and summarize vocational content from English-language documentation • create texts relevant to the vocation with structure and coherence that describe and document the pupil's own work and are adapted to the purpose, recipient and situation • explore and reflect on diversity and social conditions in the English-speaking world based on historical contexts
VG2			
Chemistry	KJE01-02	Kjemi 1	• explain the principles of green chemistry and discuss how using the principles can contribute to sustainable development

According to the World Commission on Environment and Development's 1987 Brundtland report, **sustainability** is defined as ensuring that the needs of the present are met without compromising the ability of future generations to meet their own needs (Brundtland, 1987). To address and chart progress made towards crises that threaten the survival of humanity, the Sustainable Development Goal (SDG) Indicators were first adopted in 2017 by the United Nations (UN) General Assembly and is updated annually by the Statistical Commission. The 17 SDGs balance social, economic, and environmental sustainability. Aquaponic systems have the potential to link to the SDGs in Figure 6 considering they provide food in alternative and more sustainable ways than traditional food systems and efficiently recycle and reuse resources such as nutrients and water. Earth's **natural resources** are derived from the natural environment and include *biotic* resources from living organisms and organic material, and *abiotic* organisms from nonliving and inorganic material (Lewandowski et al., 2018).

Figure 6. SDG Indicators with potential linkages to aquaponics (UN, 2023).

The relationship between humankind and the natural environment is imperfect, and this is exemplified when considering the *planetary boundaries*. **Planetary boundaries** are indicators of the safe operating space for humanity in regard to nine Earth-system processes and their associated *thresholds*, which we should avoid exceeding: climate change; rate of biodiversity loss (terrestrial and marine); interference with the nitrogen and phosphorus cycles; stratospheric ozone depletion; ocean acidification; global freshwater use; change in land use; chemical pollution; and atmospheric aerosol loading (Rockström et al., 2009). See Figure 7 for an illustration of the planetary boundaries. A **threshold** can be defined as the amount of pressure or changes of key variables in an environment at which the *tipping point* of an ecosystem shifting to a new unfavorable state becomes unavoidable (Hillebrand et al., 2023). A **tipping point** is the point at which a series of small changes of key variables becomes significant enough to cause a larger, more significant change. Little change in an ecosystem can be observed up until the passing of a critical threshold, at which point the potential for a total state shift is expected (Scheffer et al., 2001). Not all Earth-system processes have well-defined thresholds and there are knowledge gaps in understanding all thresholds and tipping points for the planetary boundaries.

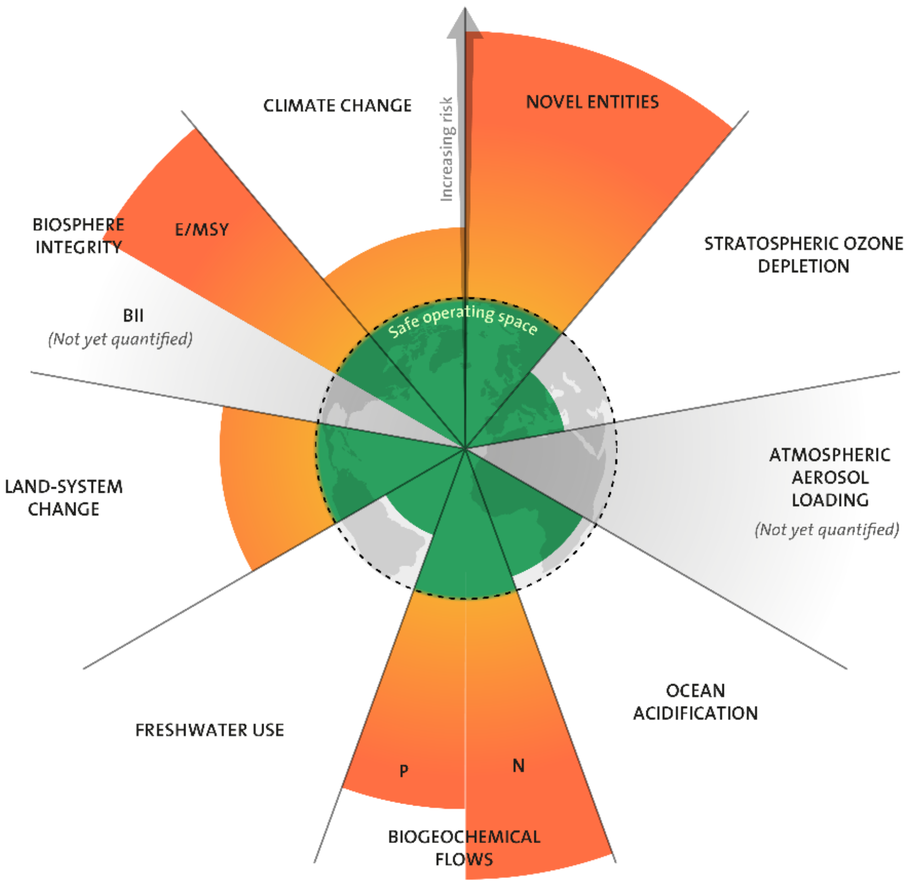


Figure 7. Illustration of the planetary boundaries first developed in 2015 and updated in 2022 to include novel entities or environmental pollutants including plastics (designed by Azote for Stockholm Resilience Centre, based on analysis in Persson et al 2022 and Steffen et al 2015).

There are different tipping point behaviors such as triggering abrupt responses (e.g., conversion of areas of the Amazon rainforest to a savanna or seasonally dry forest) or self-perpetuating after a critical threshold is crossed (e.g., large-scale loss of permafrost), and there are also indications for favorable societal tipping points (Steffen et al., 2018). Once social or societal tipping points are triggered, there is an accelerated shift toward new and preferable states (Aschemann-Witzel & Schulze, 2023), and from a systems thinking perspective, "small interventions can trigger self-reinforcing feedbacks that accelerate systemic change" (Lenton et al., 2022). Social or societal tipping points can be triggered by intervention through social and technological innovations, ecological and political interventions, public and private investments, and public information (Lenton et al., 2022). Aquaponics in urban areas have the potential to trigger a social or societal tipping point in how people perceive the sustainability of food systems, as well as the recycling and reuse of resources.

There are differing metrics and indicators across sectors and disciplines to measure sustainability. The Ecological Footprint© developed by the Global Footprint Network measures the human demand on and supply of nature. Among the many quantitative methods to measure sustainability and the environmental impacts along food supply chains, Life Cycle Assessment (LCA) is the method typically recommended by the European Commission and the United Nations Environment Programme to support policy making for sustainability assessing the environmental impacts during the entire life cycle of a product (Cucurachi et al., 2019). Figure 8 shows typical LCA boundaries for an aquaponic system.

According to ISO 14040:2006, the principles and framework for LCA include (Deconinck & Toyama, 2022):

1) Definition of the goal and scope of the LCA;
2) Life cycle inventory analysis (LCI) or a flowchart documenting and quantifying all inputs and outputs across the various activities and sub-processes under assessment;
3) Life cycle impact assessment (LCIA) or quantifying flows into impacts;
4) Life cycle interpretation of results and reporting and critical review of the LCA.

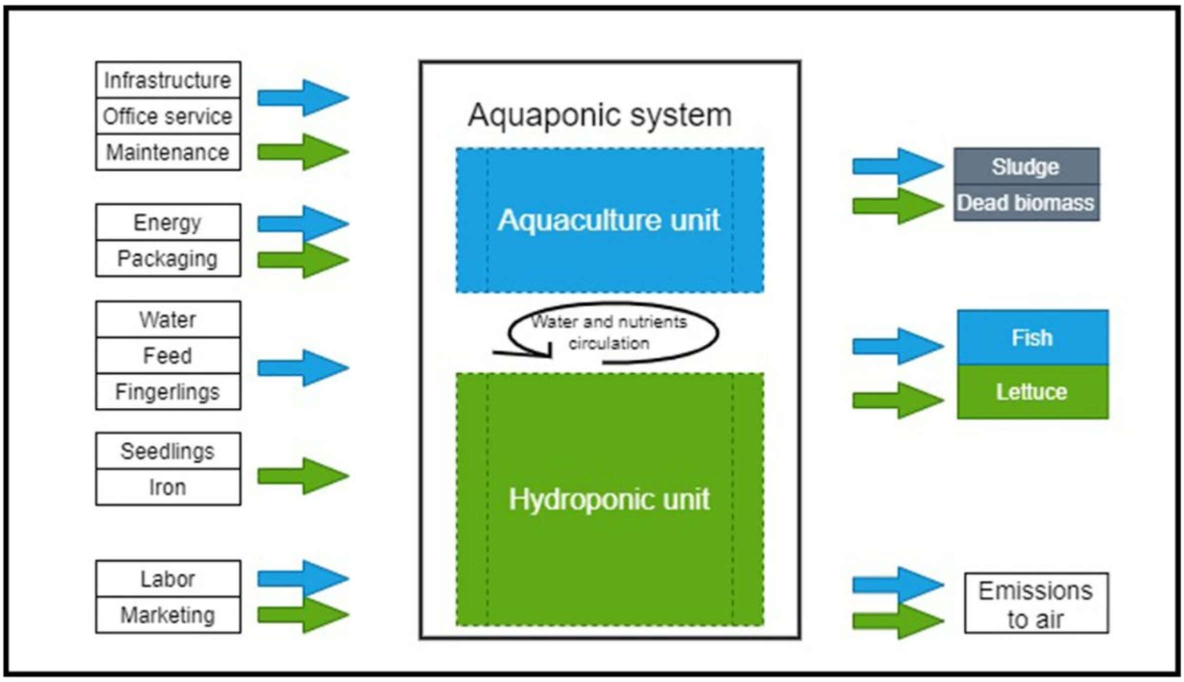
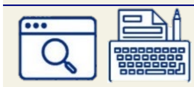
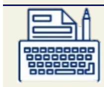


Figure 8. Generic plan of an aquaponic system for life cycle assessment boundaries (Greenfeld et al., 2022).

Table 9. Examples of activities and discussion topics that connect aquaponics to sustainability.

Learning type	Activity
	• Draw a poster showing the cycle of an aquaponic system and prepare an oral presentation describing the poster while using relevant terminology. <u>Additional activity:</u> Identify the inputs and outputs, and where the system is sustainable. • Using materials found outdoors, create a miniature model of an aquaponic system. Prepare to present the model to the rest of the class, use relevant terminology.
	• What consequences do changes in climate and land use have for biological diversity and what role might aquaponics play in measures for more sustainable management? • How do aquaponics have the potential to trigger a social or societal tipping point in how people perceive the sustainability of food systems? • How will rising water levels and extreme weather impact Norway's ability to produce its own food? • How do the processes in an aquaponic system compare to a natural ecosystem? • What are the advantages and disadvantages of aquaponics? • What are the potential shocks, stresses and risks posed to aquaponic systems? Identify how aquaponic systems are resilient to absorb these impacts and where they lack resilience.
	• Choose at least three of the SDG Indicators with potential linkages to aquaponics in Figure 6 and identify the specific targets connected to aquaponics. • Compare at least three of the SDG Indicators with potential linkages to aquaponics in Figure 6 from Norway's SDG Country profile with a country profile on another continent using the following website: https://unstats.un.org/sdgs/dataportal/countryprofiles/NOR. • Identify any other SDG Indicators and their specific targets that could link to aquaponics and are missing from Figure 6. • Calculate your Ecological Footprint© using the website: https://www.footprintcalculator.org/home/en. Compare results with your classmates and use this principle as a guide when looking at all inputs, outputs and processes of an aquaponic system.
	• Use online sources to consider whether aquaponics is more sustainable than conventional food production, distribution and consumption chains. <u>Additional activity:</u> Consider the reliability and possible bias of the sources you found. • Use online sources to search for more information on aquatic food nutrition and consumption. Write 500 words and provide references. • Using information from "Introduction to aquaponics" and searching the internet, assess the sustainability of some of the varying technology involved in aquaponics and write 500 words on the findings. Provide references. • Use online sources to search for articles on aquaponics using different keywords around sustainability, download papers of interest and order them according to relevance or topic. Choose a topic of interest and write 500 words and provide references.
	• Write 500 words about how aquaponics might be used to improve food security in a region of your choosing. Provide references. • Define and categorize different types of natural resources.
	• Search curriculum plans from the Norwegian Directorate for Education and Training for varying subjects and write 500 words on how an aquaponic system could be integrated into the curriculum.

5.2 Plant growth, health and development

Plant production or *hydroponics* is an integral part of aquaponics. Therefore, a module on plant growth, health and development is necessary for teaching and learning about aquaponic systems. Table 10 shows the competence objectives from varying subject curricula from the Norwegian Directorate for Education and Training for this module on Plant growth, health and development. Table 13 shows examples of activities and discussion topics that connect aquaponics to plant growth, health and development.

Table 10. Competence objectives from varying subject curricula from the Norwegian Directorate for Education and Training for the teaching and learning module on Plant growth, health and development.

Subject	Subject code	Title	Competence objectives
VG1			
Agriculture, fishing and forestry	NAB01-03	nature-based production and services	• take care of plants based on knowledge of the biology of the species and cycles in nature • classify and present a selection of species and materials, and choose materials based on work assignments and properties of the materials • follow instructions and use manuals for production equipment, and carry out simple inspections, maintenance and repairs • make simple estimates for raw materials and material consumption, input factors and benefits
Natural science	NAT01-04	Vg1 SF	• explore a self-chosen natural-science research question, present findings and argue for the choice of methods
Natural science	NAT01-04	Vg1 BA	• explore a self-chosen research question relating to one's own education program, present findings and argue for the choice of methods
Natural science	NAT01-04	Vg1 NA	• explore a self-chosen research question relating to one's own education program, present findings and argue for the choice of methods • carry out risk assessment of one's own experiments and manage the resulting waste in a suitable manner • explore and present technology relating to one's own education program and assess it in a sustainability perspective • explain why some elements are important for life and assess how human activity can affect the cycles of these elements
English	ENG01-04	Vg1 Vocational	• read and summarize vocational content from English-language documentation • create texts relevant to the vocation with structure and coherence that describe and document the pupil's own work and are adapted to the purpose, recipient and situation • explore and reflect on diversity and social conditions in the English-speaking world based on historical contexts
VG2			
Agriculture and horticulture	LGA02-03	produksjon og tjenesteyting	• plan, carry out, assess and document tasks within agriculture and horticulture based on the species, biology, need for care, and relevant regulations

Subject	Subject code	Title	Competence objectives
			• explain the symptoms of the most common animal and plant diseases and how they spread, and consider measures to prevent disease and infection • grow plants in different soil types and growing media and explain the importance of micro- and macronutrients for living organisms
Chemistry	KJE01-02	Kjemi 1	• plan and carry out experiments, estimate uncertainty and assess the sources of error, present results and argue for the validity of results and conclusions • use data, simulations and calculations when interpreting and drawing conclusions • explain the principles of green chemistry and discuss how using the principles can contribute to sustainable development
Biology	BIO01-02	Biologi 1	• plan and carry out surveys, collect, process and interpret data, and present results and findings • explore connects between anatomy and physiology and understand the principle for live processes in organisms • explore connections between cell structures and functions and understand how cell membranes form the basis for communication between cells • understand how viral and microbial diseases arise, spread and are combated • explore abiotic and biotic factors in an ecosystem, discuss relationships that explain biological diversity and reflect on the intrinsic value of nature
VG3			
Chemistry	KJE01-02	Kjemi 2	• understand and use chemical terminology and professional language in communication • plan and carry out experiments, discuss methods and measures to reduce risk and assess uncertainty and sources of error in personal and peer experiments • explore a theoretical or practical issue and discuss and present findings
Biology	BIO01-02	Biologi 2	• explore a biological problem, analyze collected data, argue for the choice of methods and discuss results and findings • discuss how human activity affects life cycles and explore measures to protect them • explore how enzymes work and understand the role enzymes play in metabolic processes • compare how energy is converted through photosynthesis and cellular respiration, and assess the effect different factors have on metabolism

Metabolism is a series of chemical processes or reactions that convert energy in the cells of living organisms. Plants take up light, water (H_2O) and carbon dioxide (CO_2) to produce oxygen (O_2) and energy (sugars in the form of ATP or adenosine triphosphate) in a metabolic chemical process called **photosynthesis**. Photosynthesis takes place in the organelle or subunit within plants cells called chloroplasts. Chloroplasts contain a pigment called chlorophyll which is essential for plants to absorb and use energy from light. Figure 9 shows a plant cell and the structure of a chloroplast.

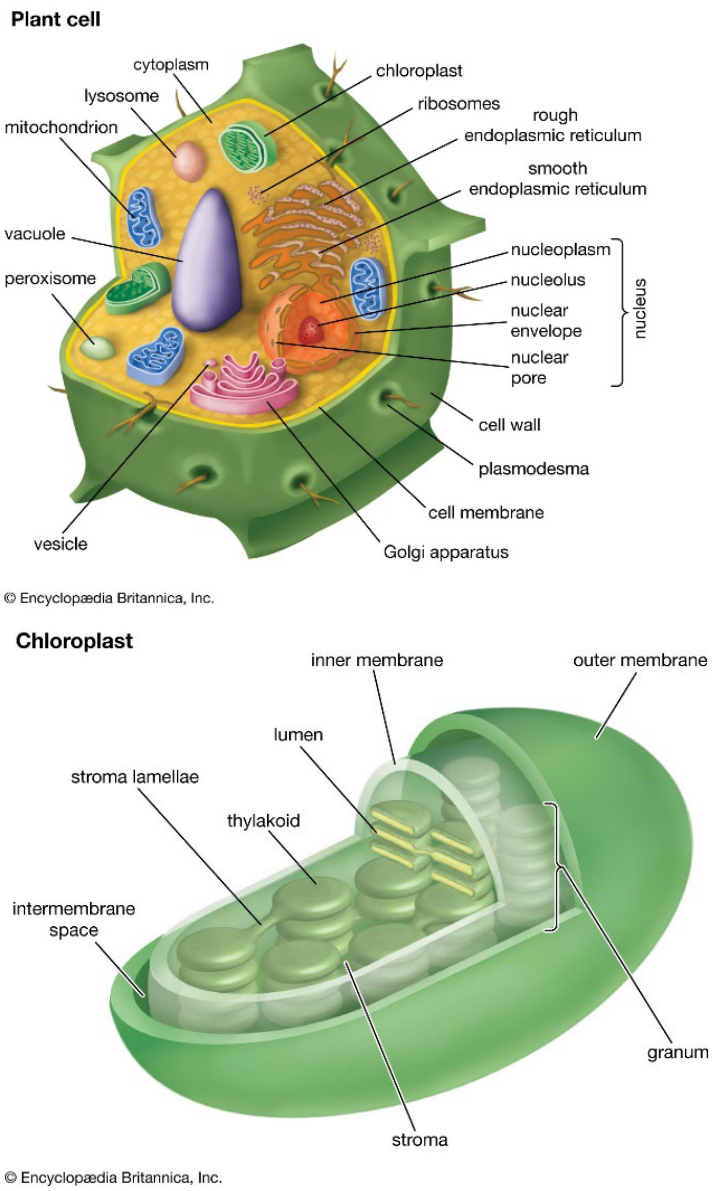


Figure 9. A plant cell showing the cell wall and internal organelles (top) and the structure of a chloroplast (bottom) (Encyclopædia Britannica; Encyclopædia Britannica).

There are 118 known elements on the periodic table, some of which are naturally occurring and vital for life. **Macronutrients** are chemical elements that are required in large amounts and provide energy to maintain fundamental functions for living organisms. For animals, macronutrients can be classified as proteins, carbohydrates and fats. **Micronutrients** are chemical elements needed in smaller amounts for normal growth and development of living organisms.

The most important nutrients for plant growth, health and development, as well as their specific function include the following (Junge et al., 2020; Maucieri et al., 2019):

- Carbon (C), hydrogen (H) and oxygen (O) are available from air and water.

- Nitrogen (N) produces amino acids, proteins, enzymes and chlorophyll in plants. It is essential for photosynthesis, cell growth, and metabolic processes. Nitrogen is usable for plant fertilization as nitrate (NO_3^-) and ammonium (NH_4^+).
- Phosphorus (P) stimulates root development, the rapid growth of buds and flower quantity via the formation of high-energy compounds (ATP) necessary for plant metabolism. It is essential for photosynthesis, as well as the formation of oils and sugars, and encourages germination and root development in seedlings. Phosphorus is usable by plants as hydrogen phosphate (HPO_4^{2-}) and dihydrogen phosphate ($H_2PO_4^-$).
- Potassium (K) is vital for cell division and extension, protein synthesis, enzyme activation and photosynthesis and also acts as a transporter of other elements and carbohydrates through the cell membrane.
- Calcium (Ca) is involved in cell wall formation, membrane permeability, cell division and extension.
- Sulphur (S) is required by the plant in quantities comparable to those of phosphorus. Sulphur is usable for plant fertilization as sulphate (SO_4^{2-}).
- Magnesium (Mg) is involved in the structure of chlorophyll molecules. Without magnesium, chlorophyll cannot capture the solar energy needed for photosynthesis.

Plant micronutrients or trace elements include iron (Fe), chlorine (Cl), manganese (Mn), boron (B), zinc (Zn), copper (Cu) and Nickel (Ni). Excessive sodium (Na) can be harmful to plants and interference with absorption of other ions (Maucieri et al., 2019). The input source for macronutrients and micronutrients, as well as symptoms of excessive and deficient nutrients for plants in aquaponic systems is explained further in Table 11.

Table 11. Source of input for macronutrients and micronutrients, and symptoms of excessive and deficient nutrients for plants in aquaponic systems (adapted from Eck et al., 2019; Junge et al., 2020; Maucieri et al., 2019; Somerville et al., 2014).

Nutrient	Chemical symbol	Source of input	Excess	Deficiency
Macronutrients				
Nitrogen	N	Fish feed; fish excreta; microorganism nitrogen uptake capacity	Yellowing along leaf margins; excess vegetative growth, increased crop cycle length, dark green leaf color, low fruit set, high water content in tissues	Pale green color or yellowing of older leaves, thin stems, reduced growth and advanced deterioration
Phosphorus	P	Fish feed (precipitation of pH at higher pH)	Algae growth in hydroponic system water; can reduce or block the absorption of other nutrients (e.g. copper, potassium, iron, zinc)	Poor root development leading to dull green-violet color of older leaves which may follow yellowing and leaf tips appear burnt
Potassium	K	Fish feed; added pH buffers	Difficult to notice physical symptoms; may lead to	Burned spots on older leaves and poor plant vigour and turgor; yellowing between the veins of leaves on the margins; susceptibility to sudden

Nutrient	Chemical symbol	Source of input	Excess	Deficiency
			magnesium, and possibly manganese, zinc or iron deficiency	temperature drops, water stress and fungal attacks
Calcium	Ca	Tap water	Can interfere with uptake of other nutrients	Stunted plant growth, distorted younger leaves with hooked tips and irregular shapes, light green or sometimes yellow coloring of new tissues and a stunted root system without fine roots; can be displayed in different ways across species
Sulphur	S	Tap water	Reduction in growth and leaf size; sometimes interveinal yellowing or leaf burning	Deficiencies are rare and difficult to notice, and physical symptoms often confused with nitrogen deficiency; pale green color or yellowing of younger leaves before falling off
Magnesium	Mg	Tap water	Can interfere with uptake of other nutrients	Tip and interveinal yellowing in older leaves
Micronutrients				
Iron	Fe	Fish feed	Not often evident in natural conditions; slight red color to water	Pale leaves and interveinal yellowing from younger to older leaves; reduced root system growth; leaf loss
Chlorine	Cl	Tap water	Plant shrinkage; scorched leaf margins, bronzing, yellowing	Infrequent; wilting and leaves drying out at margins
Manganese	Mn	Fish feed	Sometimes pale leaves and reduction in growth	Similar to iron and magnesium except for appearance of slightly sunken areas in the interveinal areas; reduced growth rates and a dull grey appearence
Boron	B	Tap water	Yellowing of leaf tip followed by deterioration on leaf margins; non-uniform exhibitions of symptoms	Incomplete bud development and flower set, growth interruption; dark green new structures, thick young leaves with leathery consistency
Zinc	Zn	Fish feed	Intensifies iron symptoms and toxic to fish	Rarely occurs though may be noticed as stunted growth poor vigour, and might be confused with other deficiencies
Copper	Cu	Tap water	Interferes with absorption of iron and manganese; reduced growth	Cupping of young leaves; pale leaves and brown or orange leaf tips, reduced growth of fruits; sometimes shows as abnormally dark green growth

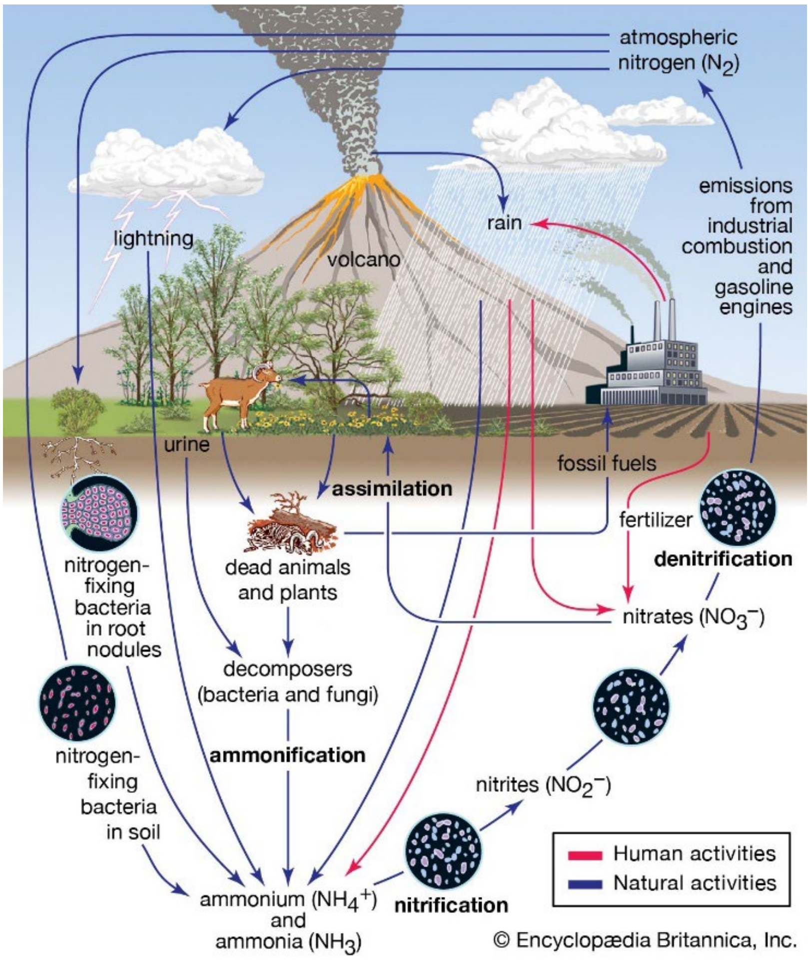
Nutrient	Chemical symbol	Source of input	Excess	Deficiency
Nickel	Ni	Tap water	Pale leaves, deterioration and wilting	Leaf burn and pale leaves or yellowing

Soilless food production or cultivation especially requires nutrient solutions for providing energy and maintaining fundamental functions, as well as normal growth and development of living organisms. Table 12 shows the recommended concentration of nutrients for lettuce in milligrams/litre.

Table 12. Recommended concentration of nutrients for lettuce in milligrams/litre (Hess-Erga et al., 2018). Note that these concentrations apply to commercial nutrient solutions, and concentrations are much lower in aquaponics.

	Nutrient (mg/l)												
	N	P	K	SO_4	Ca	Mg	Fe	Mn	Zn	Cu	B	Mo	Cl
Lettuce	200	40	200	64*	150	35	3.0	1.0	0.3	0.1	0.3	0.1	<75

*recommended value of Sulphur



Nitrogen is an essential element for all living organisms and makes up 78% of Earth's atmosphere as atmospheric nitrogen gas (N_2). A process called nitrogen fixation transforms nitrogen gas (N_2) into ammonium (NH_4^+) and ammonia (NH_3), and a process called **nitrification** converts these unusable forms into nitrite (NO_2^-) and then nitrate (NO_3^-) such that nitrogen is accessible for plants. Figure 10 shows the nitrogen cycle in the natural environment.

In aquaponics, fish produce ammonia (NH_3) in their excreta or waste, and nitrifying bacteria convert it into nitrate (NO_3^-), which plants can use to grow. Figure 11 shows the nitrogen cycle in aquaponics.

Figure 10. The nitrogen cycle (Encyclopædia Britannica).

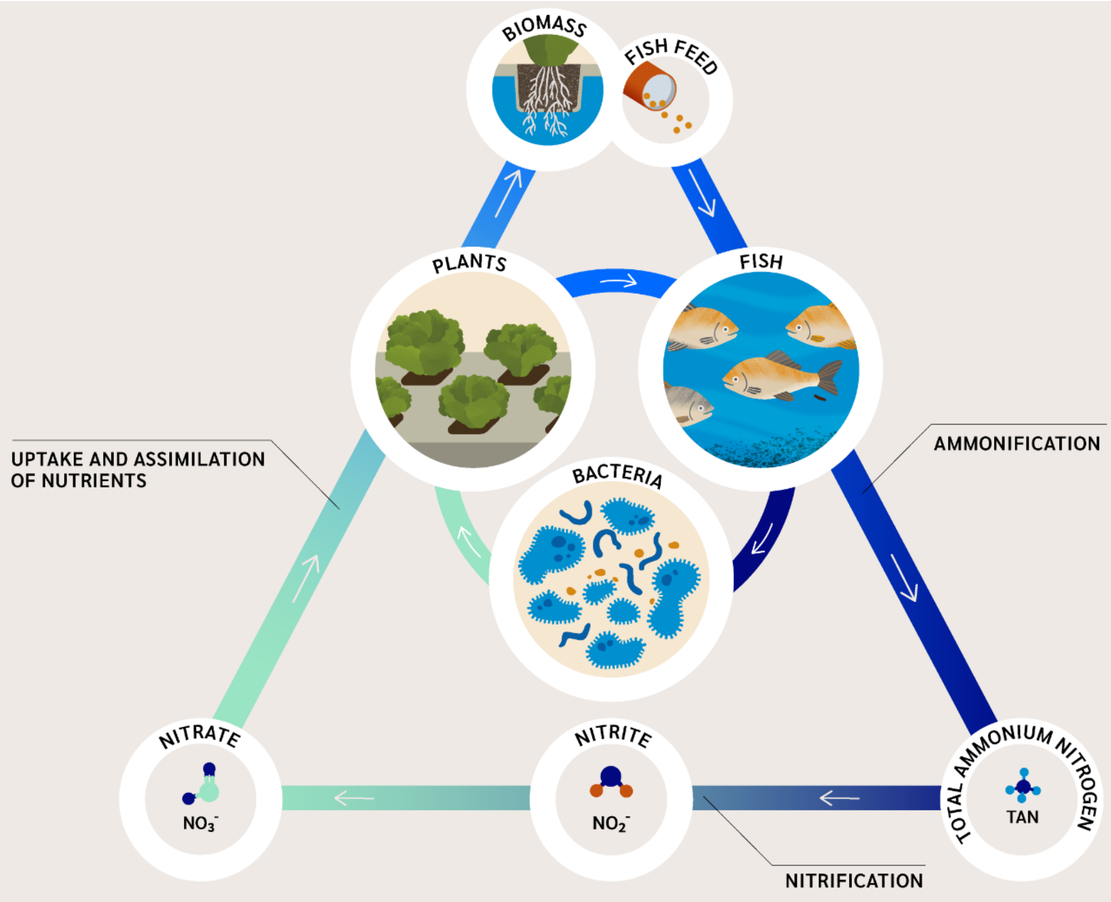


Figure 11. The nitrogen cycle in aquaponics (illustrated by AVIA Produksjon, 2024 and adapted from Goddek et al., 2015; Junge et al., 2020).

The pH or measure of acidity of water determines the availability of nutrients to plants (see Figure 12). A solution is acidic if the pH is less than 7, neutral if the pH is at 7, and alkaline or basic if the pH is above 7. The most important mechanism in plant nutrition is absorption through a plant's roots. Absorption of nutrients, takes place in ionic form following a reaction with salts dissolved in the nutrient solution (Maucieri et al., 2019).

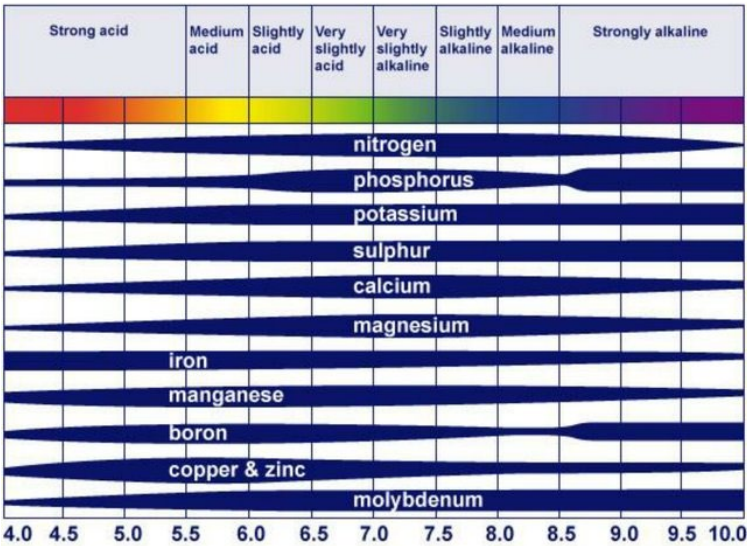
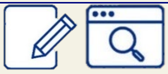
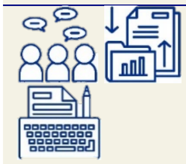
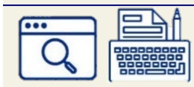


Figure 12. The effect of pH on nutrient availability (Roques et al., 2013).

Table 13. Examples of activities and discussion topics that connect aquaponics to plant growth, health and development.

Learning type	Activity
	• Draw the main features of plant cells and identify connections between cell structure and function as well as the structures that allow plants to perform photosynthesis.
	• Draw the main external anatomical features of plants by observing a plant growing in the hydroponic part of the aquaponic system as an example or from the internet. Use online sources to label the basic structures of the plant. Provide references.
	• What factors impact the size of the plants in an aquaponic system? • What are the limitations and constraints to plant growth and health in aquaponic systems? • What connections are there between cell structure and function? How do cellular membranes form the basis for communication between cells? • How does fish feed impact plant production? *Feed is the main source of nitrogen (Junge et al., 2020).* • What are the similarities and differences between the nitrogen cycle in the environment and an aquaponic system?
	• Make observations and gather data on plant growth and health using the templates provided in the “Appendix” of this CMS. Use this data to design reports with visuals and diagrams. Deliver reports to the next school year including logged data sheets and reflections. • Choose at least two different species of plants to grow in the aquaponic system and compare observations and data throughout the school semester using the templates provided in the “Appendix” of this CMS. Write 500 words drawing conclusions from the results on the observations and data. Note which species thrived and poorly produced.
	• Develop a plan for managing any residual waste from plant production and implement this strategy when operating, monitoring and maintaining the aquaponic system. • Grow the same plant(s) in different substrate types as identified in “Introduction to aquaponics” and record any similarities or differences. • Harvest plants produced by the aquaponic system and compare similar products from the local grocery store in a survey (e.g., “taste test”) with classmates, peers and/or family members.
	• Use online sources to search for examples of nutrient deficiency for all macronutrients in plants and label with species type, nutritional disorder and symptoms (Junge et al., 2020). Summarize the symptoms for the most common plant diseases and how these are spread in 500 words. Consider measures that can prevent disease and infection. Provide references. • Use online sources to search for possible plant varieties suitable for the hydroponic part of the aquaponic system. Note any species that do better or worse when grown together. Write at least 500 words on why the plant varieties were chosen, include any advantages and disadvantages. Provide references. Additional activity: Table 12 shows the recommended concentration of nutrients for lettuce. Use online sources to search for nutrient solutions for other plant varieties. • Use online sources to search for articles on aquaponics using different keywords around plant growth, health and development, download papers of interest and order them according to relevance or topic. Choose a topic of interest and write 500 words and provide references.

Learning type	Activity
	• Perform stoichiometry balance for the equation for photosynthesis: $O_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$. • Consider different scenarios where an aquaponic system has low or high concentrations of macronutrients, micronutrients, or pH. Identify possible reasons by explaining causes of nutrient excess/deficiency and what would happen to the plants, and propose a remediation plan.
	• Search curriculum plans from the Norwegian Directorate for Education and Training for varying subjects and write 500 words on how an aquaponic system could be integrated into the curriculum.

5.3 Animal welfare

Cultivation of aquatic organisms or *aquaculture* is an integral part of aquaponics. Therefore, a module on animal welfare is necessary for teaching and learning about aquaponic systems. Table 14 shows the competence objectives from varying subject curricula from the Norwegian Directorate for Education and Training for this module on animal welfare. Table 19 shows examples of activities and discussion topics that connect aquaponics to animal welfare.

Table 14. Competence objectives from varying subject curricula from the Norwegian Directorate for Education and Training for the teaching and learning module on animal welfare.

Subject	Subject code	Title	Competence objectives
VG1			
Agriculture, fishing and forestry	NAB01-03	nature-based production and services	• take care of animals or fish in respect of ethical guidelines and knowledge of animal welfare and health, and biology of the species • classify and present a selection of species and materials, and choose materials based on work assignments and properties of the materials • follow instructions and use manuals for production equipment, and carry out simple inspections, maintenance and repairs • make simple estimates for raw materials and material consumption, input factors and benefits
Natural science	NAT01-04	Vg1 SF	• explore a self-chosen natural-science research question, present findings and argue for the choice of methods
Natural science	NAT01-04	Vg1 BA	• explore a self-chosen research question relating to one's own education program, present findings and argue for the choice of methods
Natural science	NAT01-04	Vg1 NA	• explore a self-chosen research question relating to one's own education program, present findings and argue for the choice of methods • carry out risk assessment of one's own experiments and manage the resulting waste in a suitable manner • explore and present technology relating to one's own education program and assess it in a sustainability perspective • explain why some elements are important for life and assess how human activity can affect the cycles of these elements
English	ENG01-04	Vg1 Vocational	• read and summarize vocational content from English-language documentation • create texts relevant to the vocation with structure and coherence that describe and document the pupil's own work and are adapted to the purpose, recipient and situation • explore and reflect on diversity and social conditions in the English-speaking world based on historical contexts
VG2			

Subject	Subject code	Title	Competence objectives
Agriculture and horticulture	LGA02-03	produksjon og tjenesteyting	• plan, carry out, assess and document tasks within agriculture and horticulture based on the species, biology, need for care, and relevant regulations • explain the symptoms of the most common animal and plant diseases and how they spread, and consider measures to prevent disease and infection
Chemistry	KJE01-02	Kjemi 1	• plan and carry out experiments, estimate uncertainty and assess the sources of error, present results and argue for the validity of results and conclusions • use data, simulations and calculations when interpreting and drawing conclusions • explain the principles of green chemistry and discuss how using the principles can contribute to sustainable development
Biology	BIO01-02	Biologi 1	• plan and carry out surveys, collect, process and interpret data, and present results and findings • explore connects between anatomy and physiology and understand the principle for live processes in organisms • understand how viral and microbial diseases arise, spread and are combated • explore abiotic and biotic factors in an ecosystem, discuss relationships that explain biological diversity and reflect on the intrinsic value of nature
VG3			
Chemistry	KJE01-02	Kjemi 2	• understand and use chemical terminology and professional language in communication • plan and carry out experiments, discuss methods and measures to reduce risk and assess uncertainty and sources of error in personal and peer experiments • explore a theoretical or practical issue and discuss and present findings
Biology	BIO01-02	Biologi 2	• explore a biological problem, analyze collected data, argue for the choice of methods and discuss results and findings • explore factors that regulate growth in and the size of populations and discuss conflicts on interest around the management of populations • discuss how human activity affects life cycles and explore measures to protect them

Fish are a diverse group of vertebrates that are cold-blooded, meaning that their body temperature changes with the temperature of water, and they have gills to respirate oxygen and release carbon dioxide and metabolic wastes. Many species, though not all, have a swim bladder to maintain buoyancy, (Somerville et al., 2014). The main external anatomical features of fish include eyes, scales, mouth and jaws, gill cover, vent, and fins.

Koi is the species selected for the aquaponic system at Natur VGS because koi is mainly produced for ornamental reasons, and they are known throughout the world for their colorful body patterning and are kept as pets in indoor and outdoor freshwater ponds. Koi, known scientifically as *Cyprinus carpio* (also called ornamental carp, koi carp, nishikigoi, or Amur carp), are robust heavy-bodied fishes, weighing on average 16 kg and measuring 90 cm in length when fully grown (Encyclopædia Britannica). They are adaptable omnivorous cold-water fishes that consume insects, crustaceans, and other invertebrates as well as algae and vegetation (Encyclopædia Britannica). Common species of freshwater fish used in aquaponics are shown in Table 15.

Table 15. Fish species commonly used in aquaponics (Junge et al., 2020). The most relevant species in a Norwegian setting include Koi, Trout og Perch. Rainbow Trout (Oncorhynchus mykiss) is often use in aquaculture, while Brown Trout (Salmo trutta) is most common in Norway.

Common name	Species	Family	Order
Tilapia	*Oreochromis niloticus*	Cichlidae	Cichliformes
Catfish	*Pangasius pangasius*	Pangasiidae	Siluriformes
Koi	*Cyprinus carpio*	Cyprinidae	Cypriniformes
Trout	*Oncorhynchus mykiss*	Salmonidae	Salmoniformes
Bass	*Morone saxatilis*	Moronidae	Perciformes
Perch	*Sander lucioperca*	Percidae	Perciformes
Blue gill	*Lepomis macrochirus*	Centrarchidae	Perciformes

The main indicator of fish well-being is their behavior before, during and after feeding, where the following features are exhibited (Somerville et al., 2014):

- Extended fins and straight tails;
- Swimming in normal patterns;
- Strong appetite (important to note how much feed is eaten in a given time);
- No marks, discolored blotches, nor streaks or lines;
- No rubbing or scraping on sides of tank;
- No breathing air from surface;
- Clear and shiny eyes.

Table 16 lists the potential hazards for aquatic animal health in aquaponics according to varying factors: **abiotic** (nonliving and nonorganic), **biotic** (living and organic), feeding, management, welfare, and diseases.

Table 16. List of potential hazards for aquatic animal health in aquaponics (Yavuzcan Yildiz et al., 2019).

	Hazard identification	Hazard specification
Abiotic	pH	Too high/too low/rapid change
	Water temperature	Too high/too low/rapid change
	Suspended solids	Too high
	Dissolved oxygen content	Too low
	Carbon dioxide content	Too high
	Ammonia content	Too high, pH dependent
	Nitrite content	Too high
	Nitrate content	Extremely high
	Metal content	Too high, pH dependent
Biotic	Stocking density	Too high/too low
	Biofouling	
Feeding	Nutrients by the fish species	Surplus/deficiency
	Feeding frequency	Inadequate/improper feeding
	Dietary toxins	
	Feed additives	Unsuitable growth promoters
Management	Aquaponic system design	Poor system design
	Fish species	Unsuitable for aquaponics

	Hazard identification	Hazard specification
	Operational issues (water circulation, biofilter, mechanical)	
	Chemotherapeutants use	Threat for the microbial balance
	Staff hygiene	
	Biosecurity	
Welfare	Stressors	Too high
	Allostatic load	High
	Rearing conditions	Suboptimal
Diseases	Nutritional diseases	
	Environmental diseases	
	Infectious diseases	

Fish **biomass** or the total quantity or weight of organisms in a given area or volume, the size of the biofilter, and the total number of plants should be in balance to not exceed the carrying capacity of *recirculating aquaculture systems (RAS)* biofilter and accumulate toxins (Somerville et al., 2014). It is customary to weigh and measure all fish upon arrival and at regular intervals thereafter while connecting this to the amount of fish feed. It is also common to use feed tables that state how much growth is expected for a given amount of feed per day. Considering there is a great deal of information on recommended fish feed, it is suggested to ask the supplier of the aquatic organisms for further details on the type and how much feed to use. As a general rule, the amount of feed should be controlled such that there is no leftover food immediately after the feeding period. Figure 13 is an example of a fish feeding table for koi that takes water temperature into account.

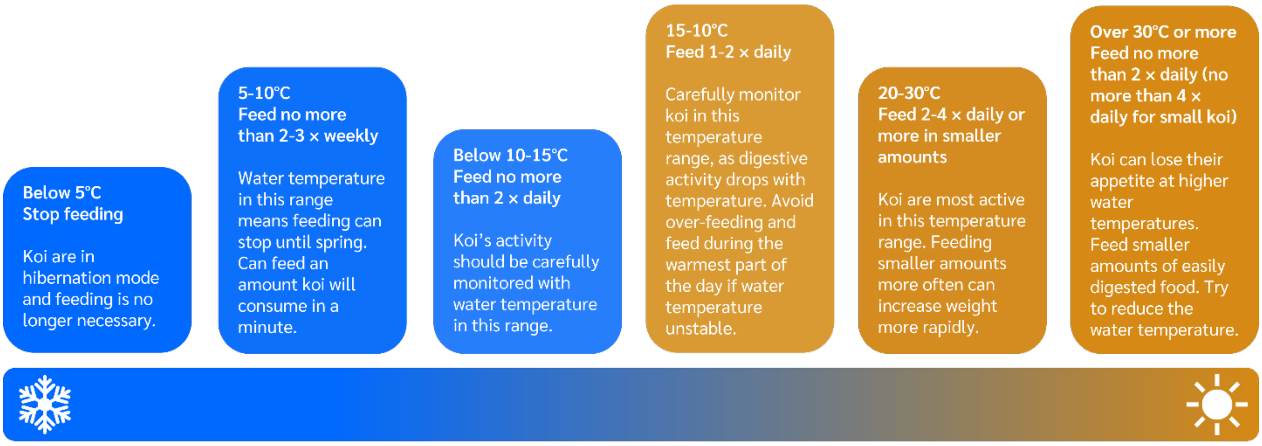


Figure 13. Feeding table for koi dictated by water temperature (adapted from Hikari, 2023). Careful consideration should always be given to the environmental conditions and level of fish activity. Note that this figure is sourced from a fish feed supplier.

Calculating fish biomass can be performed using a fish net, bathroom scale, a large tub filled with water from the fish tank(s), and a portable oxygenator to ensure that the fish do not lack oxygen and suffocate. The procedure for calculating biomass involves measuring the tub with water and the oxygenator on the scale before and after gently including the fish. When transferring the fish, it is important to not knock their bodies against the edge of the tank(s) to avoid injury and death. Table 17 defines the **stocking density**, often given as number of individuals or biomass per volume of water or surface area.

Table 17. Stocking density definitions (Junge et al., 2020).

Density of individuals		Biomass density	
per surface (#/m^2)	per volume (#/m^3)	per surface (kg/m^2)	per volume (kg/m^3)
Independent of tank depth. Relevant for bottom-dwelling fish	Is often high for small fishes even though the biomass density is higher	Independent of tank depth. Relevant for bottom-dwelling fish. It is often higher for bigger fish than for smaller species	Relevant for free swimming species

In Europe, there are no specific requirements for minimum conditions for fish due to the lack of knowledge about fish welfare, despite that any animal kept for the purpose of farming must comply with the law Directive 98/58/EC, which sets minimum conditions for adequate animal welfare for vertebrates (Junge et al., 2020). However, in Europe, there is a general agreement that fish undergo **stress** or pressure, strain or tension exerted when oxygen levels are low and when they are taken out of water, and that chronic stress in fish compromises the immune system and can make them more vulnerable to disease (Junge et al., 2020). This is among many reasons why water treatment in recirculating aquaculture systems (RAS) must continually remove waste products and left-over feed to avoid buildup of organic matter that can be harmful to fish (Fjellheim et al., 2017). Stress is a physiological response of the fish when they live in less than optimal conditions, for example overstocking, temperature and/or pH outside of range, and inconsistent feeding, and can result in a weakened immune system more susceptible to disease (Somerville et al., 2014). See Figure 14 for some examples of physical, chemical and other perceived stressors on fish.

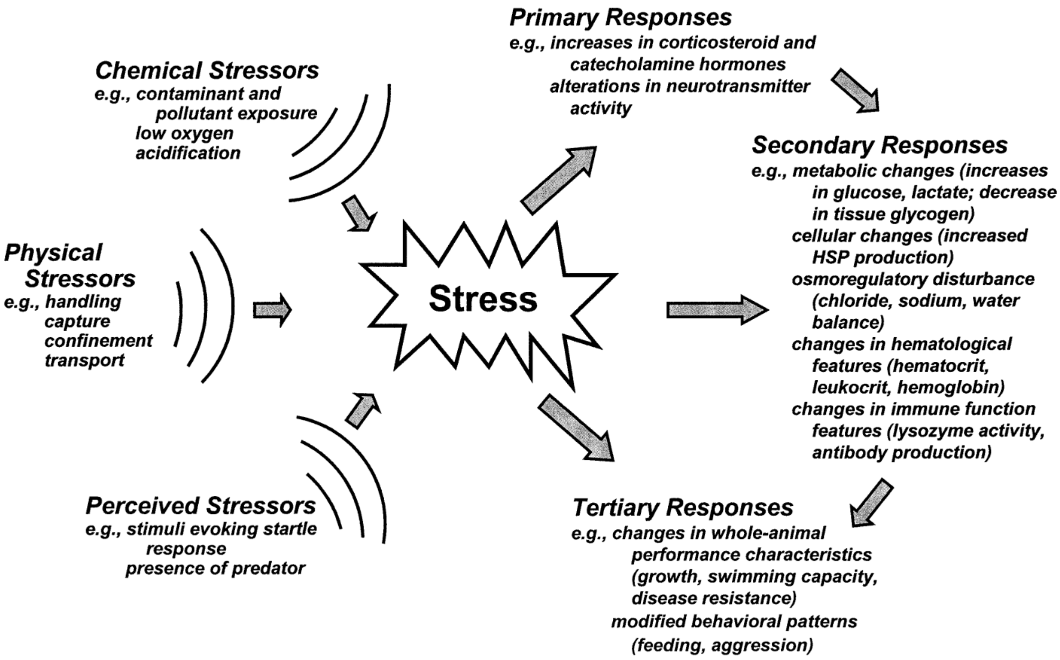


Figure 14. Physical, chemical and other perceived stressors act on fish to evoke physiological and related effects, which are grouped as primary, secondary and tertiary or whole-animal responses. In some instances, the primary and secondary responses in turn may directly affect secondary and tertiary responses, respectively, as indicated by the arrows. (Barton, 2002).

In 2016, the EU animal health law Regulation (EU) 2016/429 prevents and controls animal diseases that can be transmitted to other animals or humans, and upon its implementation in 2021, Norway revised its existing and established new regulations on animal health in 2022 (Mattilsynet, 2022). Table 18 links to all laws and regulations central to aquaculture and animal welfare in Norway.

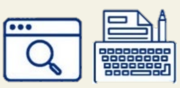
The Norwegian Directorate of Fisheries determined that the Small-Scale Urban Pilot Installation (SUPI) in Norway at Natur VGS is not considered aquaculture because the SUPI in on privately owned land, will not negatively impact the surrounding environment, and the nature, scope and duration of the activities planned there are acceptable pending training of the responsible operating personnel.

Table 18. Central laws and regulations to aquaculture and animal welfare.

Year	Norwegian ministry	Title of law or regulation (embedded link to Lovdata in Norwegian)
2022	Ministry of Agriculture and Food Ministry of Trade, Industry and Fisheries	Regulations on animal health (Animal Health Regulations)
2022	Ministry of Agriculture and Food Ministry of Trade, Industry and Fisheries	Regulations supplementing the Animal Health Regulations with provisions on notification, reporting, surveillance, eradication programs and disease-free status for specific animal diseases (Animal Health Surveillance Regulations)
2022	Ministry of Agriculture and Food Ministry of Trade, Industry and Fisheries	Regulations supplementing the Animal Health Regulations with provisions on the prevention and control of infectious animal diseases (Animal Disease Control Regulations)
2022	Ministry of Agriculture and Food	Regulations supplementing the Animal Health Regulations with provisions on land animal facilities and incubators and traceability of land animals and hatching eggs (Land Animal Traceability Regulations)
2022	Ministry of Agriculture and Food	Regulations supplementing the Animal Health Regulations with provisions on the movement of land animals, hatching eggs and animal products from land animals in the EEA (Land Animal Movement Regulations)
2022	Ministry of Agriculture and Food	Regulations supplementing the Animal Health Regulations with provisions on breeding stock from kept land animals (the Breeding Material Regulations)
2022	Ministry of Trade, Industry and Fisheries	Regulations supplementing the Animal Health Regulations with provisions on biosafety requirements for approval of aquaculture facilities and movements of aquatic animals, etc. (Aquabiosafety Regulations)
2022	Ministry of Agriculture and Food Ministry of Trade, Industry and Fisheries	Regulations supplementing the Animal Health Regulations with provisions on the import of certain live animals, breeding material and animal products from third countries (the Animal Import Regulations)
2022	Ministry of Agriculture and Food	Regulations relating to temporary control and emergency measures to prevent the spread of specified animal diseases in and to the EEA (Animal Disease Emergency Measures Regulations)
2022	Ministry of Health and Care Services Ministry of Agriculture and Food Ministry of Trade, Industry and Fisheries	Regulations on health certificates – land animals and breeding stock thereof – Regulation (EU) 2021/403 (Terrestrial Animal Health Certificate Regulations)
2022	Ministry of Health and Care Services Ministry of Agriculture and Food Ministry of Trade, Industry and Fisheries	Regulations on health certificates – food and animals – Regulation (EU) 2020/2235 (Food Health Certificate Regulations)
2022	Ministry of Health and Care Services Ministry of Agriculture and Food	Regulations on health certificates – aquatic animals and certain animal products thereof – Regulation (EU)

Year	Norwegian ministry	Title of law or regulation (embedded link to Lovdata in Norwegian)
	Ministry of Trade, Industry and Fisheries	2020/2236 (Aquaculture Health Certificate Regulations)
2008	Ministry of Trade, Industry and Fisheries	Regulation on the establishment and expansion of aquaculture facilities, zoo shops, etc.
2008	Ministry of Trade, Industry and Fisheries	Regulations relating to the operation of aquaculture facilities (Aquaculture Operations Regulations)
2005	Ministry of Trade, Industry and Fisheries	Law on aquaculture (Aquaculture Act)
2004	Ministry of Trade, Industry and Fisheries	Regulations on internal control to comply with aquaculture legislation (IC-Aquaculture)
2003	Ministry of Health and Care Services	Law on food production and food safety (Food Act)
1981	Ministry of Climate and Environment	Law on protection against pollution and waste (Pollution Control Act)

Table 19. Examples of activities and discussion topics that connect aquaponics to animal welfare.

Learning type	Activity
	• Draw the main internal anatomical features of fish. Identify the physiology that allows fish to respirate.
	• Draw the main external anatomical features of fish by observing a fish growing in the aquaculture part of the aquaponic system as an example or from the internet. Use online sources to find photos of fish from cartoons, movies or other media and comment on any anatomical aspects which are false or exaggerated (Junge et al., 2020).
	• Should fish be considered equal to other animals when it comes to animal welfare? • How would a biologist, chemist and technologist define the term *biomass* respectively? • How can there be general agreement in Europe that fish experience stress and a general lack of knowledge on fish welfare? • In Europe, there are currently no specific requirements for the minimum conditions for fish welfare. Should requirements for minimum conditions be put into place? • What factors impact the size of the fish in an aquaponic system? • What are examples of potential stressors for fish in an aquaponic system? • What are the social, ethical and environmental implications surrounding animal welfare in aquaponics?
	• Make observations and gather data on the fish using the templates provided in the "Appendix" of this CMS. Use this data to design reports with visuals and diagrams. Deliver reports to the next school year including logged data sheets and reflections.
	• Use online sources to search for more information on fish life cycles. Use this information to learn more about fish metabolism and write at least 500 words on findings. Provide references. • Use online sources to search for possible fish species suitable for farming in an aquaponic system. Write at least 500 words on why the fish species were chosen, include any advantages and disadvantages. Provide references. • The term *biomass* is defined as the total quantity or weight of organisms in a given area or volume in this module. Compare this definition with the definition in the module "Economy and business operations" and use

Learning type	Activity
	online sources to explore how communication differs across disciplines. Write 250 words and provide references. • Use online sources to search for examples of fish disease and provide information on symptoms and how it spreads. Summarize the symptoms for the most common fish diseases and how these are spread. Consider measures that can prevent disease and infection. Provide references. • Choose one of the central laws and regulations to aquaculture and animal welfare in Table 18, use online sources to write 500 words on how it might be relevant to aquaponics. Provide references. • Use online sources to search for articles on aquaponics using different keywords around animal welfare, download papers of interest and order them according to relevance or topic. Choose a topic of interest and write 500 words and provide references.
	• Develop a plan for managing any residual waste from fish cultivation and implement this strategy when operating, monitoring and maintaining the aquaponic system.
	• Calculate the biomass of fish in an aquaponic system upon their arrival in the system and at regular intervals thereafter (e.g., monthly).
	• Recall the procedure for calculating biomass. Calculate the biomass for 30 fish, each weighing approximately 0.10 g, in a tub with water weighing 40 kg.
	• Search curriculum plans from the Norwegian Directorate for Education and Training for varying subjects and write 500 words on how an aquaponic system could be integrated into the curriculum.

5.4 Water chemistry and quality

This module on water chemistry and quality is vital for teaching and learning about aquaponic systems to operate the system, as well as monitor and maintain the complex balance between the plants and fish. Table 20 shows the competence objectives from varying subject curricula from the Norwegian Directorate for Education and Training for this module on water chemistry and quality. Table 24 shows examples of activities and discussion topics that connect aquaponics to water chemistry and quality.

Table 20. Competence objectives from varying subject curricula from the Norwegian Directorate for Education and Training for the teaching and learning module on water chemistry and quality.

Subject	Subject code	Title	Competence objectives
VG1			
Agriculture, fishing and forestry	NAB01-03	nature-based production and services	• take care of plants based on knowledge of the biology of the species and cycles in nature • take care of animals or fish in respect of ethical guidelines and knowledge of animal welfare and health, and biology of the species • follow instructions and use manuals for production equipment, and carry out simple inspections, maintenance and repairs • make simple estimates for raw materials and material consumption, input factors and benefits
Natural science	NAT01-04	Vg1 SF	• explore a self-chosen natural-science research question, present findings and argue for the choice of methods
Natural science	NAT01-04	Vg1 BA	• explore a self-chosen research question relating to one's own education program, present findings and argue for the choice of methods
Natural science	NAT01-04	Vg1 NA	• explore a self-chosen research question relating to one's own education program, present findings and argue for the choice of methods • carry out risk assessment of one's own experiments and manage the resulting waste in a suitable manner • explore and present technology relating to one's own education program and assess it in a sustainability perspective • explain why some elements are important for life and assess how human activity can affect the cycles of these elements
English	ENG01-04	Vg1 Vocational	• read and summarize vocational content from English-language documentation • create texts relevant to the vocation with structure and coherence that describe and document the pupil's own work and are adapted to the purpose, recipient and situation • explore and reflect on diversity and social conditions in the English-speaking world based on historical contexts
VG2			
Chemistry	KJE01-02	Kjemi 1	• plan and carry out experiments, estimate uncertainty and assess the sources of error, present results and argue for the validity of results and conclusions

Subject	Subject code	Title	Competence objectives
			• use data, simulations and calculations when interpreting and drawing conclusions • make calculations with different units for concentration and use substance concentrations in assessments of water and air quality • explain the terms acid, base, protonolysis/protolysis and pH, and explore the properties of strong and weak acids and bases • explain the principles of green chemistry and discuss how using the principles can contribute to sustainable development
Biology	BIO01-02	Biologi 1	• plan and carry out surveys, collect, process and interpret data, and present results and findings
VG3			
Chemistry	KJE01-02	Kjemi 2	• understand and use chemical terminology and professional language in communication • plan and carry out experiments, discuss methods and measures to reduce risk and assess uncertainty and sources of error in personal and peer experiments • explore and calculate pH in water solutions and discuss the importance of buffers for regulating pH in natural and industrial processes • explore and make calculations of the solubility of substances and make assessments of solubility in biological and industrial processes • explore a theoretical or practical issue and discuss and present findings

The **water cycle**, also known as the hydrologic or hydrological cycle, describes the continuous movement of water on Earth in its different forms: liquid, solid and gas (see Figure 15). Water movement in aquaponics is essential for keeping plants and fish alive in the system, and new water must be supplied to replace the water evaporated and absorbed by plants. In *recirculating aquaculture systems (RAS)*, water is continuously recirculated through a mechanical filter that removes solids and passes through a biofilter which transforms ammonium compounds into nitrites and nitrates, and water is then pumped to the hydroponic system where it is used by plants, finally returning to the fish tank. Water moves in an aquaponic system through the RAS and sump such that the level of water in the fish tanks and hydroponic system remains undisturbed.

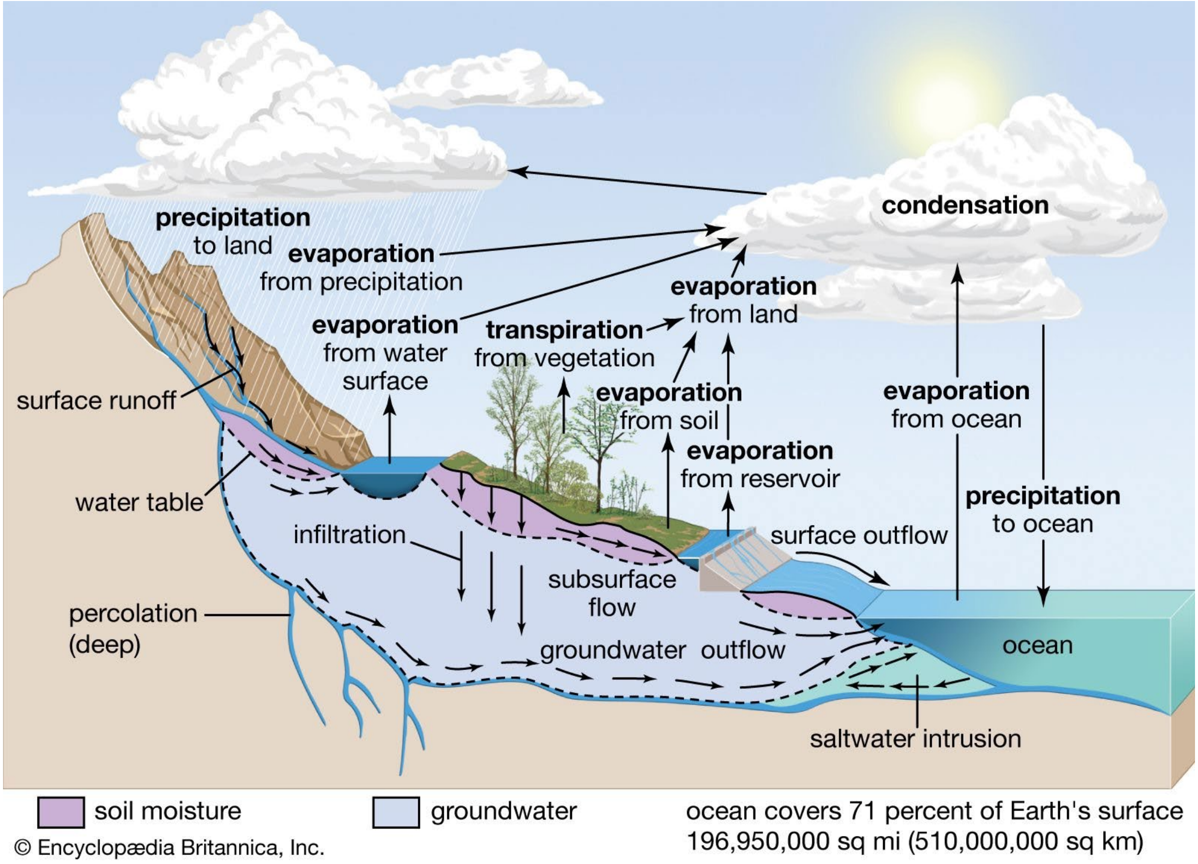


Figure 15. Hydrologic cycle (Encyclopædia Britannica).

The source and quality of water supplied to aquaponic systems is an important factor to consider for fish welfare (e.g., rainwater, tap water, surface water or groundwater). Synthetic materials such as PVC and PE should be used for valves and pipes in water distribution instead of material containing Nickel (Ni) or Copper (Cu) that can be harmful to fish due to the changing state of metals and their inability to be broken down (Maucieri et al., 2019). The five most important water quality parameters that impact fish, plants and bacteria include dissolved oxygen (DO), pH, temperature, total nitrogen, and water alkalinity (Somerville et al., 2014).

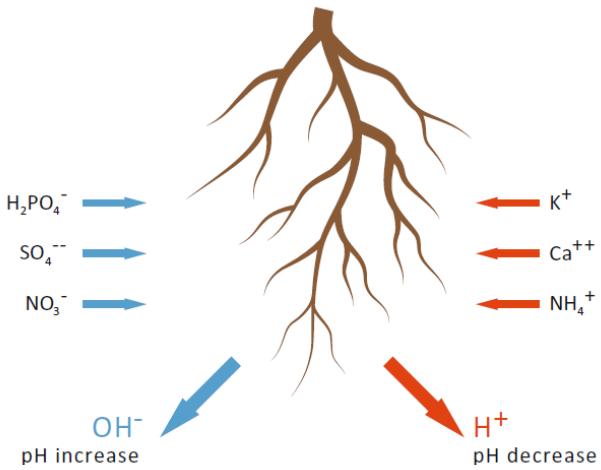


Figure 16. Ion absorption by the root system of a plant (Maucieri et al., 2019).

To maintain proper water quality, aeration using air pumps or injection of oxygen gas is essential. It is especially important during the summer because water temperature and DO have a relationship where warm water holds less oxygen than cold water, meaning that as temperature rises, the solubility of oxygen decreases (Somerville et al., 2014). As already mentioned in the module "Plant growth, health and development," the pH of water impacts a plants' ability to access *macro*- and *micronutrients*. The term pH is defined as the amount of hydrogen ions (H^+) in a solution, where an ion is an atom or molecule with positive or negative charge. Higher concentrations of H^+ results in a decrease of pH below 7 as shown in Figure 16. The concentration of hydrogen ions (H^+) in a solution indicates whether a solution is acidic, neutral or basic. Figure 17 shows the relationship between ammonia (NH_3) and ammonium (NH_4^+) in the water, depending on the pH. Supplements can be added to an aquaponic

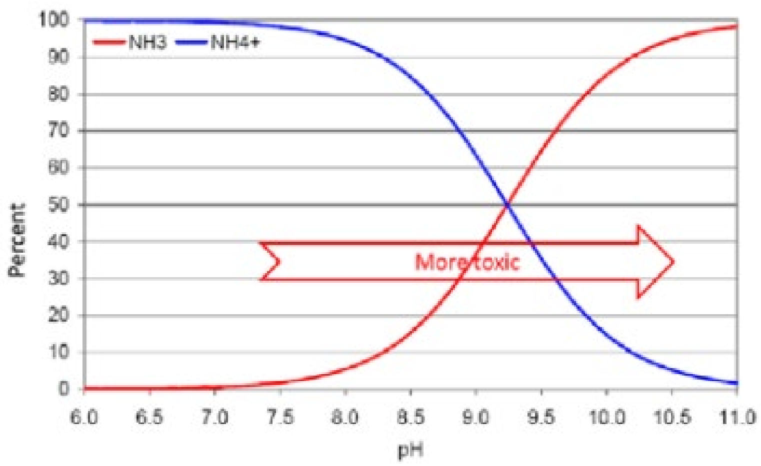


Figure 17. Relationship between ammonia (NH_3) and ammonium (NH_4^+) in water depending on the pH (Fjellheim et al., 2017).

system to adjust the pH, allowing plants to better take up nutrients. Adding supplements such as sodium bicarbonate ($NaHCO_3$) or potassium bicarbonate ($KHCO_3$) can be made to buffer and raise the pH.

Nitrogen initially enters an aquaponic system from fish feed and is released into the system through fish excrement in the form of **Total Ammonia Nitrogen (TAN)** or the sum of ammonia (NH_3) and ammonium (NH_4^+). TAN is either directly taken up by the plants or converted to nitrite (NO_2^-) and then nitrate (NO_3^-) before being taken up by plants. Higher pH and water temperature make ammonia more toxic to fish. The relative concentration of ammonia and ammonium depends mainly on pH, meaning that the pH generally determines whether a given TAN concentration is toxic or not (Fjellheim et al., 2017). See Figure 17 for the relationship between ammonia and ammonium in water and their relative toxicity. Table 21 shows the important water quality parameters to monitor and maintain the balance of an aquaponic system. Note that nitrogen products are essential for plant growth and enter an aquaponic system via fish feed.

Table 21. Important water quality parameters to monitor and maintain the balance of an aquaponic system (Fjellheim et al., 2017; Somerville et al., 2014). Note that biological parameters such as bacteria, algae and viruses also impact fish, plant health and nitrification, and are not shown in the table.

Parameter	Unit(s) of measurement	Relevance for aquaponic system
Physical		
Water level	meter (m)	Calculate water volume in fish and plant systems
Temperature	°C	Extremes and large variation in a short time impact fish and plant health and other parameters
Conductivity	(mS/cm)	Indicates the amount of ions in water (larger amounts increase buffering capacity)
Total suspended solids (TSS)	milligrams/litre (mg/l)	High amounts can lead to excess bacterial growth
Chemical		
pH	-	Decisive for the chemical state of compounds and their toxicity, and for fish and plants
Alkalinity	milliequivalents/litre (meq/l)	pH buffering capacity of water, must be added/maintained at adequate level
Dissolved oxygen (DO) Oxygen (O_2)	milligrams/litre (mg/l) %	Amount of oxygen in in the water; fish and plants require relative high levels in order to grow properly; nitrifying bacteria are dependent on oxygen to convert TAN and nitrite to be usable to plants
Total Ammonia Nitrogen (TAN) Ammonia (NH_3) Ammonium (NH_4^+)	- milligrams/litre (mg/l) total micrograms/litre (µg N/l)	Impacts fish health; the sum of ammonia and ammonium equals TAN; pH determines whether TAN concentration is toxic to fish (high pH and temperature means more ammonia and in turn means higher toxicity); adjusted through fish feed

Parameter	Unit(s) of measurement	Relevance for aquaponic system
Nitrite (NO_2^-)	total micrograms/litre (µg N/l)	Impacts fish health; accumulation of nitrite is normal in start-up period for a new biofilter; amount of oxygen in the water will affect nitrite toxicity; adjusted through fish feed
Nitrate (NO_3^-)	total micrograms/litre (µg N/l)	Impacts plant health and growth; least toxic nitrogen compounds
Carbon dioxide (CO_2)	milligrams/litre (mg/l)	Reduces capacity for fish to uptake oxygen and regulate pH

Table 22 shows guidelines for the optimal chemical requirements for fish cultivation in aquaponic systems, while Table 23 shows the recommended water quality parameters specifically for koi by the Norwegian Food Safety Authority (Mattilsynet).

Table 22. Water quality parameters for fish in land-based facilities with indicative threshold values and ranges for acceptable water quality given by the Norwegian Food Safety Authority (Fjellheim et al., 2017).

Parameter	Values
pH inlet	6.2 to 7.8
Oxygen saturation in the tank	Not over 100 per cent
Oxygen (drain)	More than 80 per cent
Total Gas Pressure (TGP) in the tank	Not over 100 per cent
Carbon dioxide	Less than 15 milligrams/litre
Aluminium (labile)	Less than 5 micrograms/litre
Aluminium (gills)	Not more than 15 micrograms/gram gill dry weight before transfer to sea
Nitrite (freshwater)	Less than 0.1 milligrams/litre
Nitrite (seawater)	Less than 0.5 milligrams/litre
Total Ammonia Nitrogen (TAN)	Less than 2 milligrams/litre
Ammonia (unionized)	Less than 2 micrograms/litre

Table 23. Recommended water quality parameters specifically for koi.

Parameter (unit)	Values	Comments
Temperature (°C)	15-20	Lives well at lower and higher temperatures, but should adapt to the plant species.
pH	6.8-7.5	Adjusted with potassium carbonate (K_2CO_3) or calcium carbonate ($CaCO_3$) which also adds important macronutrients to the plants.
Conductivity (mS/cm)	1.5-2.5	-
Alkalinity (mg $CaCO_3$/l)	50-100	Adjusted with potassium carbonate or calcium carbonate which also adds important macronutrients to the plants.
Oxygen (%)	70-100	Addition of air.
CO_2 (mg/l)	<15	Emitted out, taken up by the plants or converted into carbon trioxide (CO_3).
TAN (µg N/l)	<500	Converted in the biofilter or taken up by the plants.
NH_3 (µg N/l)	<10	The proportion is very dependent on pH.
NO_2 (µg N/l)	<250	Converted in the biofilter or taken up by the plants.
NO_3 (mg N/l)	20-60	Taken up by the plants or diluted with addition of new water.

The water quality and the amount of waste naturally produced will vary according to the amount of feed given, the design of the system, size of fish, monitoring, cleaning and disinfection routines, and the degree of water recycling (Hess-Erga et al., 2018). The degree of recycling in *recirculation aquaculture systems (RAS)* is important to define, as the complexity of the RAS increases with a higher degree of recycling. There are three different ways to calculate the degree of recycling (Fjellheim et al., 2017):

1) Recycling degree in %:

recycling rate = (water flow to the tank per hour / (new water per hour + flow to tank per hour)) x 100

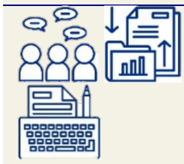
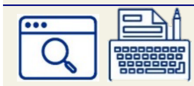
2) Replacement per day in %:

replacement per day = (supply of fresh water per day / total water volume in the system) x 100

3) Replacement per day per kg feed:

replacement / kg feed = supply of fresh water per day / daily feed consumption

Table 24. Examples of activities and discussion topics that connect aquaponics to water chemistry and quality.

Learning type	Activity
	• Draw a diagram showing the direction of water flow by observing the aquaponic system as an example or utilize online sources.
	• What are the similarities and differences between the water cycle in the environment and an aquaponic system? • What sort of materials can be used to build an aquaponic system? • What are the most relevant water quality parameters to monitor and maintain the balance of an aquaponic system? • How does an increase/decrease in pH impact the most important water quality parameters over time?
	• Monitor, measure and gather data on the water chemistry and quality in the aquaponic system using the templates provided in the "Appendix" of this CMS. Use this data to design reports with visuals and diagrams. Deliver reports to the next year including logged data sheets and reflections.
	• Develop a plan for managing any residual waste from the aquaponic system and implement this strategy when operating, monitoring and maintaining the system.
	• Use online sources to search for the components that make up the drinking water where you live and note any concentrations of macro- or micronutrients (Junge et al., 2020). Provide references. Note what impact any concentration(s) would have on aquaponic systems. • Write 500 words explaining why monitoring in aquaponics is important and include the parameters that are vital to monitor together with the frequency, the tests and methods that can be used, etc. (Junge et al., 2020). Provide references. • Use online sources to search for articles on aquaponics using different keywords around water chemistry and quality, download papers of interest and order them according to relevance or topic. Choose a topic of interest and write 500 words and provide references.

	• Consider different scenarios where an aquaponic system has low or high temperature, pH, oxygen, nitrate (NO_3^-), and nitrite (NO_2^-). Identify possible reasons, explain what would happen to the plants and fish, and propose a remediation plan.
	• Make calculations on the degree of recycling in *recirculation aquaculture systems (RAS)*:
	  ○ Recycling degree in %
	  ○ Replacement per day in %
	  ○ Replacement per day per kg feed

Learning type	Activity
	• Search curriculum plans from the Norwegian Directorate for Education and Training for varying subjects and write 500 words on how an aquaponic system could be integrated into the curriculum.

5.5 Urban farming

Teaching and learning about urban farming solutions such as aquaponics is more relevant than ever considering the growing demand for the world to feed itself, undermining of *food security* worldwide, and increase in global consumption of aquatic foods. Table 25 shows the competence objectives from varying subject curricula from the Norwegian Directorate for Education and Training for this module on urban farming. Table 26 shows examples of activities and discussion topics that connect aquaponics to urban farming.

Table 25. Competence objectives from varying subject curricula from the Norwegian Directorate for Education and Training for the teaching and learning module on urban farming.

Subject	Subject code	Title	Competence objectives
VG1			
Agriculture, fishing and forestry	NAB01-03	nature-based business activities	• discuss how nature-based products and services can be developed within the framework of sustainable development and resource management
Natural science	NAT01-04	Vg1 SF	• explore a self-chosen natural-science research question, present findings and argue for the choice of methods
Natural science	NAT01-04	Vg1 BA	• explore a self-chosen research question relating to one's own education program, present findings and argue for the choice of methods
Natural science	NAT01-04	Vg1 NA	• explore a self-chosen research question relating to one's own education program, present findings and argue for the choice of methods • explore and present technology relating to one's own education program and assess it in a sustainability perspective • explore issues related to land use, explain how changes can affect ecosystems and propose sustainable solutions
English	ENG01-04	Vg1 Vocational	• read and summarize vocational content from English-language documentation • create texts relevant to the vocation with structure and coherence that describe and document the pupil's own work and are adapted to the purpose, recipient and situation • explore and reflect on diversity and social conditions in the English-speaking world based on historical contexts
VG2			
Biology	BIO01-02	Biologi 1	• explore what consequences changes in climate and land use can have for biological diversity, and discuss measures for more sustainable management
VG3			
Chemistry	KJE01-02	Kjemi 2	• explore a theoretical or practical issue and discuss and present findings
Biology	BIO01-02	Biologi 2	• discuss how human activity affects life cycles and explore measures to protect them

Food systems consist of the actors and activities involved in the production, storage, aggregation, post-harvest handling, transport, processing, distribution, marketing, disposal and consumption of food of non-agricultural (e.g., synthetic meat) and agricultural (e.g., crops, livestock, forestry, fisheries, aquaculture) origin (FAO, 2021). Agrifood systems are broader than food systems and have three main components: 1) primary production; 2) food distribution, linking production to consumption through food supply chains and transport networks; and 3) household consumption (FAO, 2021). The relationship between food systems and agrifood systems is shown in Figure 18.

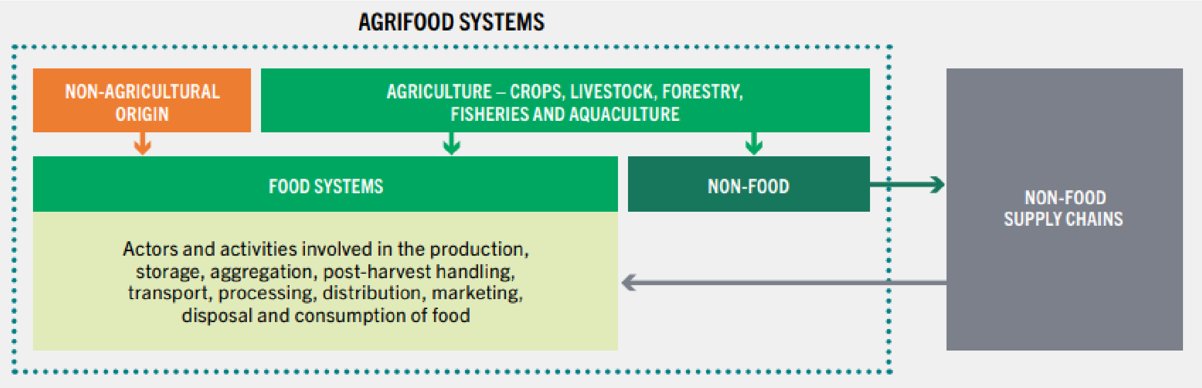


Figure 18. A conceptual framework for agrifood systems (FAO, 2021). Food of non-agricultural origin includes meat analogues produced through synthetic biology.

For decades, there has been a growing demand for the world to feed itself and meet its nutritional needs more sustainably and in harmony with the natural environment. Wars, COVID-19, climate change and growing inequality are converging to undermine *food security* worldwide (DESA, 2022). **Food security** is defined as physical and economic access to the kinds and amounts of nutritionally adequate foods at all times for each member of a household to meet dietary needs for an active and healthy life (Babu et al., 2014). Moderate to severe **food insecurity** has been rising since 2014, intensified by the COVID-19 pandemic, with over 800 million people now suffering from hunger and 2.4 billion people having severely limited access to adequate food (FAO, 2022). Aquatic foods offer highly accessible and affordable sources of animal proteins and micronutrients, and play a vital role in the food and nutrition security for people all over the globe (FAO, 2022). Annual per capita consumption of aquatic foods are projected to increase from 20.2 kg in 2020 to 21.4 kg in 2030, as a result of high demand due to rising incomes and *urbanization*, linked with the expansion of production, improvements in post-harvest operations and distribution and changes in dietary trends (FAO, 2022).

According to the Food and Agriculture Organization (FAO) 2022 Draft Guidelines for Sustainable Aquaculture (GSA), integrated agriculture-aquaculture (IAA) systems should be promoted through policy and institutional frameworks to create incentives, promote research and develop and multi-stakeholder partnerships to attract investment and develop markets. The GSA is projected to be published in 2024.

Aquaponic production produces food in a more sustainable manner without the addition of nutrients or synthetic fertilizers, use of pesticides, and by minimal use of chemical and antibiotic additives and reducing water consumption due to reuse. The main inputs that contribute to environmental impact in aquaponic systems are identified as system infrastructure and fish feed, and in cold climates, the energy consumed for heating the system, though each aquaponic system has its own unique impact on the environment (Greenfeld et al., 2022). Ensuring optimal growing conditions for plants and aquaponic fish can be highly energy intensive, thus environmental impact should be considered when supplying urban populations with locally grown food are more a sustainable and resource-efficient option (Junge et al., 2020).

Agriculture drives global land use change and impacts climate change by emitting global greenhouse gases (GHGs), threatening biodiversity loss and interfering with the nitrogen and phosphorus cycles through land clearing, crop production and fertilization (Tilman et al., 2011). Agriculture already accounts for 70 percent of total global freshwater withdrawals, making it the largest user of water along the entire agrofood supply chain to produce, transport and use all forms of energy required to produce, transport and distribute food as well as to extract, pump, lift, collect, transport and treat water (Flammini et al., 2014). The Water-Energy-Food Nexus shown in Figure 19 attempts to balance the interdependence of water, energy and food security and use of ecosystem resources (such as water, energy, land, soil and socio-economic factors) between human and natural systems.

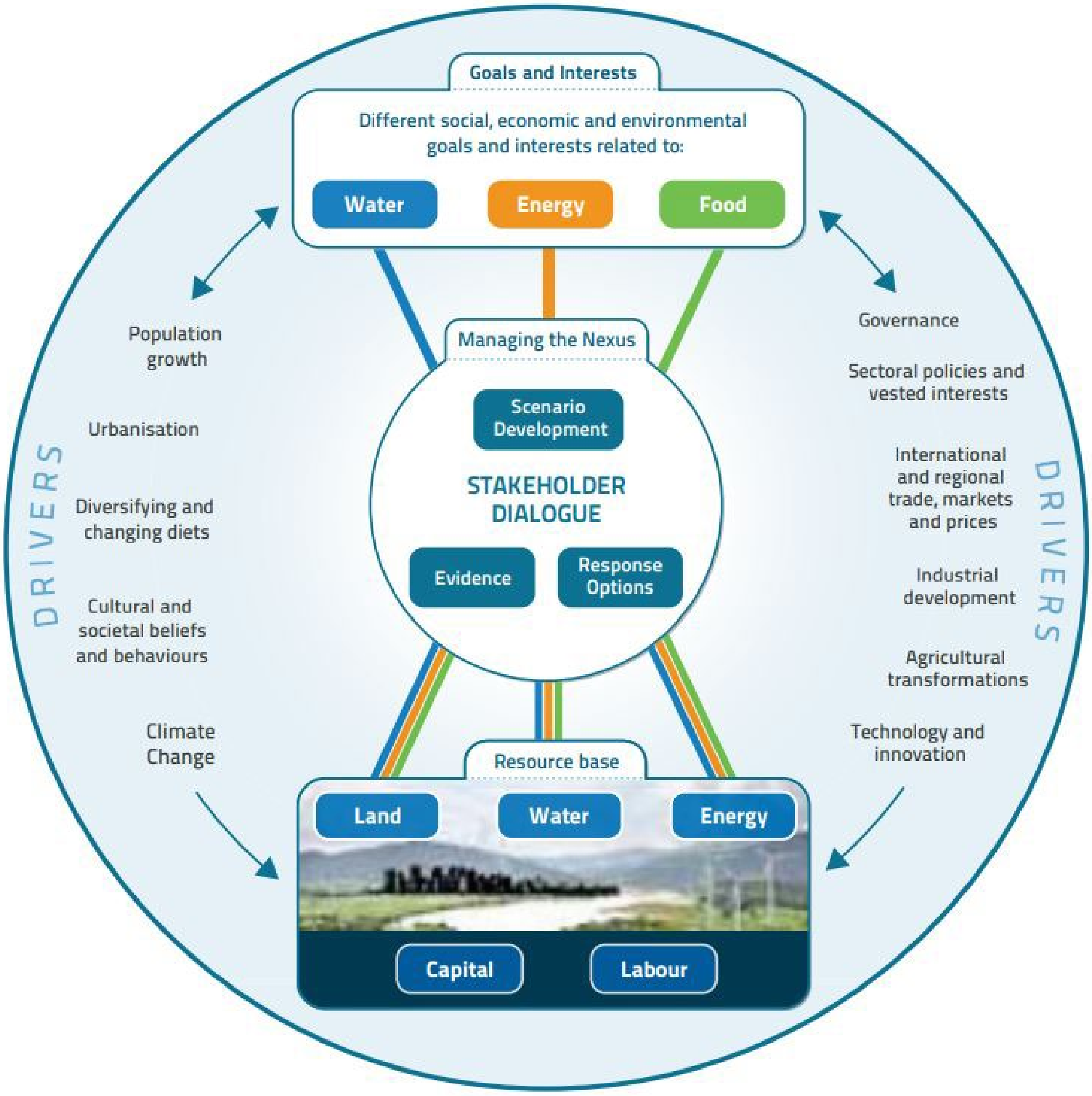


Figure 19. The FAO Approach to the Water-Energy-Food Nexus addressing interactions and feedback between human and natural systems (Flammini et al., 2014).

According to the UN, global demand for food has increased steadily and the world's population reached 8 billion people on 15 November 2022, increasing the likelihood of agricultural impacts on planetary boundaries. By 2050, an estimated 7 out of 10 people will likely live in urban areas (DESA, 2022), with a gradual shift in the human population moving from rural to urban areas, also called **urbanization**. This means that more people will be particularly vulnerable to food insecurity on account of them being almost completely dependent on produce imported from other regions far from where they live. (Milliken & Stander, 2019). An increased population implies an expansion of urban areas that demand more food, expanding the rift between production and consumption and the distance of food imports, while the expansion of local food markets in cities counteracts these effects (Sanyé Mengual, 2015). This is depicted in Figure 20. Expansion of *urban farming* means occupying otherwise empty sites such as vacant lots, existing rooftops, and underutilized warehouses that are affordable for an agricultural business (Proksch et al., 2019). The use of urban areas for food production promotes the *circular* *economy* through restorative solutions for nutrient and waste recycling, water reuse, and the potential for energy reuse through solar-powered design. **Urban farming** or agriculture includes farming activities taking place in and around a city's limits, with **peri-urban farming** situated on the fringe of a city and urban farming performed in a city. Rural agriculture is not performed in urban areas or cities, neither inside nor on the fringe. Urban farms can include non-profit gardens and for-profit businesses that can provide jobs and training, promote education, and can contribute to better nutrition and health for the community by providing locally grown, fresh products (Junge et al., 2020).

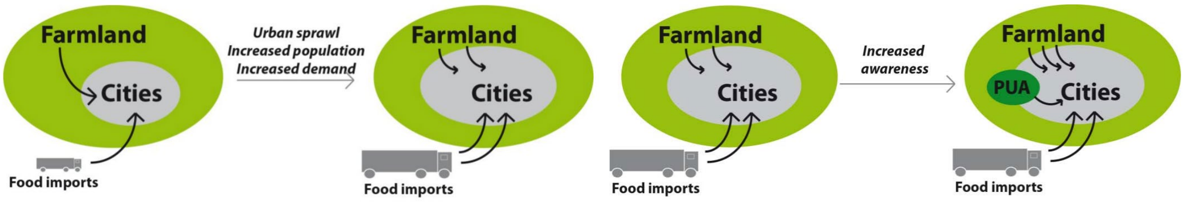


Figure 20. Food implications of urban expansion and revitalization of local produce, where PUA stands for peri-urban and urban (Sanyé Mengual, 2015).

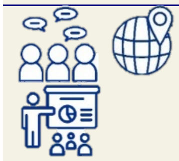
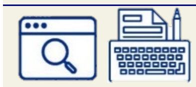
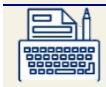
Global consumption of aquatic foods increased at an average annual rate of 3% from 1961 to 2019, and projections foresee an increase in the importance of farmed aquatic animals in global aquatic food consumption in the future (FAO, 2022). According to the FAO, societal changes, including higher incomes, greater female participation in the workforce, urbanization, and decreasing family sizes, have increased the use of convenient food products. This suggests that consumers in more advanced economies want healthy, sustainable, and convenient aquatic products. Suppliers have been able to access increasingly distant markets, while consumers have seen their aquatic food options greatly diversified beyond the species caught or farmed in local waters. At the same time, income growth, a larger middle class and urbanization, particularly in low- and middle-income countries, have caused aggregate demand for traded aquatic food products to increase considerably (FAO, 2022). Community participation and rebuilding relationships where people have power within the food system puts the aspirations and needs of those who produce, distribute and consume food at the heart of food systems and policies, rather than the demands of markets and corporations (Junge et al., 2020).

Benefits of aquaponics in urban settings (Proksch et al., 2019):

1. Human
    a. Growing consumer market with an interest in fresh, high-quality and locally grown produce
    b. Competitive pricing for plants grown in aquaponics
    c. Enhancement of economic viability with fish production
    d. Transport distance reduction to consumers
    e. Reduction of need for crop storage
2. Environmental
    a. Systems can utilize average higher temperature in urban versus rural areas
    b. Integration with building systems can utilize waste heat and CO_2 in exhaust air
    c. Mitigate urban heat island in summer
    d. Recirculating water infrastructure reduces overall water consumption
    e. Avoids production of agricultural run-off

Table 26. Examples of activities and discussion topics that connect aquaponics to urban farming.

Learning type	Activity
	• How does aquaponics play into the Water-Energy-Food Nexus? • What challenges global food security? *Increasing food demand, availability of agricultural land (due to soil degradation, nutrient depletion), water consumption.*

Learning type	Activity
	• What are the benefits of using aquaponic systems in urban areas? *Reliable production systems that supply fresh foods close to urban areas (Joyce et al., 2019), recycling of nutrients, recycling of water, prevention of disease transmission between farmed stocks and wild populations.* • Identify other examples of nature-based and sustainable products and/or services that can be developed or utilized in urban areas. • How does Norway's consumption and production of aquatic products compare to that of the rest of the world?
	• Walk around your respective neighborhoods to identify potential areas that could be utilized for an aquaponic system. It is important to keep in mind all the inputs and outputs of an aquaponic system. Note the geographical location, take photos and provide reasoning why this area was chosen. Bring all potential locations back to a group with classmates and peers for discussion and choose the best option to present in plenum. • Use online sources to find out 1) how soilless food production may impact financial equality in a society, 2) whether soilless food production provides more or fewer job opportunities than conventional soil-based food production. Based on your findings, discuss with classmates if soilless food cultivation is more or less beneficial with respect to social sustainability when compared with conventional agricultural methods using soil?
	• Use online sources to explore the challenges surrounding farming in urban areas and issues related to land use in urban areas. Write at least 500 words and provide references. • Use online sources to search for articles on aquaponics using different keywords around urban farming, download papers of interest and order them according to relevance or topic. Choose a topic of interest and write 500 words and provide references.
	• Identify potential stakeholders to finance a new aquaponic system and write a letter arguing why they should invest. Include plans for the system, a budget, and further reasoning to demonstrate the systems' relevance and the importance of their involvement. Potential stakeholders could include representatives of national or local governments, different farming associations, aquaponic system operators or manufacturers, etc.
	• Search curriculum plans from the Norwegian Directorate for Education and Training for varying subjects and write 500 words on how an aquaponic system could be integrated into the curriculum.

5.6 Economy and business operations

Aquaponic systems produce resources that can be bought and sold, and this module covers varying economy concepts, as well as a few fundamentals when starting a student-led business. Table 27 shows the competence objectives from varying subject curricula from the Norwegian Directorate for Education and Training for this module on Economy and business operations. Table 30 shows examples of activities and discussion topics that connect aquaponics to the economy and business operations.

Table 27. Competence objectives from varying subject curricula from the Norwegian Directorate for Education and Training for the teaching and learning module on economy and business operations.

Subject	Subject code	Title	Competence objectives
VG1			
Agriculture, fishing and forestry	NAB01-03	nature-based production and services	• carry out assignments along various parts of the value chain based on applicable rules and standards • make simple estimates for raw materials and material consumption, input factors and benefits
Agriculture, fishing and forestry	NAB01-03	nature-based business activities	• discuss how nature-based products and services can be developed within the framework of sustainable development and resource management
Natural science	NAT01-04	Vg1 SF	• explore a self-chosen natural-science research question, present findings and argue for the choice of methods
Natural science	NAT01-04	Vg1 BA	• explore a self-chosen research question relating to one's own education program, present findings and argue for the choice of methods
Natural science	NAT01-04	Vg1 NA	• explore a self-chosen research question relating to one's own education program, present findings and argue for the choice of methods • carry out risk assessment of one's own experiments and manage the resulting waste in a suitable manner • explore and present technology relating to one's own education program and assess it in a sustainability perspective
English	ENG01-04	Vg1 Vocational	• read and summarize vocational content from English-language documentation • create texts relevant to the vocation with structure and coherence that describe and document the pupil's own work and are adapted to the purpose, recipient and situation • explore and reflect on diversity and social conditions in the English-speaking world based on historical contexts
Mathematics P	MAT08-01	1P-Y NA	• read, use and create spreadsheets when working with budgets, bids and cost calculations related to Agriculture, Fishing and Forestry, and evaluate how different factors affect the result
VG2			
Agriculture and horticulture	LGA02-03	produksjon og tjenesteyting	• assess the quality and profitability of nature-based productions according to current certification schemes for product quality and the environment

Subject	Subject code	Title	Competence objectives
Agriculture and horticulture	LGA02-03	forvaltning og drift	• prepare a product or service for sale and provide an account of the forms of sales and turnover in agriculture and horticulture • describe key elements for good financial and operational management in agriculture and horticulture and identify the most important key figures for such companies
VG3			
Chemistry	KJE01-02	Kjemi 2	• explore a theoretical or practical issue and discuss and present findings
Biology	BIO01-02	Biologi 2	• discuss how human activity affects life cycles and explore measures to protect them

All economies are dependent on *natural resources* which are limited by the *planetary boundaries* (as defined in the module "Sustainability"). Aquaponic systems have the potential to impact the planetary boundaries surrounding climate change, the nitrogen and phosphorus cycles, water usage, and changes in land usage. An economist, as well as others responsible for the business operations of an aquaponics system, needs to understand the availability of natural resources to be able to plan a resource supply strategy and to decide which biomass resource is best suited for a specific biobased product chain and how these product chains can be optimized (Zörb et al., 2018). A **value chain** describes the full range of activities required to bring a product or service from conception through different phases of production, to delivery to final consumers, and final disposal after use (Zörb et al., 2018). Value chains start with the extraction or production of raw material, followed by logistics to transport and processing, then continues with each following intermediate product until the final product is reached, marketed and sold to the customer (Zörb et al., 2018).

There are varying economy concept approaches to encourage, adapt to or transform the current economy towards the three pillars of sustainability: society, economy, and environment. Table 28 outlines the economy concepts that have been gaining popularity in recent decades and can be defined from a number of different perspectives. The International Organization for Standardization (ISO) develops and publishes standardization in varying fields, and in 2018 established the ongoing ISO/FDIS 59004 to define terminology, principles, and guidance for implementation of the *circular economy* (Nobre & Tavares, 2021). Despite its ongoing interpretation, the **circular economy** can be defined as an economic system that targets zero waste and pollution throughout materials lifecycles, from environment extraction to industrial transformation, and to final consumers, applying to all involved ecosystems, where materials return to processes or the environment (Nobre & Tavares, 2021). The **bioeconomy** links to all economic activities developing and using biological products and processes and is the sustainable and innovative use of *biomass* and biological knowledge to provide food, feed, industrial products, bioenergy, and ecological and other services (Lewandowski et al., 2018; Loiseau et al., 2016). The **green economy** is an umbrella term guided by environmental principles that encompass different implications with regard to growth and well-being or efficiency and risk reduction in the use of natural resources (Loiseau et al., 2016). The circular

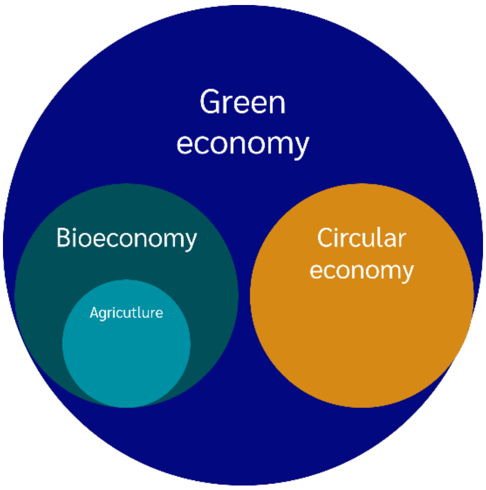


Figure 21. Example of how agriculture fits into the economy concepts (adapted from Birner, 2018; UNECE, 2018).

economy and bioeconomy are both centered around resources, while the green economy addresses natural processes (D'Amato et al., 2017). From another perspective, the bioeconomy can be seen as addressing the *biomass*-based sectors of a green economy, while the circular economy is concerned with the more abiotic-based sectors of a green economy, such as industry and manufacturing (UNECE, 2018). Figure 21 shows an example of how agriculture is arranged in the economy concepts.

According to the EU, **biomass** is defined as the biodegradable fraction of products, waste and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin (European Parliament, 2018). However, biomass changes as organisms interact with each other and with their *abiotic* environment, so this biological definition can be simplified to organic matter derived from living or recently living organisms (Zörb et al., 2018). Biomass can be used for energy for heating, generating electricity, and transport fuels as bioenergy. Bioenergy helps to reduce greenhouse gas emissions by lowering energy dependence on nonrenewable resources. Other types of renewable energy such as solar panels would add onto an aquaponic systems' sustainability, as energy is essential for heating, cooling, lighting, and pumping water.

Table 28. Main aspects included in circular economy, green economy and bioeconomy concepts in regard to the social and environmental dimensions of sustainability (D'Amato et al., 2017).

Concepts	Sustainability dimensions	
	Environmental	Social
Circular economy	Recovery and recycling, extended product lifetime, servitization, industrial symbiosis, circular and efficient supply chains, sustainable consumption	Job creation, social inclusion, consumer empowerment, innovation
Green economy	Conservation, water, land, biodiversity, food, security	Sustainable development; green investments, tourism, business, employment, education
Bioeconomy	Biosecurity, crops, species, risk, yield, invasive	Rural policies; research and applications in health science

Here we define an **entrepreneur** as a person who sets up a business with the aim of creating sustainable value for themselves and society in addition to making a profit. Entrepreneurs identify problems and discover solutions that create value while also adhering to the regulatory frameworks that surround business activities. Regulatory frameworks can include the taxes and permits needed in addition to any environmental requirements to start a business. Figure 22 shows an example of the phases that can be/are usually involved in creating a business. The startup phase involves identifying needs or problems and coming up with solutions that create value. In idea development it is important to ensure that the ideas are solutions to the needs or problems identified that focus on the target audience or stakeholders. The establishment phase involves defining branding and roles within the business to ensure strong internal processes. In the operation phase, solutions can be tested, and it is important to set up a timeline and budget. Profits are distributed during liquidation and reflections on what was learned should be performed.

Figure 22. Phases when creating a business (Entreprenørskap, 2022).

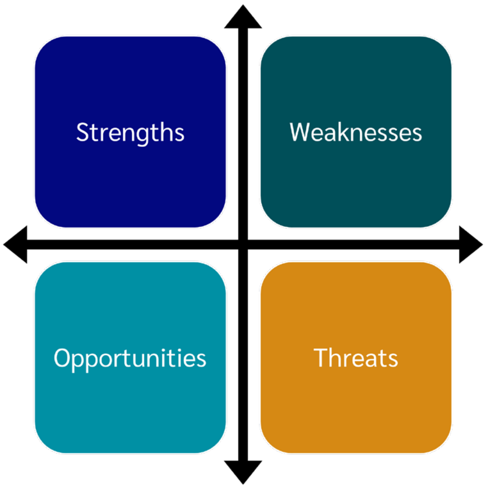


Figure 23. Depiction of a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis.

When focusing on delivery of final products or services to consumers, knowledge of public relations and market acceptance is key in understanding value creation. One tool entrepreneurs can use to evaluate internal capabilities and position their business on the market is the SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis shown in Figure 23. For understanding the external factors that can impact a business, a PESTLE analysis can be used to examine the political, economic, social, technological, legal, and environmental factors. Note that other variations for this analysis can be PESTEL, where legal and environmental factors are swapped and/or PESTELE, where ethical factors are also considered. An example of a PESTLE analysis related to the aquaponics industry is shown in Table 29. Such analysis is often used in commercial organizations as a part of the strategic development of business and marketing plans, as well as a part of considering the external factors in a SWOT analysis. To find further information on these factors, investigate websites and databases from government sources, news and media platforms, industry, research, as well as financial and corporate social responsibility reports and patents.

Table 29. PESTLE analysis with examples connected to the aquaponics industry. An assessment can be made whether each of these factors influence the business in a positive or negative way.

Political	Economical	Social	Technological	Legal	Environment
Government regulations and policies (e.g., water usage regulations and agricultural subsidies)	Impact on the industry from factors such as inflation, economic growth, and consumer spending	Consumer preferences and demographics can provide insights into the market for aquaponic related products	Impact of technological advancements in aquaponics systems (e.g., digitalization of monitoring systems)	Regulations related to animal health, food safety, environment and labor	Impact of climate and climate change and sustainability initiatives

Central to establishing a successful business is establishing a viable and sustainable business model. A business model describes how to create, deliver, and capture value back from your customers (Osterwalder & Pigneur, 2010). This can be explored and iterated by using the business model canvas tool developed by Strategyzer as shown in Figure 24.

Setting up a **budget** is essential in starting a business and estimating the cost needed to establish, build and install, as well as operate, monitor and maintain an aquaponic system. Identifying all of the varying components needed to build an aquaponic system and their costs is necessary when setting up a budget. Components can include fish tanks, grow beds, grow lights, water and air pumps, tubing and pipes, heating, cooling, a filtration system, a monitoring system, and timers and controllers. Identifying other materials needed to operate an aquaponic system is also important and can include water quality test kits, fish feed, gardening supplies, seeds, and fish. Other intangible costs include water supply and electricity. Once all costs are accounted for, it is crucial to track expenses and spending to have an understanding of the actual costs to set realistic goals for future costs and make adjustments. Reviewing a budget regularly is also essential to ensure that the initial business plan for an aquaponic system remains on track.

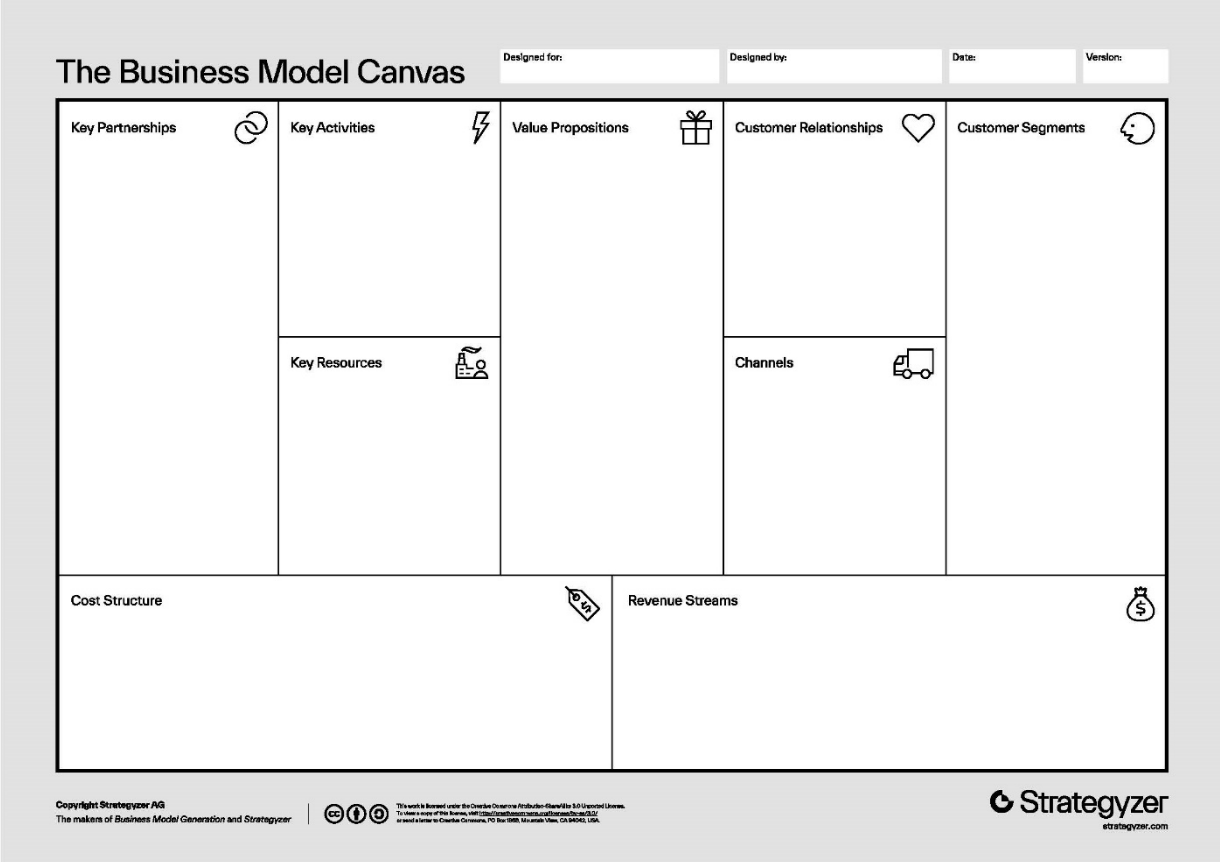
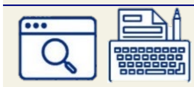
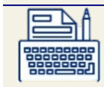


Figure 24. Strategyzer business model canvas tool (Strategyzer, 2023).

Table 30. Examples of activities and discussion topics that connect aquaponics to the economy and business operations.

Learning type	Activity
	• Draw diagrams of aquaponic systems showing water and nutrient recycling. Share the diagrams in a group with classmates and peers for discussion and choose the best option to present in plenum. • Draw a poster designing the marketing strategy for an aquaponic system and prepare an oral presentation describing the poster as if it were a visitor workshop.
	• How can natural resources be utilized efficiently in aquaponics? • How can a growing bioeconomy help meet global challenges in terms of energy and food production? • How would a biologist, chemist and technologist define the term *biomass* respectively? • What are the key elements for good financial and operational management in agriculture and horticulture? • What processes and inputs should be considered when calculating the total cost of an aquaponic system? • What are different renewable energy solutions appropriate for aquaponics? • Assume roles of different aquaponic industry stakeholders to understand market challenges.

Learning type	Activity
	• Perform a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis to evaluate internal capabilities and market positioning of a business idea surrounding aquaponics. • Conduct a PESTLE (political, economic, social, technological, legal, and environmental) analysis to understand the external environment of a business idea surrounding aquaponics. • Watch the YouTube Video “Business Model Canvas Explained” by Strategyzer to better understand how to use their business model canvas tool: https://www.youtube.com/watch?v=QoAOzMTLP5s. Explore different business models for an aquaponic system.
	• Consider the products from an aquaponic system from the perspective of an economist following the products’ value chain. Compare the value chain of aquaponic products with the value chain of similar products at your local grocery store. How does the distance from production to consumption differ? Prepare to present to the rest of the class, use relevant terminology. • Develop a concept for a commercial aquaponic business selling fresh local products by identifying the following: any competitors, local legislation, the type of system, plants and fish, location, and target customers. Prepare to present your business to the rest of the class, use relevant terminology. Additional activity: Perform a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis to evaluate internal capabilities and market positioning for the aquaponics business. • Explore potential customer bases for aquaponic products. Present findings on customer demographics and preferences.
	• An increasing number of countries have adopted bioeconomy strategies or policies. Use online sources to gain a better understanding of Norway’s bioeconomy strategy. Establish the natural conditions, labor resources, knowledge resources, capital resources and infrastructure for the Norwegian bioeconomy strategy. Provide references. • Use online sources to search for any regulations surrounding the labelling of food products in Norway. Provide references. Additional activity: Think about what measures would need to be taken to sell products from an aquaponic system. • Use online sources to search for any regulations surrounding organic food products in Norway. Provide references. Additional activity: Think about what measures would need to be taken to sell organic products from an aquaponic system. • The term *biomass* is defined as the biodegradable fraction of products, waste and residues of biological origin from agriculture, forestry and related industries in this module. Compare this definition with the definition in the module “Animal welfare” and use online sources explore how communication differs across disciplines. Write 250 words and provide references. • Use online sources to search for articles on aquaponics using different keywords around energy, the economy and communications, download papers of interest and order them according to relevance or topic. Choose a topic of interest and write 500 words and provide references.
	• Identify potential stakeholders to finance a new aquaponic system and write a letter arguing why they should invest. Include plans for the system, a budget, and further reasoning to demonstrate the systems’ relevance and the importance of their involvement. Potential stakeholders could include representatives of national or local governments, different farming associations, aquaponic system operators or manufacturers, etc.

Learning type	Activity
	• Develop a marketing plan for aquaponics products. Cover components such as target audience, unique selling proposition, pricing and budgeting, marketing goals, marketing strategies (including channels and tactics), and an evaluation plan. Reflect on ethical branding and advertising.
	• Calculate the cost of maintaining an aquaponic system by setting up a budget.
	• Search curriculum plans from the Norwegian Directorate for Education and Training for varying subjects and write 500 words on how an aquaponic system could be integrated into the curriculum.

6 Resources

6.1 Norwegian National Curriculum

The Norwegian Directorate for Education and Training Competence Objectives:
https://sokeresultat.udir.no/finn-lareplan.html?fltypefiltermulti=Kunnskapsl%C3%B8ftet%202020&filtervalues=all

6.2 Lesson plans and inspiration

AQU@TEACH Aquaponics Curriculum and Textbook: https://aquateach.wordpress.com/curriculum/

Facebook group for those teaching natural science in Norway (Naturfagdidaktikk):
https://www.facebook.com/groups/725754897485234/

KlimaSkolen (in Norwegian): https://www.klimaskolen.no/

Map of nearly all known aquaponics facilities in Europe:
https://www.google.com/maps/d/u/0/viewer?ll=35.352940376586105%2C0.4574513507217155&z=4&mid=1bjUUbCtUfE_BCgaAf7AbmxyCpT0

Naturfagsenteret (in Norwegian): https://www.naturfagsenteret.no/

Norwegian Digital Learning Arena (in Norwegian): https://ndla.no/subject:1:f2e831f5-2365-4ac8-bfce-4fc38323d91b/topic:7:1c484b3e-7f3d-4a81-8c24-c8ffc95d421d/resource:b9c7439c-c6a0-41d8-b38b-0dccdcc9d69a

Skolerom (in Norwegian and requires registration): https://skolerom.no/

Spire Skoleportal (in Norwegian): https://skoleportal.spireorg.no/

Ungt Entreprenørskap (in Norwegian and requires registration): https://portal.ue.no/logg-inn

6.3 Podcasts

NRK Radio Ekko – Akvaponi - planter elsker fiskebæsj! (in Norwegian):
https://radio.nrk.no/podkast/ekko_-_et_aktuelt_samfunnsprogram

6.4 Videos

EU Aquaponics Hub networking action YouTube page – Realising Sustainable Integrated Fish and Vegetable Production for the EU: https://www.youtube.com/EUAquaponicsHub

OECD Trade and Agriculture – Making Better Policies for Food Systems: https://youtu.be/poaxeoVVwMs

Project AQUAROM E-learning course: https://www.zhaw.ch/en/lsfm/institutes-centres/iunr/ecotechnologies-and-energy-systems/ecotechnology/food-products/aquaponic/aquarom/

6.5 Glossary

Section/module	Relevant term	Definition
What is aquaponics?	Aquaponics	Combination of hydroponics and aquaculture in a closed loop system
Basics of aquaponics	Aquaculture	Breeding, rearing, and harvesting of aquatic plants and animals in all types of water environments
	Hydroponics	Plant cultivation in water without soil
	Recirculating/recirculation aquaculture systems (RAS)	Systems that treat and recycle water for fish production
Sustainability	Natural resources	Resources derived from the natural environment that include biotic resources from living organisms and organic material and abiotic organisms from nonliving and inorganic material
	Planetary boundaries	Framework to describe limits or the safe operating space of human activities on the nine Earth-system processes
	Sustainability	Ensuring that the needs of the present are met without compromising the ability of future generations to meet their own needs
	Threshold	Level at which something coming into effect or the amount of pressure or changes of key variables in an environment at which the tipping point of an ecosystem shifting to a new unfavorable state becomes unavoidable
	Tipping point	Point at which a series of small changes of key variables becomes significant enough to cause a larger, more significant change
Plant growth, health and development	Macronutrients	Chemical elements required in large amounts that provide energy to maintain fundamental functions for living organisms
	Metabolism	Series of chemical reactions that convert energy in the cells of living organisms
	Micronutrients	Chemical elements needed in smaller amounts for normal growth and development of living organisms
	Nitrification	Biological transformation of ammonia to nitrite and nitrite to nitrate
	Photosynthesis	Process where plants take up light, water and carbon dioxide to produce oxygen and energy
Animal welfare	Abiotic	Nonliving and nonorganic
	Biomass	Total quantity or weight of organisms in a given area or volume
	Biotic	Living and organic
	Stocking density	Number of individuals placed in a given unit of area
	Stress	Pressure, strain or tension
Water chemistry and quality	Total Ammonia Nitrogen (TAN)	Sum of ammonia and ammonium
	Water cycle	Continuous movement of water on Earth between Earth’s oceans, atmosphere, and land as a liquid, solid and gas
Urban farming	Food insecurity	When a person lacks regular access to enough safe and nutritious food for normal growth and development and an active and healthy life
	Food security	Physical and economic access to the kinds and amounts of nutritionally adequate foods at all times for each

Section/module	Relevant term	Definition
		member of a household to meet dietary needs for an active and healthy life
	Peri-urban farming	Agricultural activities situated on the fringe of a city
	Urban farming	Agricultural activities taking place in a city
	Urbanization	Population moving from rural to urban areas
Economy and business operations	Bioeconomy	Sustainable and innovative use of biomass and biological knowledge to provide food, feed, industrial products, bioenergy, ecological and other services
	Biomass	Biodegradable fraction of products, waste and residues of biological origin from agriculture, forestry and related industries
	Budget	Estimate of income and costs for a set period of time
	Circular economy	An economic system that targets zero waste and pollution throughout materials lifecycles, from environment extraction to industrial transformation, and to final consumers, applying to all involved ecosystems, where materials return to processes or the environment
	Entrepreneur	Person who sets up a business in the aim of creating sustainable value for themselves and society in addition to making a profit
	Green economy	Umbrella term guided by environmental principles that encompass different implications with regard to growth and well-being or efficiency and risk reduction in the use of natural resources
	Value chain	The full range of activities required to bring a product or service from conception to production and delivery to final consumers and to eventual final disposal after use

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8 Appendix

Templates ready to print and use in the classroom for a contact list, daily monitoring of species growth and health, and water chemistry and quality in aquaponic systems.

Contact list for the aquaponic system

Main point of contact:	
Name	
Telephone	
Email	
Role	
Organization	
Responsible for operations:	
Name	
Telephone	
Email	
Role	
Organization	
Responsible for daily care and monitoring:	
Name	
Telephone	
Email	
Role	
Organization	
Aquaponic system supplier:	
Name	
Telephone	
Email	
Role	
Organization	
Other:	
Name	
Telephone	
Email	
Role	
Organization	

Species growth and health status of the aquaponic system

Fish / Plant:	Species:

Date	Fish / Plant	Wet weight (g)	Length / Height (cm)	External observation(s)	Gills / Deficiency or disease	Initials	Comments

Monitoring water chemistry and quality of the aquaponic system

Fish tank / Plant system / Other:	Species:	Start date:	Start number:	Weight:

Date	Temp (°C)	pH	DO (mg/l)	O_2 (%)	Condt (mS/cm)	NH_4^+ (µg N/l)	NO_2^- (µg N/l)	NO_3^- (µg N/l)	Feed (g)	Died (total)	Initials	Comments (behavior, deviations, etc.)