CIRCULAR ECONOMY FOR BREWERIES

Utilising brewery wastewater for growing hydroponics hops

Lappeenranta–Lahti University of Technology LUT

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ABSTRACT

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This research is a novel approach to finding solutions for breweries to move towards sustainability by recovering nutrients from their wastewater to produce organic liquid fertilisers for growing hydroponics hop plants that can yield dry hops demand necessary for their beer production. Hops is one of the main ingredients used in beer production that determines the quality of beer and brewers usually use dry hops in the brewing process. The assessment done in this research is the first of its kind for the brewery industries, no previous research about it has been done earlier. The potentiality of three Finnish breweries' (Hartwall, Sinebrychoff, and Laitilan) wastewater has been evaluated in this thesis by conducting research on nutrient availability in the breweries' wastewater and assessing if those nutrients are sufficient for producing organic liquid fertiliser to grow hydroponics hop plants in a large scale.

The findings of this research show that when the dry hops use is in small quantity, for example, 2 g/L of beer produced, then most of the nutrient quantity in breweries' wastewater is sufficient to produce annual dry hops demand for beer production. For example, in the case of Hartwall brewery, when the dry hops use is 2 g/L of beer produced, the necessity of buying artificial N, P, and Zn fertilisers can be replaced by about 74%, 156%, and 230% respectively. But when the dry hops use is 12 g/L of beer produced, the replacement of artificial N, P, and Zn fertilisers are about 12%, 26%, and 38% respectively.

The environmental benefits that can be achieved by the recovery of nutrients from the brewer's wastewater are reduction in carbon footprint by less CO_2e emissions of about 400 to 146 000 kg CO_2e, that will otherwise be emitted by the application of artificial N and P fertilisers to produce hops; about 95% of less demand of land area by land use change from soil-based hops farm to hydroponics hops farm; fewer GHG emission by becoming self-reliant in hops and fertilisers demand; reduction in spillage of fertilisers into the sea due to fewer shipment of them, thus less contribution towards the eutrophication of the sea, such as Baltic Sea; reduction in water footprint by reusing treated wastewater that is generated after production of organic liquid fertiliser; and preservation of non-renewable resources of fertilisers such as phosphate rock. Simultaneously, breweries will be profited economically by becoming self-sufficient in the dry hops demand to meet their beer production.

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SYMBOLS AND ABBREVIATIONS

Symbols

As	Arsenic
B	Boron
cm	centimeter
Ca	Calcium
Cd	Cadmium
Cl	Chlorine
Cr VI	Hexavalent chromium
Cu	Copper
d	day
Fe	Iron
g	gram
h	hour
hL	hector litre
Hg	Mercury
kg	kilogram
L	litre
mg	milligram
mL	millilitre
Mg	Magnesium
Mo	Molybdenum
Mn	Manganese
m	meter
m^2	square meter
mS	millisiemens
N	Nitrogen
NPK	Nitrogen, Phosphorus, Potassium
Ni	Nickel
P	Phosphorus
Pb	Lead

S	Sulphur
t	tonnes
Zn	Zinc

Abbreviations

°C	Degree Centigrade
Agritech	Agricultural Technology
BOD	Biological Oxygen Demand
BOD_{7atu}	Biological Oxygen Demand (subscript 7 refers to the incubation time of 7 days)
$C_2H_5N_3O_2$	Biuret
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
COD	Chemical Oxygen Demand
COD_{Cr}	Chemical Oxygen Demand (subscript Cr refers to oxidation by dichromate)
CIP	Cleaning in Place
EC	Electrical Conductivity
EU	European Union
FIWA	Finnish Water Utilities Association
GHG	Green House Gas
GWh	Gigawatt-hour
HELCOM	Baltic Marine Environment Protection Commission, Helsinki Commission
kWh	Kilowatt-hour
LCA	Lifecycle Assessment
LUC	Land Use change
NA	Not Available
NTUs	Nephelometric Turbidity Units
pH	Potential of Hydrogen
PAHs	Polycyclic Aromatic Hydrocarbons
ppm	Parts per Million

SDGs	Sustainable Development Goals
SG	Spent Grains
SP	Spent Hops
SY	Spent Yeasts
TDS	Total Dissolved Solids
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TOC	Total Organic Carbon
TS	Total Solids
TSS	Total Suspended Solids
TP	Total Phosphorus
USA	United States of America
VFA	Volatile fatty acids
WW	Wastewater
WWTP	Wastewater Treatment Plant

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1. Introduction

Beer is known since ancient times as a fermented drink (Rachwał et al. 2020). It is the fifth most consumed beverage in the world after tea, carbonates, milk, and coffee with an average consumption of 23 litres (L) per person per year. Modern brewing is mainly a large-scale industry. The world's 10 largest brewing groups shared almost 50% of the world's production and they have a production capacity of million hectolitres (hL) per year. However, microbrewery has an annual production of close to 1 000 hL. (Fillaudeau et al. 2006) Global beer production exceeded 1.94 billion hL in 2018, which makes the brewing industry one of the significant economic industries. It is a profitable source for an economy with huge annual revenues for many countries around the world. (Rachwał et al. 2020)

In the current scenario of the climate crisis, the world has united to mitigate climate change. Different policies and regulations have already been implemented by many countries and organizations to meet the climate target. Sustainable Development Goals (SDGs) set by United Nations are one example of it. Finland also aims to be the world's first fossil-free welfare society by passing the most ambitious climate target into law to reach net zero emissions by 2035 (Ympäristöministeriö 2022). To move under the climate law or meet climate targets, most industries are obliged to change their unsustainable work practice in a sustainable direction. Brewing industries cannot be excluded from it.

There is an existing challenge to manage the wastes generated by the brewery. Large-scale brewery generates substantial amounts of beer and by-products. The side streams from the brewery are mostly organic solid wastes and wastewater (WW). The organic wastes and the residues in the WW from the brewery have high resource value and are potential sources of nutrients that can be used for plants, animals, and humans as well. For example, nutrients present in WW of breweries such as nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), and others can be recycled to make fertilisers that can be used for plant production. Other nutrients and vitamins such as vitamin D_2 derived from Brewer's spent yeast (BSY) are a source of vitamin D, which can be applied as a dietary supplement for food products. In most cases, WW from breweries is disposed to the sewerage system after a simple pre-treatment process or without any treatment, and consequently, a high value of nutrients and resources are lost. (Rachwał et al. 2020)

The topic of this thesis is important because it can play an indispensable role to move brewery industries towards a sustainable path by capturing the valuable nutrients from their WW and concurrently supporting them to become self-sufficient for beer production by producing their hops. Hops is one of the main ingredients used in beer production that determines the qualities of beer (Keukeleire 2000). The HydroHumala pilot experiment research was conducted by Finnish biotech company Redono Oy at Urban Farm Lab, Vantaa, Finland in 2019, in collaboration with the City of Vantaa, to find different properties of demand for growing indoor hydroponics hops. Based on that experiment two thesis studies were conducted previously. One thesis examined the amount and concentration of the nutrients needed to grow hydroponics hop plants. Another thesis examined the conditions, i.e., the amount of water, energy, and fertilisers needed to grow indoor hydroponics hop plants. From these previous studies, the required quantity of different nutrients with their concentration and other properties demand to grow indoor hydroponics hop plants are known. Further, the total amount of dry hops yield from the planted hop rhizomes is known. This thesis is the continuous research of the HydoHumala pilot experiment.

1.1. Nutrients recycling and circular economy

The circular economy (CE) is regarded as a systems solution framework to tackle global challenges such as climate change, biodiversity loss, waste, and pollution. In the CE model waste being produced is stopped by circulating the materials, unlike linear economy model where the materials are taken from the Earth to make products and eventually discarded as waste. (Ellen Macarthur Foundation 2022)

Recycling of nutrients has become an integrated part of CE, for example in the European Union (EU), which aims to limit or avoid the production of waste through the reuse or recycling of secondary raw materials. The EU action plan for the CE includes policies for waste management, such as legislative proposals on waste and landfills, and proposed changes to extended lifetime of products, remanufacture, or recycling. (European Commission 2015) This policy fits well with recovering residual organic materials for producing fertilisers. In this context, breweries' WW has significance since nutrients such as N and P composition in them can be recycled. Reducing waste and pollution by recycling and through efficient exploitation of renewable resources fits with the concept of a circular and bioeconomy and is also the general interest of organic farming (Løes and Adler 2019).

1.1. Research problem, objectives, research questions, and limitations

The problem of most conventional breweries is that they have unsustainable WW management practices. They mostly discard their WW directly to the sewerage system neglecting the high resource value capacity of WW. The disposal of WW with high nutrient loads poses the risk of polluting water sources. Moreover, when nutrients released from the brewery are not recycled, there is always extraction of raw material resources which poses the risk of depletion of non-renewable resources such as phosphate rock, a resource of phosphorus. Concurrently, carbon dioxide equivalent (CO_2e) emissions continue to rise during the extraction and in the processing of nutrients to make artificial fertilisers such as NPK fertilisers. The use of freshwater also continues to grow if WW is not recycled. Implementing the circular economy (CE) model plays a significant role in moving towards sustainability and mitigating climate change. Recycling WW from breweries is a CE approach for breweries to move towards sustainability.

Until now there are no previous studies conducted on the effective utilisation of nutrients available in the brewery WW to produce liquid fertilisers which are suitable to grow indoor hydroponics hop plants that can yield dry hops demand necessary for their beer production. Hops is one of the main ingredients used in beer production and brewers usually use dry hops in the brewing process. This research is a novel approach to finding solutions for breweries to move towards sustainability by recovering nutrients from their WW and becoming self-sustained for the dry hops demand to meet their beer production. The objective of this thesis work is to provide innovative, sustainable, and efficient solutions for the WW management in conventional breweries, and simultaneously achieve self-sustained, environment-friendly, and profitable breweries by implementing the agricultural technologies (agritechs) developed by Redono Oy and applying the CE model. This thesis aims to evaluate the potentiality of breweries' WW by researching nutrient availability in the breweries' WW and examine if those nutrients are sufficient for producing organic liquid fertiliser to grow hydroponics hop plants on a large scale.

Upon implementing the concept of this thesis work breweries contribute to meeting 7 SDGs set by the United Nations (UN) out of the 17 goals, which are *Goal 6: Clean Water and Sanitation*, which states, "Ensure access to water and sanitation for all"; *Goal 9: Industry, Innovation and Infrastructure*, which states, "Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation"; *Goal 11: Sustainable Cities and Communities*, which states, "Make cities inclusive, safe, resilient and sustainable"; *Goal 12: Responsible Consumption and Production*, which states, "Ensure sustainable consumption and production patterns"; *Goal 13: Climate Action*, which states, "Take urgent action to combat climate change and its impacts"; *Goal 14: Life Below Water*, which states, "Conserve and sustainably use the oceans, seas and marine resources for sustainable development"; *Goal 15: Life On Land*, which states, "Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss". (UN 2021)

The ideal concept is that the WW from the brewery goes to the BioFeed unit developed by Redono Oy where nutrients present in WW are recovered to produce organic liquid fertiliser. The treated WW from BioFeed unit can be reused again in brewery for cleaning purposes. The produced organic fertiliser can be used to grow hydroponics hops or microalgae. Microalgae production is out of the scope of this thesis. The BioFeed unit and the HydroHumala unit developed by Redono Oy, where indoor hydroponics hop plants are grown, are placed in the vicinity of the brewery so that the circular economy model can be applied efficiently without the requirement of long-distance transportation. The environmental and economic benefits are evaluated upon implementation of the concept of this research. Based on the results conclusion are drawn on the feasibility of achieving a sustainable brewery in a realistic scenario.

Considering the objectives of this thesis, the following research questions are purposed:

- How Redono agritech solutions can make the conventional brewery sustainable?
- What environmental and economic benefits brewery can achieve if nutrients in brewery WW are recovered to produce liquid fertiliser for growing hydroponics hop plants?

The limitation of this thesis work is that nutrients other than nitrogen (N), phosphorous (P), and zinc (Zn) present in the WW of case example breweries are not known. Calculation on mass balance, nutrient balance, and circularity is done based only on the availability of these nutrients. Further, the exact nutrients present in the runoff solution coming out from hydroponics hops growing unit are not known. The volume of treated WW after production of organic liquid fertiliser is also not known to evaluate water footprint reduction. Further, the carbon dioxide (CO_2) emissions from a brewing process are not known to evaluate if circulated CO_2 from a brewing process meets the need for CO_2 supplement for growing indoor hops.

1.2. Research methodology

This research work is based on the pilot experiment results, literature reviews, and the data collected from the environmental permits of Finnish breweries about their inputs to the brewery and outputs from the brewery. Data from the previous pilot experiment of growing indoor hydroponics hop plants are considered a valuable source of information in this study. Data on nutrients needed to grow hydroponics hop plants are also retrieved from the guidebook provided by Hydro Hop Farms LLC, USA (Clark, 2017). Three Finnish breweries Hartwall Oy, Sinebrychoff Oy, and Laitilan Oy are studied as case examples to evaluate the potentiality of nutrients present in their WW to grow indoor hydroponics hops.

Total inputs and outputs of the brewery are modelled. In other words, the total resources used to produce beer and the total waste after producing a beer are studied from the literature reviews and case examples. The modelling of a sustainable brewery is done by mass balance, nutrient balance, and circularity calculation. Calculations are done based on the nutrients (N, P and Zn) recovered from the BioFeed unit that produces organic liquid fertiliser. In the calculation, it has been assumed that nutrients are fully recovered in the BioFeed unit and produced fertiliser is completely bioavailable for plant production. After the calculations, the circular economy model for breweries is visualised in a flow diagram and the overall financial benefits are estimated.

The calculation of the potentiality of nutrients presents in the WW of each case example brewery to grow indoor hydroponics hops is done. Further potentiality of them to replace dry hops demand and artificial fertilisers demand to produce dry hops that are required for their annual beer production is evaluated. In addition, a reduction in CO_2e emissions by the recovery of total nitrogen (TN) and total phosphorus (TP) that is applied for growing hops according to demand of each brewery is evaluated. The reduction in land use by implementing hydroponics farming over soil-based farming for growing hops is evaluated.

2. Brewery Inputs and Outputs

According to Cambridge Dictionary (2021) 'brewery' means ‘a company that makes beer or a place where beer is made’, and 'brew' means 'to make beer'. Beer is an aqueous drink produced by fermentation of starch (sugar) and flavoured by hops. Beer brewing is a complex process that includes mixing and further refinement of four essential raw materials: germinated barley (malt), brewing water, hops, and yeast. The quality of these raw materials determines the beer quality. Among them, water is the most abundantly consumed raw material that highly affects beer character and quality. (Belitz et al. 2004, 892) The brewing process is also energy intensive, especially mashing and wort boiling processes consume the main heat with high fuel consumption. Despite significant technological improvements over the last 20 years, energy consumption, water consumption, WW, solid waste and by-products, and emissions to air remain major environmental challenges in the brewery (Olajire 2020).

2.1. Basics of the brewery

The main component of the beer is malt, which is germinated barley with high starch content. Starch or sugar-rich raw materials, such as wheat, rice, or corn may be used partly as a substitution for malt. Barley must be subjected to controlled germination to produce enzymes mainly amylases but also proteases in the barley grain, which are needed in the degradation process. (Keukeleire 2000)

The stepwise brewing beer process is summarized below.

1. Malt milling and mashing with the brewing water

Malts must be stored with care to prevent the development of insect colonies. Temperature and moisture contents must be monitored in storage containers. Regular disinfection of storage containers and grain handling equipment is necessary to prevent contamination. Malt milling is done before mashing which is aimed at crushing malt kernels into small particles to allow malt enzymes to act on malt contents and break them down during mashing. Malts are passed through magnetic separators and destoner, before milling, during which metallic particles, stones, and dust that might cause spark and damage to the mills are removed. Malt should have the husk still attached to the grain because if it is badly disintegrated, it is less effective in forming a permeable filter bed during wort recovery from the mash. (Hough 1985, 55-56.)

2. Degradation of starch and proteins by malt enzymes

A slurry of barley malt and brewing water is called 'mash'. During the degradation process, the mash is heated at a temperature of around 60 degrees Centigrade (°C) and starch and proteins are degraded to a mixture of sugars and peptides or amino acids by the malt enzymes. (Keukeleire 2000)

3. Wort recovery by filtration

The sugar solution after the mashing process is called 'wort', which is recovered after filtration and transferred to the brewing kettle (Keukeleire 2000).

4. Wort boiling with the addition of whole hops

Wort is boiled for at least one hour with the addition of hops (Humulus lupulus L.). Beer qualities such as bitter taste, hoppy flavour, and foam stability are determined by hops to a great extent. However, on exposure of beer to light, hop-derived bitter acids can form an offending light-struck flavour. Although the quantity of hops needed is only a fraction of the substantial quantities of malt used in the brewery, hops act as a major ingredient qualitatively with a crucial impact on the features of beer. Besides contributing to the colloidal stability of beer, hops sterilize the wort solution and give the bacteriological stability of beer. (Keukeleire 2000)

Adding hops in a brewing process can be dry hopping or wet hopping. Dry hopping means adding dry hops late in the brewing process either during fermentation or conditioning, whereas wet hopping means adding freshly picked hops during brewing at any point (Allagash 2020). Brewers add dry hops between 2-12 grams (g) per L of beer in the form of cones or pellets into the beer during fermentation or conditioning for periods ranging from several days to weeks (Oladokun et al. 2017). However, the usage of hops quantity can be beyond this range depending on the desired bitterness taste of beer. The addition of more hops early in the brewing process results in greater potential for bitterness in the beer (Senger 2021). Hops added in the later phase, also known as dry hopping, result in a more hoppy aromatic flavour (Allagash 2020).

After cooling the boiled wort with hops, the residue of hops i.e., spent hops, is removed and the outcome liquid, known as 'hopped wort', is pumped to the fermentation vessels and yeast is added under aeration for growth. Fermentation takes place in the anaerobic phase, where yeast cells convert sugars in hopped wort to ethanol and carbon dioxide, as shown by the equation below,

$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$. (Keukeleire 2000)

5. Fermentation

After about one week of fermentation ‘green beer’ or ‘young beer’, is produced which is not drinkable, as several offending compounds that have bad taste and smell, are formed. Spent yeast is removed during this process. (Keukeleire 2000) If hops are added during fermentation, then spent hops are also removed after the process.

6. Maturation or Lagering of several weeks at about 0°C

In the maturation of beer, also called the lagering period the unwanted components are slowly decomposed. This process takes several weeks at about 0°C. (Keukeleire 2000)

7. Packaging

High concentrations of obnoxious chemicals such as diacetyl and pentane-2,3-dione deteriorates the quality of lager beers and thus, strict monitoring is required. Beer is packaged only after the content has decreased below critical values. Beers may be pasteurized for prolonged conservation. (Keukeleire 2000)

2.2. Inputs and outputs in breweries

The overall inputs and outputs in breweries with the involved technological processes to produce 1 L of beer are outlined in the flow diagram of Figure 1.

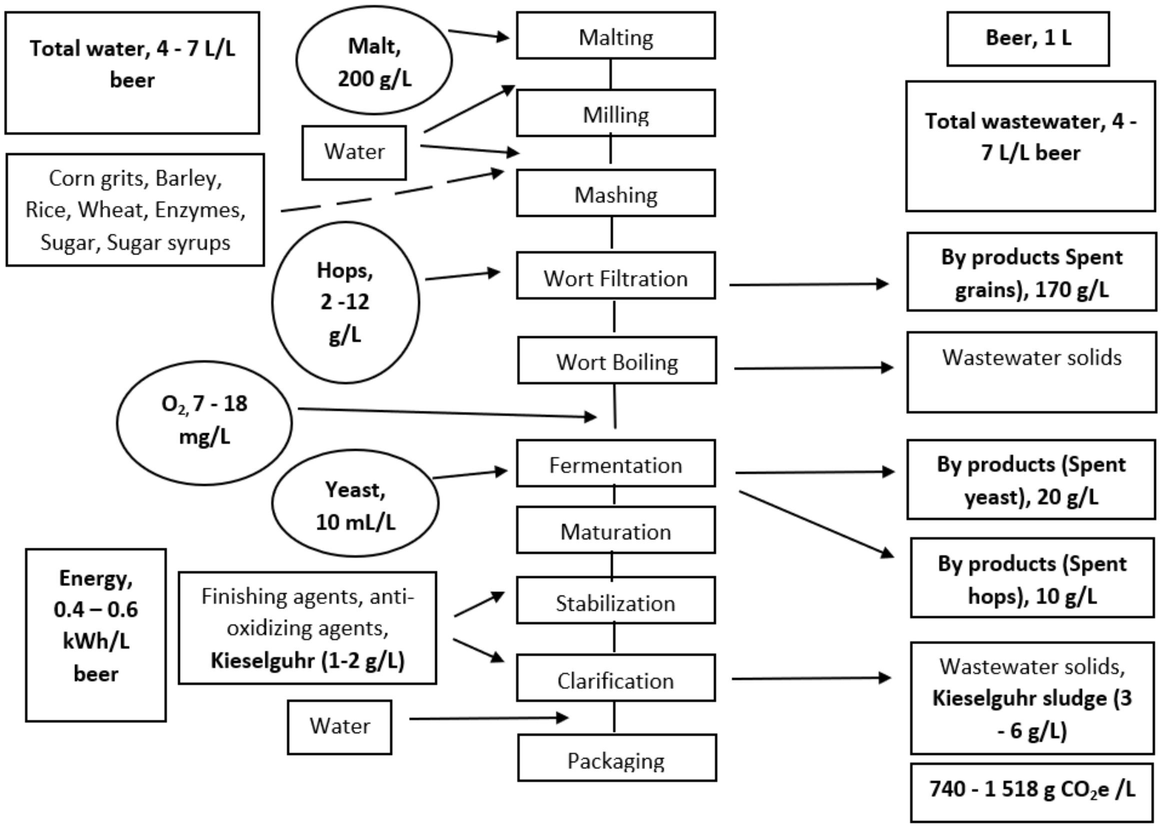


Figure 1. Technological process in breweries and their main inputs and outputs with the amount to produce 1 L of beer (Barker 2018; Conduah et al. 2019; Fillaudeau et al. 2006; Goldammer 2008; Kao 2018; Malteurop 2022; Olajire 2020).

Water is the most abundantly used resource in breweries. The typical value for water consumption to produce 1 L of beer is between 4 to 7 L (Olajire 2020). Water used in brewing is called brewing liquor and its taste, and flavour depends on the brewing liquor quality and water characteristics may vary depending on the process (Briggs et al 2004). Beer contains about 90 – 95% water by mass. Brewery consumes large quantities of good-quality fresh water for beer brewing. Water is consumed in almost every step of the brewing process. Further, water is lost through wort boiling and with spent grains. In addition to water for the product, water is used for heating and cooling, cleaning packaging vessels, production machinery and process areas, cleaning vehicles, and sanitary water. Water consumption is divided into 2/3 used in the process and 1/3 in the cleaning operations. (Olajire 2020)

Besides water, other main input resources in brewing are malt, other fermentable (e.g., rice), hops, clarifying agents, oxygen, yeasts adding and dry hopping (adding dry hops in pellet form to the fermenter), filtering materials (e.g., diatomaceous earth or Kieselguhr), and packaging materials such as kegs, bottles, cans, etc. Energy is another important input that is needed in all the processes. (Olajire 2020) To produce 1 L of beer use of electrical energy can range from 0.4 to 0.6 Kilowatt-hour (kWh) (Conduah et al. 2019). In brewing, filters usually utilise about 1 to 2 g of Kieselguhr for every L of beer produced (Fillaudeau et al. 2006). The quantity of main resources for breweries to produce a L of beer is given in Table 1.

Table 1. The main input resources for breweries with their amount per L of beer produced (Fillaudeau et al. 2006; Goldammer 2008; Malteurop 2022; Olajire 2020).

Brewery Inputs	**Input amount (per L beer produced)**
Total water	4 - 7 L*
Malt	200 g*
Dry hops	2 - 12 g
Oxygen	7 - 18 mg*
Yeast	10 mL*
Kieselguhr	1 - 2 g

*L, litre; g, gram; mg, milligram; mL, millilitre

WW is the major sidestream of the brewery which has been estimated to generate approximately 3 to 7 L per L of beer produced in breweries (Olajire 2020). After that there are three main solid waste by-products which include brewer's spent grains (SG), spent hops (SP), and spent yeasts (SY). Every 100 L of beer brewed produces approximately 20 kilograms (kg) of by-products, which is equivalent to 200 g of by-products per L of beer produced. SG, SP, and SY account for approximately 85%, 5%, and 10%, of total by-products respectively. SG is mainly composed of cellulose, hemicellulose, and lignin, of which cellulose and hemicellulose account for 50% of all spent grains. In addition, SG is rich in protein, essential amino acids, minerals, single sugars (glucose, xylose, and arabinose), phenolics, and mineral. Only 15% of the added hops remain in the final product of beer and the other 85% are residue in spent hops. Therefore, SP is rich in nitrogen-free extract, carbon, fibre, and protein. SY contains carbon, which accounts for up to 50% of the dry weight, followed by oxygen (30–35%), nitrogen (5%), helium (5%), and phosphorus (1%). Thus, SY mainly contains proteins and saccharides. Both SP and SY also are rich in prenylflavonoids and hop bitter acids. These products have the potential to be used for the health benefits of human beings. (Kao 2018) The quantity of main output waste products from breweries to produce a L of beer is given in Table 2.

Table 2. The main output wastes from breweries with their amount per L of beer produced (Barker 2018; Fillaudeau et al. 2006; Kao 2018; Olajire 2020).

Brewery outputs	**Output amount (per L beer produced)**
Total wastewater	4 - 7 L
Total by-products (BP)	200 g
Spent grains (SG) (85% BP)	170 g
Spent hops (SH) (5% BP)	10 g
Spent yeasts (SY) (10% BP)	20 g
CO_2	740 - 1 518 g CO_2e
Kieselguhr sludge	3 - 6 g

Besides, three main solid wastes, diatomaceous earth (DE), also called Kieselguhr sludge is also one of the by-products. It is a naturally occurring siliceous sedimentary rock that is used during the filtration process of brewing to remove particulates and obtain desired clarity and beer stability (Brewers Association). The Kieselguhr sludge nearly triples in weight at the end of the filtration process (Olajire 2020), as it retains numerous organic particulates, such as proteins and polyphenols, that give it a variable organic composition with a high volume of suspended and dissolved materials. As a result, this makes its disposal difficult, where it must be treated before discharged or paid to be disposed of in landfills. The quantity of Kieselguhr sludge can be approximately 3 - 6 g/L of beer produced. (Fillaudeau et al. 2006)

Other wastes include pollutants and effluents such as noise, heat, odors, dust, domestic and laboratory waste, carbon dioxide, and packaging wastes such as plastic waste, and broken glass. To minimize the risk of microbial contamination, and environmental risks, save space and reduce cost, these wastes must be dealt with in the least costly manner and if possible, profitably. (Briggs et al 2004, 68; Rachwal et al. 2020).

Production of 1 L of beer releases approximately 740 - 1 518 g of CO_2e into the atmosphere. Emissions include retail electricity use, bottle production, and transport, and malt production and transport. The emissions are different based on the types of beer such as internationally, locally produced, and home-brewed lager and ale. (Barker 2018) Packaging materials such as corrugated cardboard, glass bottles, aluminium cans, wood pallets, etc. can account for 30% to 50% of total finished goods costs, therefore, a reduction in the amount of packaging can directly impact the company's finance. (Brewers Association)

2.4. Properties of brewery wastewater

Wastewaters from the brewing industry are non-toxic mostly contain easily biodegradable organic matter and do not contain high amounts of heavy metal (Olajire 2020). Organic matter of brewery WW mainly contains different forms of sugars such as cellulose, starch, maltose, glucose, etc., proteins and amino acids, lipids, residues of yeast and hops, and finally ethanol and volatile fatty acids. High nutrient (e.g., nitrogen and phosphorus) contents of the organic wastes in WW, make them a good source for fertilising plants and microalgae or microphytes. (Hill 2015, 426)

Breweries' WW also has high biological oxygen demand (BOD) and even higher chemical oxygen demand (COD) due to presence of the organic components such as sugars, soluble starch, ethanol, volatile fatty acids, etc. Biological treatment plants are needed to reduce BOD and COD and unfortunately, it is the most expensive part of effluent treatment plants. (Agyingi 2020) The characteristics of brewery’s WW are summarized in Table 3 (Hill 2015, 428; Simate et al. 2011).

Table 3. The characteristics of brewery’s wastewater (Hill 2015, 428; Simate et al. 2011).

Parameter	Value
pH	3 - 12
Temperature (°C)	18 - 40
COD (mg/L)	2 000 - 6 000
BOD (mg/L)	1 200 - 3 600

COD:BOD ratio	1.667
VFAs* (mg/L)	1 000 - 2 500
Nitrogen (mg/L)	25 - 80
Phosphates as PO_4 (mg/L)	10 - 50
TKN* (mg/L)	25 - 80
TS* (mg/L)	5 100 - 8 750
TSS* (mg/L)	2 901 - 3 000
TDS* (mg/L)	2 020 - 5 940

*VFAs, Volatile Fatty Acids; TKN, Total Kjeldahl Nitrogen; TS, Total Solids; TSS, Total Suspended Solids; TDS, Total Dissolved Solids

Due to the high content of protein substances, brewery's wastewaters can putrefy easily, resulting in the emission of gases such as hydrogen sulphide (H_2S), ammonia (NH_3), methane (CH_4), and hydrogen (H_2) (Hill 2015, 426). Some substances, compounds, and metal salts can present in brewing WW that is considered harmful to the environment. They are the oxidizable substances (e.g., phosphorus in the form of phosphates, nitrogen in the form of nitrates), organic halogen compounds, and salts of metal such as mercury (Hg), lead (Pb), cadmium (Cd), and chromium (Cr). Oxygen is needed to degrade oxidizable substances and if they pass into drainage systems untreated, they may not be fully degraded due to insufficient oxygen. As a result, they putrefy and produce foul smells that can kill living organisms. Phosphates and nitrates promote the growth of algae in surface water. Nitric acid is used in cleaning in place (CIP) to dissolve beer stones in tanks and form nitrate into WW which can pollute surface waters and soils. Organic halogen compounds used for disinfecting purposes in the brewery have the potential to pollute soil and groundwater. (Agyingi 2020)

2.6. Properties demand to grow hydroponics hop plant

Hop (*Humulus lupulus*) is a perennial herbicide and nettle-like vine plant (Dodds 2017). It is found wild in Finland in almost the whole country except Northern Lapland (Koivisto 2021). Hops are the flowers or seed cones of the hop plant. This cone contains a yellow gland called lupulin as shown in Figure 2. Lupulin glands contain resins, oils, and a multitude of chemicals. Among them, the three chemicals alpha and beta acids, and essential oils are very important in the brewing process. (UW-L 2009) Lupulin can be separated from the green leaves of the hop itself into fine yellow powder. Lupulin powder creates hop flavours and aromas in a beer. (James Squire 2018)

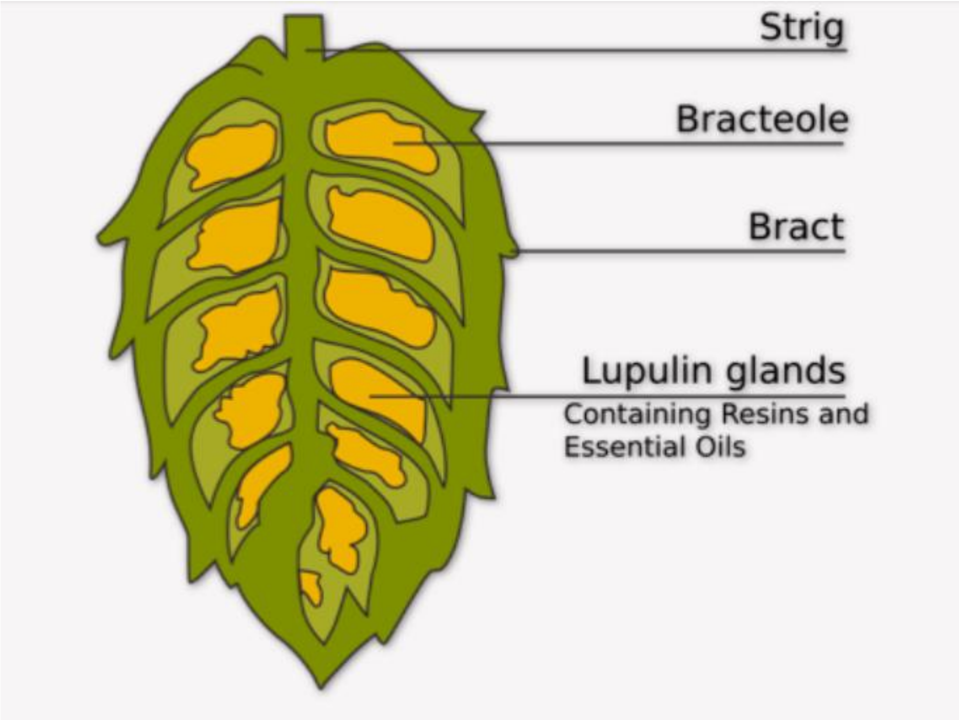


Figure 2. The cross-section drawing of a hop (UW-L 2009).

Hops can grow into vines up to 6 meters (m) high, therefore growing hops require plenty of space. Long vines grow gripping each other and forming a bushy crop. They can grow at a temperature of approximately 4-24°C. However, for a large harvest, the optimum temperature for most European hops varieties is approximately 18-24°C and the relative humidity is approximately 55-75%. Hop plants need a proper infrastructure to support the mature bine with cones. Hop plants can weigh more than 45 kg per plant in the harvesting phase. The highest yielding varieties are Columbus, Nugget, Chinook, and Centennial. (Clark 2017; Rossini et al. 2021).

Freshly harvested hops are called wet hops and they are full of moisture. Wet hops cannot be stored for a long time because of their high moisture content, which promotes microbial spoilage, colour degradation, and chemical reactions, thus reducing the hop quality. They need to be dried before storage to maintain their quality in storage until used. Convection drying is a commonly used preservation technique to increase the stability of hops. The moisture content of dried hops is in the range of 8 to 10%. (Raut et al. 2021) The optimal hops yield can be about 0.9 kg of dry cones per plant per year. Wet hops are 4-5 times more in weight than dry hops, which means about 3.6-4.5 kg of wet cones per plant per year can be produced. (Clark 2017)

According to literature, hydroponics hop plants consume an average of about 1.51 L of water a day per plant. At the beginning of the season, consumption is closer to about 1.1 L per day until the plants get larger, then it will be close to about 2.2 L per day. (Clark 2017) However, hops grown in soil-based farming are dependent on seasonal rainfall. Studies have revealed that supplementing rainfall with irrigation can improve the yield and quality of hops. Supplemental irrigation with a total water volume of 3-8 L of water per plant twice per week may be required during dry hot periods, which means about 0.8-2.2 L (on average about 1.5 L) of water per day per plant. Hop plantings in the first year usually require more frequent water applications but in lesser amounts. (Elford 2021)

Besides water, light and carbon dioxide (CO_2) are also important factors for optimal plant growth. Light is usually considered the limiting variable for optimal plant growth. However, in indoor gardens or tightly enclosed greenhouse rooms, carbon becomes the limiting variable if CO_2 levels are too low in a growing environment no matter how much light and nutrition is given to the plants. In indoor farms, ambient CO_2 can get used up quickly, for instance, in a plastic greenhouse, CO_2 levels can be reduced to less than 200 ppm just 1-2 hours after sunrise. If the CO_2 levels drop below 200 ppm, the plant growth will be greatly limited, and at levels below 100 ppm, plants will stop growing altogether. Atmospheric air contains about 370 ppm of CO_2, and it is very important to provide adequate ventilation and air movement on indoor farms. But still, it may not be enough. It is beneficial to have CO_2 levels between 800 and 1 200 ppm for indoor growers for higher yields**.** CO_2 levels above 1 500 ppm are wasteful, and levels above 5 000 ppm are harmful. CO_2 can be supplemented by different methods such as burning fuel like natural gas or propane; releasing compressed CO_2 that is stored in a tank under pressure; using a decomposition process by fungi in the growing environment to produce CO_2. (Smith 2021; Storey 2016) Nevertheless, no specific study has been done until now about the approximate level of CO_2 that is necessary for indoor hydroponics hop plants.

Soil often contains most of the nutrients needed by plants, but in a hydroponics system nutrient must be added to the irrigation of plants. Due to this reason, commercially prepared fertilisers for hydroponics are in crystal form and water-soluble, for example, nitrate fertiliser. The nutrients required for hops are divided into three categories, which are explained below. (Koivisto 2021)

1. Main nutrients include nitrogen (N), phosphorus (P), and potassium (K). These are the most significant nutrients for growth in terms of quantity for most plants. They are commonly called NPK fertilisers. (Koivisto 2021)
2. Macro-nutrients include calcium (Ca), magnesium (Mg), and sulphur (S). These are often referred to as "supplements", which are added to the nutrient solution in addition to the main nutrients. (Koivisto 2021)
3. Micro-nutrients include iron (Fe), manganese (Mn), boron (B), zinc (Zn), copper (Cu), molybdenum (Mo), and chlorine (Cl). Plants usually need only very small amounts of micro-nutrients but are still important for plant health and growth. Most commercial fertilisers and irrigation water contain small amounts of these, so micro-nutrients do not need to be added to the hydroponics system in some cases. (Koivisto 2021)

The nutrients need for the plant vary according to the stage of the growth cycle. For example, N consumption peaks at the beginning of the growing cycle when plant size and biomass increase sharply, while P consumption peaks at the end of the cycle when plant yields mature (Dodds 2017; Roy et al. 2006). Plants need macronutrients in large quantities to grow. The need for calcium is higher in hops than that of P. Usually, calcium is not included as the main nutrient for most plants. (Clark 2017)

The nutrient recipe requirement to grow hydroponics hops is provided in a guidebook by Clark (2017) from *Hydro Hop Farms LLC* which is illustrated in Table 4. This nutrient recipe is considered a literature value for the basis of calculation in this thesis. The target quantity of nutrients is listed as mg/L of the nutrient solution. Once the rhizomes are planted just water and vitamins such as *Superthrive* should be fed for the first 3 weeks. During that time growth rate of plants and water flow rates should be monitored. The *vegetative* formula must be used from week 4 until reproductive growth starts. When hops begin to flower small burrs start forming, which will be the start of hop cones. From this point until harvest, the nutrient formula must switch over to the *mature* formula. (Clark 2017) Hop plants are very sensitive to boron, zinc, calcium, and magnesium (Koivisto 2021).

Table 4. Literature value of nutrient recipe needed to grow hydroponics hops in mg/l of water (Clark 2017).

Element	**Vegetative (mg/L)**	**Mature (mg/L)**
Nitrogen	100	175
Phosphorus	35	50
Potassium	200	240
Calcium	110	150
Magnesium	40	50
Sulphur	75	75
Iron	2	1.5
Copper	0.8	0.8
Manganese	0.6	0.6
Zinc	0.4	0.4
Boron	0.3	0.3
Molybdenum	0.05	0.05

In the hydroponics plant growing unit, daily monitoring of Electric Conductivity (EC) of runoff water from the bucket planted with hop plants should be done to know if the daily nutrient feed solution to plants is going inappropriately. For this, the runoff from one bucket of each row of plantation units should be collected. The grower should have a goal of about 10% runoff from each plant each day and lower EC in coming out runoff solution than going in the nutrient solution. After measuring EC of runoff, it is compared to EC of the nutrient solution going in and it will give an idea of salt content in buckets. For example, if going in solution has an EC of 1.2 and runoff has 1.8 then feeding is too much and there is an excess salt build-up in a medium. In this case, EC must be lowered until runoff EC is lower than input EC. Hop plants do not like high EC levels in the feeding nutrient solution. (Clark 2017)

EC should be around 0.5 when starting the first feedings. EC needs to be raised gradually as the plants continue to grow. It should not exceed 1.5 before flowering. If plants maintain a healthy green colour, then, the feed is at the right level. Otherwise, the leaves will start to curl up become brittle and start to burn around the margins if plants are getting a high amount of nutrients. Just like in vegetative crops, close monitoring of hops is required and gradually EC of feeding nutrient solution should be raised from 1.5 up to 2.0 around harvest time. pH should always be around 5.8 during the lifetime of plants. (Clark 2017)

3. Waste Legislation

It is crucial that breweries and their workers understand the waste origin, handling, and proper disposal, considering the philosophy, approaches, and tools for a good environmental management system. Most importantly they must be ready to take the required actions at the right time. However, for the long-term and overall benefit of the companies, strict management systems are necessary that monitor the environment, health, and safety issues. (Briggs et al. 2004, 68)

Side streams must always be handled before they can be returned to the water network. Processing methods of side streams can be avoidable if different ways of utilising side streams can be devised. In January 2016, the Ministry of the Environment, Finland has also set a restriction on the disposal of organic biodegradable waste in landfill. This compels and facilitates many companies in the food industry to invest in the exploitation of by-products and developing cooperation around this thesis topic. (Niskanen 2021)

The EU sets the standard for nutrient removal in various fields, which must be followed by the member states. The Urban Wastewater Treatment Directive (91/271/EEC) authorizes the requirements for the European communities at the European level. Finland has also introduced numerous acts and decrees at the national level that relate to the nutrient removal from Wastewater Treatment Plants (WWTPs) as well as the laws on the free movement of fertilisers inside the community. It is crucial to know European and Finnish directives to utilise industrial WW because, without permission, the high-quality fertilisers recovered from the WW nutrients cannot have the legal rights to be applied in food production. (KC 2018)

3.1. EU Urban Wastewater Treatment Directive 91/271/EEC

In the EU Urban Wastewater Treatment Directive (91/271/EEC), *urban wastewater* refers to domestic WW or the mixture of domestic WW with industrial WW and/or run-off rainwater. *Domestic wastewater* refers to WW that originates mainly from human metabolism and household activities. *Industrial wastewater* refers to any WW which is discharged from premises used for carrying on any trade or industry, other than domestic WW and run-off rainwater. The directive encourages the recycling of the sludge from the WW treatment and discourages the disposal of sludge into the surface waters. To ensure total natural protection, the monitoring of the treatment plants is suggested, and the member states must present their national programs to the European Commission. (EUR-Lex 2022)

3.2. The EU Sewage Sludge Directive 86/278/EEC

The directive is concerned with soil protection when sludge is used in agriculture. It has set the rules and regulations on the usage of sewage sludge as fertiliser without causing pollution to soil, surface, and groundwater. The limits have been set on the concentration of the following heavy metals: cadmium, copper, nickel, lead, zinc, mercury, and chromium. The application of sludge that exceeds the limit of these heavy metals is banned inside the EU. In most cases, the sludge must be treated before being used in farming. But some EU countries may allow it if it is worked or injected into the soil. (EUR-Lex 2022)

Nevertheless, the use of sludge is not allowed at all on grasslands or crops that are going to be grazed by animals and for a minimum of 3 weeks before harvesting. Likewise, sludge application is not allowed on fruits and vegetable crops during the growing season (except for fruit trees). Also, it is not allowed on soil, where fruit and vegetables are grown in direct contact with soil and eaten raw. This prohibition applies for 10 months before the harvest as well as during the harvest. (EUR-Lex 2022)

3.3. Fertilizing Products Regulation (EU) 2019/1009

Fertilizing Products Regulation (EU) 2019/1009, shortly referred to as EU FPR, enter into force on 15th July 2019, which amends EC Regulation 1069/2009 - which formulates health rules as regards animal by-products and derived products not intended for human consumption - and EC Regulation 1107/2009 - which controls placing plant protection products on the market - and repeals EC Regulation 2003/2003. (Renewable Energy Association 2022) These existing fertilisers regulations ensure free movement for only traditional fertilisers usually made of mined or synthetic raw materials, but it does not include a clearing procedure for organic fertilisers. Consequently, around half of all fertilisers produced currently stay in the country where they were produced. (EC 2016)

EU FPR provides rules to recover nutrients into secondary raw materials, such as bio-waste transformed into composts and digestates. Thus, it facilitates the production of organic fertilisers from organic materials, such as animal by-products or other agricultural residual products, or recycled bio-waste, within the scope of the Fertilisers Regulation and grants access to CE marking. Binding the CE marking to a product declares that the product meets all the legal requirements. If these products are included in CE-marked fertilisers, they are no longer considered to be waste within the meaning of the Waste Framework Directive and they can be traded freely in the EU. Simultaneously, it guarantees a high level of safety and environmental protection of all CE-marked fertilising products by enforcing common requirements for quality, safety, and labeling in a uniform way. It allows European farmers to make informed choices, contributing to making food production more cost and resource effective. (EC 2016) It covers a range of product types that are not currently covered by harmonisation rules, such as organic fertilisers, organo-mineral fertilisers, soil improvers, growing media, and plant bio-stimulants (Renewable Energy Association 2022).

To avoid contamination of the food chain and limit environmental damage, EU FPR proposes harmonised limits for heavy metals (cadmium, chromium, mercury, nickel, lead, arsenic) in CE-marked fertilisers. For both solid and liquid organic fertilisers, contaminants in them must not exceed the limit values illustrated in Table 5. Further, biuret ($C_2H_5N_3O_2$) must not be present in them at all. (Regulation 2019)

Table 5. Limit values for contaminants in solid and liquid organic fertilisers set by EU FPR (Regulation 2019).

Contaminants	**Limit values (mg/kg dry matter)**
Cadmium (Cd)	1.5
Hexavalent chromium (Cr VI)	2
Mercury (Hg)	1
Nickel (Ni)	50
Lead (Pb)	120
Inorganic arsenic (As)	40
Copper (Cu)	300
Zinc (Zn)	800

There are also limits set out for pathogens such as Salmonella spp. and Escherichia coli or Enterococcaceae. Both solid and liquid organic fertiliser shall contain at least one of the following declared primary nutrients: nitrogen (N), phosphorus pentoxide (P_2O_5), or potassium oxide (K_2O). In general fertilising products derived from treated bio-waste and biomass are less contaminated with heavy metals. But they could contain other types of contaminants, such as polycyclic aromatic hydrocarbons (PAHs). Therefore, it sets a maximum content limit for PAHs in organic products, for example, composts and digestates (both solid and liquid parts) shall contain no more than 6 mg/kg of dry matter of PAHs. Similarly, there are also limits for organo-mineral and organic fertilisers. The revised fertilisers regulation creates links between the different regulatory frameworks to avoid duplication of procedures. (Regulation 2019)

EU FPR can enhance better use of the resources that are already available. Only 5% of waste organic material is recycled to use as fertilisers currently, but recycled bio-waste can substitute up to 30% of inorganic fertilisers. The EU imports more than 6 million tonnes of phosphate rocks a year, but recycled nutrients can recover up to 2 million tonnes of phosphorus from sewage sludge, biodegradable waste, meat, and bone meal or manure. Further, it can also substitute synthetic nitrogen fertilisers. (EC 2016)

3.4. Fertiliser Product Act 539/2006 of Finland

The Fertiliser Product Act of Finland aims to ensure that all fertiliser products placed on the market in Finland are safe, of good quality, and suitable for plant production. It also promotes the utilisation of by-products suitable for use as fertilisers, if they have a proven positive impact on plant growth and cause no damage or danger to humans, animals, plants, or the environment. (Finlex 2022)

Since Finland's soils and inland waters are more acidic than those in other EU countries, special efforts are needed to control and reduce soil-related and other environmental risks in Finland. For this, key priorities are needed to ensure high quality and safety, which includes low heavy metal content of fertiliser products used in agriculture, horticulture, landscaping, and forestry. Fertiliser products must comply with the legislative requirements, i.e., only fertilisers that are included in either national designation or EC designation list of fertilisers can be imported or marketed in Finland. Finnish Food Safety Authority (Evira) decides on the approval of a new fertiliser product. (Finlex 2022)

3.5. BOD_7 and COD_{Cr} ratio

BOD_7 measurement illustrates the amount of oxygen-consuming organic substances in WW. The quality of WW can be estimated with the help of the ratio between the BOD_7 (biological oxygen demand, subscript 7 refers to the incubation time of 7 days) and COD_{Cr} (chemical oxygen demand, subscript Cr refers to oxidation by dichromate) values. The organic substance in WW is highly degradable and WW is most probably not very toxic when the ratio is over 0.5. The organic substances in WW are only barely biodegradable or the toxic substances in WW inhibit the biochemical oxygen uptake when the ratio is low. This can relate to high COD concentrations and especially a high COD/BOD ratio. It results when there are large amounts of organic substance in industrial WW that degrades only with difficulty. Nevertheless, very high BOD in the sewer network can cause the formation of an anaerobic state with an explosive formation of methane, odour emissions, and indirect corrosion. Further, it may cause the overgrowth of filamentous bacteria and can cause poor settlement of sludge. (VVY 2018)

3.6. Nutrients, nitrogen, and phosphorus

The nutrients are not necessarily harmful to the treatment process because N and P in domestic WW are needed for the formation of activated sludge mass. However, sometimes nutrients in domestic WW can be more than needed and which is like that of industrial WW which contains an abundance of nutrients that burden both the treatment plant and the recipient water body. Nutrient loading can be high from meat processing, fish farming and fertiliser industries, landfills, and composting facilities as well as by reject water from biogas plants. When there are high loads of nutrients beyond the treatment plant's capacity, then there is demand for the pre-treatment. An agreement must be done with the water utility to convey nutrient-rich WW to the sewer. The WW fee is increased if large amounts of nutrients are conveyed to the sewers. (VVY 2018)

The fluctuation in P loading of incoming WW causes problems in the maintenance of a good P value. For example, detergent and phosphoric acid release these kinds of P loads. P is removed chemically and hence a P load increases especially the costs for chemicals. N is removed usually in a biological process. N load increases the need for basins capacity and may require additional carbon input and alkalisation. (VVY 2018)

4. Recovery of materials from brewery wastewater

Due to the valuable properties of brewery waste materials, it is wise to treat them as efficiently as possible to recover the valuable materials such as nutrients, so that economic and environmental benefits can be achieved. To achieve this, agritech solutions and emerging technologies that have more benefits over conventional treatment should be considered.

4.1 Conventional treatment of brewery wastewater

In the conventional system, brewery WW is disposed to municipal sewer after completing pre-treatment through physical, chemical, or biological methods or a combination of these. However, in some cases, especially for craft breweries no pre-treatment is required but sewer discharge fees are imposed on effluent volumes, suspended solids, and organic loads. (Simate et al. 2011)

Physical pre-treatment is the first unit operation applied in which physical forces such as sedimentation or flotation are applied to remove contaminants and coarse solid materials. This process does not remove any dissolved pollutants. The solid materials removed from physical pre-treatment are disposed to bio-waste. After physical pre-treatment, chemical pre-treatment is used to remove dissolved pollutants through chemical reactions which occur after the addition of chemicals to the WW. Due to added chemicals pH is adjusted and dissolved contaminants form mass by coagulating and flocculating. (Hill 2015, 427)

Biological pre-treatment of WW involves the activities of different microorganisms acting on the WW, breaking down the biodegradable organic and inorganic pollutants. It further results in nitrification, denitrification, and stabilization of the WW. Biological treatment can be aerobic or anaerobic. This treatment method is more efficient in the removal of BOD and COD at low costs of investment compared to the physical and chemical pre-treatment methods. However, chemical, and biological treatment can result in unsatisfactory results and due to tighter water quality regulations, if brewery WW is to be reused, further, intensive treatment processes are necessary. (Hill 2015, 427)

In aerobic biological pre-treatment, aerobic microorganisms, mainly bacteria, metabolize the organic matter in the WW in the presence of oxygen, producing more microorganisms and inorganic end-products such as carbon dioxide, ammonia, and water. The microorganisms help in sedimentation and the separation of non-settleable solids by converting them into settleable solids. Aerobic treatment usually produces large quantities of sludge, which requires disposal. Handling and dewatering excess sludge is one of the most expensive processes. (Hardwick 1994, 543)

In anaerobic biological pre-treatment, anaerobic microorganisms convert organic compounds in the WW into biogas in the absence of oxygen. Biogas is mainly composed of methane and carbon dioxide with traces of hydrogen sulphide. This treatment can either be done through an Up-flow Anaerobic Sludge Blanket (UASB) or a Fluidized Bed Reactor (FBR) process. Anaerobic treatment is preferred to aerobic treatment because it is more efficient in treating highly polluted wastewaters and consumes low energy or no energy at all, and rather energy can be recovered from biogas production. Meanwhile, aerobic treatment consumes a great deal of energy. (Kunze 2014, 803) A comparison between anaerobic and aerobic treatment processes is illustrated in Table 6.

Table 6. Anaerobic treatment as compared to aerobic treatment (Simate et al. 2011).

Parameters	**Aerobic systems**	**Anaerobic systems**
Energy consumption	High	Low
Energy production	No	Yes
Biosolids production	High	Low
COD removal (%)	90 - 98	70 - 85
Nutrients (N/P) removal	High	Low
Space requirement	High	Low
Discontinuous operation	Difficult	Easy

4.2 Redono agritech solutions

Redono Oy is a biotechnological company that offers services and technologies for future farming solutions, which include urban farming, hydroponics greenhouses, microalgae production, and production of organic liquid fertilisers. As the name suggests Redono meaning "giving back" in Latin, the company is giving back to nature by creating a circular loop in the industry. The technologies of the company can purify industrial wastewaters, utilise CO_2 emissions, and recycle the nutrients content of industrial side streams to produce organic liquid fertilisers that can produce high-value organic foods in future farming technologies such as hops in the hydroponics system. CO_2 produced from industries such as breweries can be utilised for growing hops or the production of microalgae. (Redono Oy 2017)

The technologies developed by Redono Oy are BioFeed (fertiliser production), Vertical hydroponics, HydroHumala (indoor hydroponics hops growing solution), and BioAlgae (microalgae production) units. The circular model of Redono Oy that includes all these units is shown in Figure 3. (Redono Oy 2017)

Figure 3. Circular economy model for brewery formulated by Redono Oy (Redono Oy 2017).

Biofeed technology is oriented to treat brewery WW which differs from conventional treatment in terms of environmental and financial benefits, which are elaborated on below section.

4.2.1. BioFeed unit

Redono has developed BioFeed unit (BF), which can be used to pre-treat the industrial side streams from different industries such as breweries, biogas plants, aquaculture, and agriculture. In the pre-treatment process unwanted solids, bacteria, or other organisms and impurities from the industrial side streams are removed. In the case of a brewery, WW impurities can be residual solids and there are mostly organic nutrients after beer production which are utilised to produce fertilisers. The residual solids removed after the pre-treatment process is disposed to waste treatment plant. Pre-treatment process is monitored and controlled to guarantee a continuous nutrient recycling process. The result of the pre-treatment process is organic liquid fertilisers called BioFeed, which are rich in necessary nutrients such as N and P, including other macro- and micro-nutrients that are needed for effective microalgae cultivation and hydroponics plant cultivation such as hops. BF unit can produce liquid fertiliser of 12 000 L/day. About 90% of nutrient-rich WW can be recovered in the unit and the remaining WW (about 10% of original WW) can be recycled in the BioAlgae unit. (Redono 2018) BF technology differs from the conventional brewery WW treatment process in the way that total nutrients in WW are recovered and recycled to produce organic liquid fertilisers.

4.2.2. Vertical hydroponics unit

Hydroponics is the system of growing plants without the use of soil. It can be done in an indoor or outdoor environment. The indoor environment is suitable in the context of Finland. Hydroponics has a significant benefit over traditional soil-based farming and soil-based greenhouse farming. The general comparison among them is illustrated in Table 7. From the table, it can be clearly noted that the number of crops yielded per square meter (m^2) in hydroponics farming can be about 15 times more than that of traditional soil-based farming. (Redono Oy 2017)

Table 7. Comparison of traditional, greenhouse, and hydroponics farming (Redono Oy 2017).

Parameter	**Traditional**	**Greenhouse**	**Hydroponics**
Growth cycle	70 days	40-50 days	21 days
Water consumption per crop	35 L	15 L	1.5 L
Number of crops per square meter	18	25	250-300
Crop cycles	Seasonal	Seasonal	Year-round
Pesticides/Herbicides	Often	Less often	None
Location	Open field	Open field	anywhere
Post-harvest handling	High	Medium	Low

Redono has developed the vertical hydroponics unit, where BioFeed-fertilisers can be utilised to grow different vegetables and microgreens. In addition, other nutritional and medicinal plants, such as Gynostemma Pentaphyllum (Jiaogulan-tee) and Ashwagandha (Indian Ginseng) (Redono Oy 2017).

4.2.3. HydroHumala unit

Redono has developed a modular solution called HydroHumala unit to grow urban hop plants for breweries in an indoor hydroponics system. During the growth of hop plants, runoff comes from the HydroHumla unit which goes back to the BioFeed unit for nutrient recovery. Each HydroHumala unit has a surface of 7 m^2 for farming. The production capacity is 30-50 kg wet hops per harvest. A total of three harvests can be done in a year, which yields 90-150 kg wet hops per year. If on average about 1 kg of wet hops is estimated to produce 100 L of beer, one HydroHumala unit has potential to produce up to 15 000 L of beer at maximum level can be produced by the hops yield from. (Redono Oy 2017)

Redono also has a hops farm unit for the big brewery. It required a space of 1 500 m^2 (50 m x 30 m). The growing surface is approximately 800 m^2. It has 150 growing plots (3.6m x 1.1m) and 14 hop plants can be grown per plot, which means a total of 2 100 plants can be grown. This can yield about 15 000 kg hops per year. (Redono Oy 2017).

4.2.4. BioAlgae unit

BioAlgae unit developed by Redono is a microalgae production unit where the cultivation of microalgae takes place in the Varicon Aqua Phyco-Flow tubular photobioreactors (PBR), with the support of high-tech LED-grow lights. During the cultivation, the recycled water is purified, as the nitrogen and phosphorus in the recycled waters are used for the growth of microalgae. The industrial CO_2 emissions can be recycled in this controlled and automated microalgae cultivation system. The produced BioFeed-fertilisers from the industrial side streams can also be utilised in this unit. Microalgae species like *Haematococcus Pluviali*s and *Auxenochlorella Protothecoides* can be grown in the unit. The purified water from the unit can be used as industrial process water or returned to nature. The cultivated microalgae are considered the ultimate SuperFood, which contains high nutritional values for human consumption and is beneficial for human health. They can also be used as nutritious feeds for fish and animals. (Redono Oy 2017)

5. Results from Previous Pilot Experiment

In the pilot experiment, a total of 20 hop rhizomes were planted. Approximately 80 L of water and 25 mL of vitamin *Superthrive* solution were added to the hydroponics system reservoir to support rhizomes to accelerate the formation of new roots. Rhizomes took about 4 weeks to take root (Koivisto 2021). Strong roots are needed to support the hop plants, and freshly planted rootstocks do not grow into vines until the roots have grown enough (Rossini et al. 2021). Hops grow into vines up to 6 m high. The duration to grow hops was about 176 days, from the first hem of hops to the first harvest. Total hops yield was not evaluated in this pilot experiment. (Koivisto 2021)

According to Clark (2017), one hop plant can yield about 0.9 kg of dry hops which is like that of soil yields. Usually, dry hops are used in the brewing process. During the harvest hops are wet and their weights are 4 - 5 times more than dry hops (Clark 2017). Each plant can produce three harvests per year (Koivisto 2021). In the pilot experiment, by considering literature value, the total hops yield from 20 plants in one harvest is about 20 kg and in a year with 3 harvests total dry hops, the yield can be approximately 54 kg (20 x 0.9 kg x 3) per year.

The Amtra Stream 1300 submersible pump was used for the water circulation. It has a pumping capacity of 1 300 cubic decimeter per hour (dm^3/h) and a maximum lifting height of 1.15 meters. The nutrient solution was pumped timely every two hours for 15 minutes to the planted rhizomes, allowing the culture medium in the pots to get wet through and part of the nutrient solution to return to the water tank as a run-off. (Koivisto 2021) The pH, conductivity, dissolved oxygen (DO), and turbidity of water that is circulated in growing indoor hydroponics hops in the pilot experiment were maintained as in Table 8 (Niskanen 2021).

Table 8. The pH, conductivity, DO and turbidity of water used in growing indoor hydroponics hops in a pilot experiment (Niskanen 2021).

Parameter and unit	**Hops growing in a pilot experiment**
pH	5.29
Conductivity, mS /cm*	1.09
Dissolved oxygen (DO), mg/L	8.83
Turbidity, NTUs*	1.5

* mS, millisiemens per centimeter; NTUs, Nephelometric Turbidity Units

The approximate consumption of water, electricity, and fertiliser solution per plant for indoor hops growing in the pilot experiment is summarized in the following sections.

5.1. Electricity consumption

Total electricity consumed in the project was approximately 1 360 kWh, which means that energy consumption per hop plant was approximately 68 kWh. Electricity consumption is given in Table 9.

Table 9. Total electricity consumed in the pilot experiment.

Consumption categories	**Electricity consumed (kWh) / year**
Total (20 hop plants)	1 360
Per plant	68
Lighting (80% of total electricity)	1 088
Climate control (18% of total electricity)	244.8

Pumps (water and air) (2%)	27.2

The significant amount of electricity used in the project was spent on lighting, which is about 80% of the energy used. The share of climate control, i.e., fans and humidifiers, was around 18%. Water pump for watering and air pump for water aeration accounted for only about 2%. The energy consumed by the pH of the nutrient solution and the monitoring of the performance is not included in the calculations.

5.2. Water consumption

The total water consumption during total operation of 176 days of pilot experiment was approximately 2 000 L, of which 1 500 L was irrigated to total 20 hop plants and 500 L was used for washing equipment and culture platforms. Water irrigated to plants was partially lost as *leachates or runoff* which accounts for 200 L in total 176 days. It translates that actual water consumption by total 20 hop plants were only 1 300 L during the whole operation. The measurement uncertainty for these results is estimated to be ± 20%. (Koivisto 2021) If total water of 2 000 L is considered for 20 plants for 176 days, then water consumption per plant is about 0.5 L per day. Table 10 presents water consumption by individual hydroponics hop plant based on pilot experiment (Koivisto 2021) and literature value (Clark 2017).

Table 10. Water consumption per hydroponics hop plant based on pilot experiment (Koivisto 2021) and literature value (Clark 2017).

Categories	**Pilot experiment (L / day)**	**Literature (L / day)**
Per hop plant	0.5	1.5

5.3. Fertiliser and nutrients consumption

During the project, commercially available aquaculture fertilisers and nutrients were used. Their commercial names are Superthrive and General Hydroponics Flora Series (six different types of them were used). Altogether, about 5 L of these fertilisers were added in 1 500 L of water for total 20 plants in the whole duration of project that was running for 176 days. The nutrients rich runoff water was 200 L, which accounts for about 13% (200 L / 1 500 L) loss of nutrient rich water. The runoff water was known nutrient rich by testing its electrical conductivity (EC) which was close to the original nutrient added solution. (Koivisto 2021) The combination of these fertilisers includes the nutrients composition mentioned in the column, “Pilot experiment value to grow hop plant (mg/L)” of Table 12. (Niskanen 2021).

The total nutrients added to the water tank was 4.915 L, which includes main supplements, supplements, and pH adjusters. Their quantity is given in Table 11. The measurement uncertainty of these results is estimated to be ±5%. These measurements do not include the amount of nutrients lost when emptying the water tank, therefore, the actual consumption was lower than the measurement result. (Koivisto 2021)

Table 11. Total quantity of fertilisers consumed by indoor hydroponics hop plants in the pilot experiment (Koivisto 2021).

Consumption categories	**Fertilisers consumed (L)**
Total	5
Main supplements	4.315
Supplements	0.36
pH adjusters	0.24

Total nutrients consumption to grow hop plants according to the literature value (for both vegetative and mature hop plants) and their corresponding values for indoor hydroponics hop plants in the pilot experiment are given in Table 12. (Niskanen 2021)

Table 12. Total nutrients demand to grow hop plants based on the literature (Clark 2017) and the pilot experiment (Niskanen 2021).

Nutrients	**Literature value for vegetative hop plant (mg/L)**	**Literature value for mature hop plant (mg/L)**	**Literature value in average for hop plant (mg/L)**	**Pilot experiment value for hop plant (mg/L)**
Total nitrogen	100	175	137.5	100
Total phosphorus	35	50	42.5	NA
Potassium	200	240	220	93
Calcium	110	150	130	94
Magnesium	40	50	45	22
Sulphur	75	75	75	NA
Iron	2	1.5	1.75	0.95
Copper	0.8	0.8	0.8	NA
Manganese	0.6	0.6	0.6	11
Zinc	0.4	0.4	0.4	0.25
Boron	0.3	0.3	0.3	0.13
Molybdenum	0.05	0.05	0.05	NA
Sodium	NA	NA	NA	53
Nitrate	NA	NA	NA	51
Ammonium	NA	NA	NA	16
TOC*	NA	NA	NA	41

*TOC, Total Organic Carbon

In the pilot experiment, there was an error in the measurement of total phosphorus, therefore its value is not available (NA).

6. Materials and methods

Three brewery case examples from Finland are selected to study the real case scenario of beer production with their inputs and outputs. Mass, nutrient balance and circularity calculations are done to evaluate how a sustainable brewery can be achieved. Calculations are focused to find the dry hops demand of each brewery, the annual demand of nutrients for hop plants, the potentiality of nutrients composition of breweries' WW to yield the dry hops annually and to replace the demand for artificial fertilisers (N, P and Zn) to grow the required hydroponics hops, reduction in carbon footprint from N and P recovery by producing organic liquid fertiliser at BioFeed unit and decrease in land area demand by adopting hydroponics farming over soil-based farming of hops.

6.1. Description of the case study

Hartwall Oy, Sinebrychoff Oy, and Laitilan Oy brewers are the real case examples taken for the study. The environmental permits of the breweries were studied to collect the data. The data of all breweries were taken from different years, i.e., from the years 2008, 2007, and 2006 for Hartwall Oy, Sinebrychoff Oy, and Laitilan Oy respectively. The main inputs and outputs of all these three breweries are compared, which is illustrated in Table 13. Laitilan Oy is connected to a district heating system, and the total heat input of the company is not available (NA). (Puska 2009; Inkinen 2009; Haijanen 2013)

Table 13. Comparison of major inputs and outputs Hartwall Oy, Sinebrychoff Oy and Laitilan Oy (Puska 2009; Inkinen 2009; Haijanen 2013).

Inputs	**Harwall (2008)**	**Sinebrychoff (2007)**	**Laitilan (2006)**
Tap water, m^3	NA	87 839	NA
Groundwater, m^3	NA	38 880	NA
Total water, m^3	919 000	126 719	21 000
Electricity, GWh	34.84	4.1	0.6
Heat, GWh	17.85	9.9	NA
Steam	28.24 GWh	75 kWh	660 kWh
Total energy, GWh	80.93	14 GWh	0.6 GWh
Outputs			
Beer production, million L/year	273	32	1.5
Dry mash production, tonnes	NA	1218	NA
Wet yeast production, m^3	NA	724	NA
Wastewater, m^3	871 650	63 299	15 900
Wastewater, L	871 650 000	63 299 000	15 900 000

Water consumption per L of beer produced and WW per L of beer produced for each brewery is illustrated in Table 14. For Hartwall and Sinebrychoff breweries, these values are close to the value provided by Olajire (2020), which is about 4 to 7 L of water consumption per L of beer produced and 3 to 7 L of WW generated per L of beer produced. However, for Laitilan brewery water consumption and WW generated per L of beer produced is higher than the range provided by Oljaire (2020).

Table 14. Water consumption and WW generated per L of beer produced (Puska 2009; Inkinen 2009; Haijanen 2013).

Parameter	Hartwall Oy	Sinebrychoff Oy	Laitilan Oy
Water, L	919 000 000	126 719 000	21 000 000
Beer, L	273 000 000	32 000 000	1 500 000
WW, L	871 650 000	63 299 000	15 900 000
Beer + WW, L	1 144 650 000	95 299 000	17 400 000
(Beer + WW), % of water	125	75	83
Water - (Beer + WW), L	-225 650 000	31 420 000	3 600 000
Water, L per L beer	3	4	14
WW, L per L beer	3	2	10.6

The total volume of beer and WW is smaller than that of water consumption, which accounts for 75% and 83% of water supplied for Sinebrychoff and Laitilan breweries respectively. It means that 25% and 17% of water supplied for beer production is not accounted for in total beer and WW produced by Sinebrychoff and Laitilan breweries respectively. This remaining water might be soaked into barley during the malting process. However, in the case of Hartwall brewery, the volume of beer and WW is larger than the water supplied to the brewery. The probable reason might be that besides beer, Hartwall Oy also produces mineral water, soft drinks, cider, and other alcoholic beverages, and WW from these productions is included in the total WW, as shown in Table 14. However, the water consumption of Hartwall Oy, shown in Table 14 is solely used for beer production.

6.1.1. Nutrients composition in wastewater of case examples

In the environmental permit, the annual WW load of all three breweries is provided in *kilograms* (*kg)*. In Laitilan Oy's case, the average concentration of nutrients in WW is also provided, i.e., in *milligram per litre* (*mg/L) of WW generated*. The annual WW load of all three breweries in *kg* is presented in (*Puska* 2009; Inkinen 2009; Haijanen 2013)

Table 15. Total Nitrogen (TN) content in the WW of Sinebrychoff brewery is not available in their environmental permit. The data on Zinc (Zn) content is only available for Hartwall brewery's WW. (Puska 2009; Inkinen 2009; Haijanen 2013)

Table 15. The annual WW load of Hartwall Oy, Sinebrychoff Oy and Laitilan Oy in *kg* (Puska 2009; Inkinen 2009; Haijanen 2013).

Parameter	**Hartwall Oy, kg**	**Sinebrychoff Oy, kg**	**Laitilan Oy, kg**
Total Nitrogen	27 831	NA	60
Total Phosphorus	18 030	1740	209
Zinc	253	NA	NA
Solids	222 371	51 300	4 000
BOD_{7atu}*	1 833 759	144 600	75 000
COD_{Cr}*	2 681 589	147 000	NA

*BOD_{7atu}: Biological Oxygen Demand in wastewater.

*COD_{Cr}: Chemical Oxygen Demand, dichromate. In COD_{Cr} method dichromate is used to oxidise the organic substances (Naturvårdsverket 2022).

The values of TN, TP, and Zn in *kg* for Hartwall Oy and Sinebrychoff Oy are converted into *mg/L of total WW generated*. It is done by converting total nutrients in *kg* unit into *mg* unit value (1 kg = 1 000 000 mg) and dividing it by total WW produced in *L* (1 m^3 = 1000 L). For e.g., in case of Hartwall Oy, TN = (27 831*1 000 000) mg / 871 650 000 L = 32 mg/L.

After conversion, they are compared with the literature and the pilot experiment values for the nutrients (TN, TP, and Zn) needed to grow hydroponics hop plants, whose units are mg/L of water. This comparison is illustrated in Table 16.

Table 16. The nutrient composition of three breweries in mg/L of WW produced and their comparison with the literature and pilot experiment values needed to grow hydroponics hop plants (Clark 2017; Niskanen 2021; Puska 2009; Inkinen 2009; Haijanen 2013).

Parameter	**Hops literature**	**Hops pilot experiment**	**Hartwall Oy, 2008**	**Sinebrychoff Oy, 2007**	**Laitilan Oy, 2006**
Total nitrogen, mg/L WW	100	100	32	NA	4
Total phosphorus, mg/L WW	35	NA	21	27	13
Zinc, mg/L WW	0.4	0.25	0.29	NA	NA

From the comparison, it can be noticed that the TN content in the WW of each brewery is lower than the nitrogen (N) values commonly used in hops fertilisation waters. It simply means that the TN content in WW of each brewery is not sufficient to grow hydroponics hop plants that meet the annual beer production of each brewery, and thus the additional amount of N fertiliser is needed. TP content in all breweries except Laitilan Oy is quite close to the literature value. Zn content in WW of Hartwall Oy is sufficient to grow hydroponics hop plants if compared with the pilot experimental value, however, it is not sufficient if compared with the literature value.

6.3. Mass balance calculation

The chosen three breweries in case examples, Hartwall, Sinebrychoff, and Laitilan can be considered big, medium, and small-scale breweries based on their beer production, which are 273, 51, and 1.5 million L of beer per year respectively. In the mass balance, total dry hops demand, the annual demand of nutrients per hop plant, hops growing potential of each brewery WW, and the potential of each brewery to replace the demand of dry hops are calculated.

6.3.1. Dry hops demand of each brewery

To meet the annual beer production of the brewery, there is a demand for a certain mass of dry or wet hops. The total number of hop plants needed to get the yield of desired dry or wet hops demand must be estimated.

The mass of hops (dry or wet) used in beer production of all case example breweries is not known. Therefore, the total hops demand to meet the annual beer production of each case example brewery is calculated by considering 2 g and 12 g of dry hops per L beer, which is taken from Oladokun et al. (2017). The process of calculation is done by using the following formula:

Dry hops demand = Total annual beer production * Dry hops used per L beer (2 - 12 g of dry hops).

After that total hop plants need to yield annual demand of dry hops is calculated. The yield of 0.9 kg of dry hops per hop plant per year in a hydroponics system is considered in the calculation, which is based on the manual of Clark (2017). The calculation is done as follows:

Total hop plants need = Total annual need of dry hops (kg/year) / Dry hops yield per plant (0.9 kg/year/plant).

6.2.1. Annual demand of nutrients per hop plant

The annual demand of nutrients per hop plant must be calculated to evaluate the hop plant growing potential of breweries WW. According to Clark (2017), about 1.5 L of water per day (d) per hop plant. From the case examples, only two main nutrients, TN and TP present in their WW are known, except Zn in Hartwall brewery. Therefore, the daily and annual requirements of only TN, TP, and Zn for each hop plant are calculated based on 1.5 L water consumption per day per hop plant.

It has been assumed that the total days of farming of hop plants is 300 days in a year. In the literature, the nutrient recipe is divided into vegetative and mature hop plants (Clark 2017).

Therefore, in this calculation average value of nutrient recipes from vegetative and mature hop plants is considered. In a day, the average consumption of TN, TP, and Zn are 137.5 mg//L, 42.5 mg/L, and 0.4 mg/L of water per hop plant (Clark 2017). The calculation is done as follows:

First, nutrients (TN/TP/Zn) demand per 1.5 L of water per day per plant is calculated by using the following formula:

Nutrients demand per 1.5 L of water per day per plant = 1.5 L/d * Average nutrients demand per L of water per day per plant.

Then, nutrients demand in a year per hop plant is calculated by using the following formula:

Nutrients demand per year (300 days) per plant = Nutrients demand per 1.5 L of water per day per plant * 300 days/year.

For, example the detail of the TN demand calculation is given below.

TN demand:

According to the literature, the average TN demand is 137.5 mg//L of water per day per plant (Clark 2017).

In a day, for 1.5 L of water, TN demand per plant is 1.5 L/d * 137.5 mg/L/plant = 208.08 mg/plant/d.

In a year (300 days), TN demand = 208.08 mg/plant/d * 300 d/year = 62 425 mg/year/plant

= about 62 g/year/plant.

TP and Zn demand per year per hop plant is calculated similarly.

6.3.2. Annual dry hops yield potential of breweries' wastewater

Total hop plant growing potential of Hartwall, Sinebrychoff, and Laitilan breweries are calculated based on the quantity of TN, TP, and Zn composition of their WW. The calculation is done by using the following formula:

Total hop plants growing potential = Total nutrient (TN/TP/Zn) in WW per year / Nutrient (TN/TP/Zn) demand per year per plant.

Then, the total dry hops yield potential per year of each brewery is calculated as follows:

Annual dry hops yield potential = Total hop plant growing potential * Dry hops yield per plant (0.9 kg/year/plant).

For example, in the case of Hartwall Oy, the calculation is done as follows:

Hartwall Oy (2008)

Based on the TN composition in the WW of Hartwall Oy, total hop plants growing potential = Total TN content * 1000 g per year / TN demand per year per plant = 27 831 * 1 000 g/year / 62 g/year/plant = about 445 831 hop plants.

Therefore, total hops yield based on TN = 445 831 hop plants * 0.9 kg dry hops/year/plant = 401 248 kg dry hops/year = about 401 tonnes dry hops/year.

Based on the TP composition in the WW of Hartwall Oy, total hop plants growing potential = Total TP content * 1 000 g per year / TP demand per year per plant = 18 030 * 1 000 g/year / 19 g/year/plant = 934 439 hop plants = 934 439 hop plants * 0.9 kg dry hops/year/plant = 840 995 kg dry hops/year = about 841 tonnes dry hops/year.

Similarly, based on the Zn composition in the WW of Hartwall Oy, total hop plants that can be grown = Total Zn content * 1 000 g per year / Zn demand per year per plant = 253 * 1 000 g/year / 0.18 g/year/plant = 1 393 172 hop plants = 1 393 172 hop plants * 0.9 dry hops/year/plant = 1 253 855 kg dry hops/year =1 254 tonnes dry hops/year.

For Sinebrychoff and Laitilan breweries calculation is done in similar ways.

6.3.3. Replacement of dry hops demand

After evaluating the total annual dry hops yield potential of each brewery based on TN, TP, and Zn, the annual demand for dry hops for beer production of each brewery can be replaced. The calculation of the replacement of dry hops demand for each brewery is done by using the following formula:

Replacement of dry hops demand = (Annual dry hops yield potential based on nutrients (TN/TP/Zn) / Total annual dry hops demand) * 100 %.

The dry hops produced by recovering the nutrients from WW of breweries can be surplus than the actual demand or it may not be sufficient to meet the demand requiring the additional quantity, depending on the dry hops use from 2 g to 12 g per L of beer produced. The surplus dry hops or the additional dry hops demand are calculated as follows:

Surplus dry hops = Annual dry hops yield potential based on nutrients (TN/TP/Zn) - Total annual dry hops demand.

Additional dry hops need = Total annual dry hops demand – Annual dry hops yield potential based on nutrients (TN/TP/Zn).

6.2. Nutrient balance calculation

It can be difficult to predict averages for fertiliser application rates and types of fertilisers for hops due to variation in nutrient demand based on soil quality from field to field, as well as variation from farm to farm (Hauser and Shellhammer 2019). The nutrient demand for a hydroponics system can be completely different as the nutrients available in tap water differs from the soil (Clark 2017). From the pilot experiment and the hydroponics hops growing guidebook of Clark (2017), it has been outlined that N, P, K, Ca, Mg, and S are the main nutrients that are required in large quantities to grow hops. Other nutrients that are required in small quantities are Fe, Cu, Mn, Zn, B, and Mo. However, in this research, as only TN, TP, and Zn composition in the WW of case example breweries are known, the nutrient balance calculation is based on these nutrients. In the nutrient balance, the annual demand of nutrients for the total demand of hop plants that can yield required dry hops to meet the annual beer production of each brewery is calculated. Further, assuming the 100% recovery of nutrients composition of WW of each brewery, the capacity of them to replace the demand for artificial fertiliser to grow total hop plants demand is calculated.

6.2.2. Annual demand of nutrients for total hop plants

The demand of TN, TP, and Zn to grow total hop plants that can yield required dry hops to meet the annual beer production of each brewery is calculated by using the following formula:

TN demand for total hop plants production = TN demand per plant (62 g/year) * Total need of hop plants.

TP demand for total hop plants production = TP demand per plant (19 g/year) * Total need of hop plants.

Zn demand for total hop plants production = Zn demand per plant (0.18 g/year) * Total need of hop plants.

6.2.3. Replacement of artificial fertilisers demand

It is assumed that total recovered nutrients including TN, TP, and Zn in the brewery WW are completely bioavailable for the plants. Since the amount of nutrient (TN, TP, and Zn) composition in WW of three case example breweries has the potential to grow hop plants, they have the potential to replace the demand for artificial N, P, and Zn fertiliser that is required to grow total hop plants demand. The potential of nutrient (TN/TP/Zn) composition of WW of each brewery to replace the total demand of artificial fertilisers to produce the total annual demand of dry hops is calculated as follows:

Replacement of N/P/Zn fertiliser, % = (TN/TP/Zn present in WW of brewery / TN/TP/Zn demand for total hop plants production) *100 %.

Like in the calculation of replacement of dry hops demand, the recovery of the nutrients from WW of breweries can be surplus than the actual demand to grow hop plants or it may not be sufficient to meet the demand requiring the additional quantity, depending on the dry hops use from 2 g to 12 g per L of beer produced. The surplus of nutrients or the need for them is calculated as follows:

Surplus of N/P/Zn fertiliser = Nutrients (TN/TP/Zn) present in WW of the brewery - Nutrients (TN/TP/Zn) demand for total hop plants production.

Additional need of N/P/Zn fertiliser = Nutrients (TN/TP/Zn) demand for total hop plants production - Nutrients (TN/TP/Zn) present in WW of the brewery.

6.4. Circularity calculation

The circular economy path is followed when the nutrients from brewery WW are recovered to make organic liquid fertiliser that is utilised to grow hydroponics hop plants or other plants such as barley. Circulating nutrients present in the WW of the brewery not only replace the demand for artificial fertilisers to grow required hop plants to meet beer production of the brewery but also reduces CO_2e emissions that are otherwise emitted using artificial fertilisers. Emissions can be further reduced if CO_2 emitted during the beer production from the brewery is utilised to grow hydroponics hop plants. In the circularity calculation, reduction in CO_2e emissions is calculated based on the utilisation of recovered nutrients from each case example brewery WW. In addition, land use change (LUC) is evaluated if hydroponics system farming is applied instead of soil-based farming to grow hop plants.

6.4.1. Reduction in carbon footprint from N and P recovery

The assumptions regarding fertilisers (N and P) application emissions to grow hop plants in soil-based farming are adapted from Hauser and Shellhammer (2019). It is illustrated in Table 17, which indicates the emission coefficient in kg of CO_2e/kg of fertiliser (N or P) applied. The emission coefficient includes all upstream emissions from fertilisers that are related to production, packaging, storage, and distribution (Hauser and Shellhammer 2019). Other potential nutrient demands such as Ca, Mn, Zn, S, and B are not included in this analysis because of their relatively low application rates, as well as their amount in the WW of case example breweries are not known.

Table 17. Fertiliser emissions data per kg of hops production (Hauser and Shellhammer 2019).

Nutrients	**Emission coefficient, kg of CO_2e/kg of fertiliser**
Nitrogen	4.8 ± 1.1
Phosphorus	0.7 ± 0.2

The emissions from TN and TP application that is required to cultivate the total dry hops demand of each brewery is calculated by using the following formulae:

Emission from TN application to cultivate dry hops demand = N emission coefficient (4.8 kg of CO_2e/kg of N) * TN needs to produce total dry hops demand (kg).

Emission from TP application to cultivate demanded hops = P emission coefficient (0.7 kg of CO_2e/kg of P) * TP need for total dry hops production (kg).

Total emissions from TN and TP application = Emission from TN + TP application to cultivate demanded hops.

After that, a reduction in total CO_2e emissions by utilisation of recovered TN and TP from WW of each brewery to grow hop plants is calculated. It has been assumed that TN and TP present in the WW of the brewery are completely recovered to produce organic liquid fertiliser. The calculation is done by using the following formulae:

Emission reduction from TN recovery = TN present in WW of brewery * N emission coefficient (4.8 kg of CO_2e/kg of N).

Emission reduction from TP recovery = TP present in WW of brewery * P emission coefficient (0,7 kg of CO_2e/kg of N).

Total emission reduction from TN and TP recovery = Emission reduction from TN + TP recovery.

Total emission reduction from TN and TP recovery, % = (Total emission reduction from TN and TP recovery / Total emission from TN and TP) * 100%.

6.4.2. Land use change

According to Clark (2017), about 4 047 m^2 of the land area is required to grow 20 000 hop plants hydroponically and the yield can be approximately 0.9 kg of dry hops per year per plant. Then, the total yield from 4 047 m^2 of hydroponics farm is 18 000 kg (20 000 * 0.9) of dry hops. The average yield of dry hops in soil-based farming in the USA is about 907 kg dry hops per 4 047 m^2 in 2019 (Hauser and Shellhammer 2019; PennState Extension 2021). These figures are illustrated in Table 18. This indicates that the average yield of dry hops per 4 047 m^2 from hydroponics farming is about 20 times higher yield than that of normal soil-based farming.

Table 18. The dry hops yield in kg per 4047 m^2 on hydroponics and soil-based farms. (Clark 2017; Hauser and Shellhammer 2019; PennState Extension 2021).

Farm types	**Dry hops yield, kg/4047 m^2**
Hydroponics farm	18 000
Soil-based farm	907

Land area demand for both hydroponics farms and soil-based farms to grow total hop plants that meet the annual dry hops demand for beer production of each case example brewery is calculated. The calculation is done by using the formula as follows:

Land area demand (Hydroponics / Soil-based) to grow total hop plants need = Total dry hops demand, kg / Dry hops yield, kg per 4047 m^2 of the farm (Hydroponics / Soil-based).

Land use change (LUC) is evaluated by calculating the reduction in land area demand by replacing soil-based hops farming with hydroponics farming. The calculation is done as follows:

Reduction in area demand, acre = Land area demand for soil-based farm – Land area demand for hydroponics farm.

Reduction in land area demand, % of acre = (Reduction in land area demand / Land area demand for soil-based farm) * 100%.

7. Results

The results from mass balance, nutrient balance, and circularity calculations are presented in the following sections. There are uncertainties in the calculation which are due to the assumption of 100% bioavailability of nutrients and 100% recovery of total nutrients (TN, TP, and Zn) from the WW of the brewery. This would reduce the amount of nutrients that plants will get. There is the runoff of nutrient solution from the HydroHumala unit since hop plants may not consume all the nutrients and water. From the pilot experiment, it has been found that about 13% of nutrient solution water is runoff solution. According to Clark (2027), the grower should have a goal of about 10% runoff from each plant each day. After the calculations, the CE model for breweries is visualised with the calculation results. And finally, financial benefits are estimated without numerical calculations.

7.1. Dry hops demand of each brewery

The calculated figure for dry hops demand to meet the annual beer production of each brewery is illustrated in Table 19.

Table 19. Total demand for dry hops and hop plants based on dry hops use of 2 – 12 g/L of beer produced to meet the annual beer production of each brewery.

Parameter (per year)	**Hartwall**	**Sinebrychoff**	**Laitilan**
Beer production, million L	273	32	1.5
Dry hops demand, kg	546 000 - 3 276 000	64 000 - 384 000	3 000 - 18 000
Dry hops demand, t*	500 - 3 000	64 - 384	3 - 18
Total hop plants need	606 700 - 3 640 000	71 100 - 426 700	3 300 - 20 000

*t = tonnes

The total hop plants need to yield dry hops demand is also given in the table. The calculation is based on the dry hops use of 2 g and 12 g/L of beer produced. From the calculation it has been clear that if dry hops use is 2 g/L of beer produced, then dry hops demand is lower compared to dry hops use of 12 g/L of beer produced. For example, in the case of Hartwall brewery annual dry hops demand is about 500 t and 3 000 t if the dry hops use is 2 g and 12 g/L of beer produced respectively.

7.2. Annual demand of nutrients per hop plant

The value of nutrients (TN, TP, Zn) demand per day per hop plant in mg/L of water and mg/1.5 L of water consumption are presented in Table 20.

Table 20. TN, TP, and Zn demand per day per hop plant.

Parameter	**mg/L water/day**	**mg/1.5 L water/day**
TN demand/plant	137.5	151
TP demand/plant	42.5	53
Zn demand/plant	0.4	0.6

The demand for nutrients in mg and g per year per hop plant is illustrated in Table 21.

Table 21. TN, TP, and Zn demand per year per hop plant.

Parameter	**In a year, mg**	**In a year, g**
TN demand/plant	62 000	62
TP demand/plant	19 000	19
Zn demand/plant	182	0.18

It can be noted from the table that the need for TN is about three times higher than TP for a hop plant in a year. The amount of Zn needed is comparatively very smaller than TN and TP.

7.3. Annual dry hops yield potential of breweries' wastewater

The estimated results that determine the capacity of nutrients (TN, TP, Zn) composition of each case example brewery to grow hop plants and yield dry hops are presented in Table 22.

Table 22. Production potential of total hop plants with their dry hops yield for Hartwall, Sinebrychoff, and Laitilan breweries based on the TN, TP, and Zn content in their WW.

Production potential per year		**Hartwall Oy**	**Sinebrychoff Oy**	**Laitilan Oy**
Based on TN	Plants	446 000	NA	960
	Dry hops, kg	401 000	NA	870
	Dry hops, t	401	NA	0.87
Based on TP	Plants	934 000	90 000	11 000
	Dry hops, kg	841 000	81 000	1 000
	Dry hops, t	841	81	10
Based on Zinc	Plants	1 393 000	NA	NA
	Dry hops, kg	1 254 000	NA	NA
	Dry hops, t	1 254	NA	NA

The calculation is based on nutrient demand per year per hop plant. It has been found that breweries have the potential to produce dry hops from about 1 tonne to 1 254 tonnes (t) depending on TN, TP, and Zn composition in their WW.

7.4. Replacement of dry hops demand

The calculation results of replacement of dry hops demand for each brewery based on dry hops use of 2 g and 12 g per L of beer produced is depicted in Table 23. The results show that, if the dry hops use is 2 g/L of beer, then dry hops produced by TP and Zn quantity in

WW of Hartwall can replace about 154% and 230% respectively, and dry hops produced by TP quantity in WW of Sinebrychoff and Laitilan breweries can replace about 127% and 325% of their annual dry hops demand respectively. It means that the dry hops produced by the recovering TP (also Zn for Hartwall brewery) nutrient from WW of all three breweries are surplus than the actual demand and thus the replacement is more than 100% if the dry hops use is 2 g/L of beer. In the table, the minus (-) sign represents the surplus quantity of dry hops produced in *tonnes*. For example, if dry hops use is 2 g/L of beer produced, then dry hops produced by TP and Zn quantity in WW of Hartwall brewery is in the surplus amount of about 290 t and 700 t respectively. And the plus () sign represents the additional need for dry hops in *tonnes*.

Table 23. Replacement percent of dry hops demand per year by each brewery's dry hops yield potential and surplus of dry hops or additional demand of them based on the nutrients (TN, TP, and ZN) composition of their WW and based on dry hops use of 2 - 12 g/L of beer produced. The surplus yield of dry hops and the additional need for dry hops are represented by the minus (-) and plus () signs respectively.

Parameter (per year)		**Hartwall Oy**	**Sinebrychoff Oy**	**Laitilan Oy**
Based on TN	Replacement of dry hops demand, %	73 - 12	NA	29 - 5
	Surplus dry hops / Additional need, t	140 - 2 900	NA	2 - 17
Based on TP	Replacement of dry hops demand, %	154 - 26	127 - 21	325 - 54
	Surplus dry hops / Additional need, t	(-290) - 2 400	(-17) - 300	(-7) - 8
Based on Zn	Replacement of dry hops demand, %	230 - 38	NA	NA

	Surplus dry hops / Additional need, t	(-700) - 2 000	NA	NA

However, if the dry hops use is 12 g per L of beer produced, then the dry hops produced by the recovering nutrients (TN, TP, and also Zn for Hartwall brewery) from WW of all three breweries are not sufficient to meet the annual demand requiring the additional quantity, and the results show that the replacement is less than 50% in all breweries except about 54% in the case of Laitilan brewery based on TP present in their WW.

7.5. Annual demand of nutrients for total hop plants

The results of calculations for the annual demand of nutrients for total hop plants that are required to produce dry hops to meet the annual beer production of each brewery are illustrated in Table 24.

Table 24. The demand of TN, TP, and Zn to grow total hop plants to yield required dry hops that meet the annual beer production of each brewery.

Parameter (per year)	**Hartwall Oy**	**Sinebrychoff Oy**	**Laitilan Oy**
Beer production, million L	273	51	1.5
Total hop plants need	606 700 - 3 640 000	71 100 - 426 700	3 300 - 20 000
TN demand per hop plant, g	62	62	62
TP demand per hop plant, g	19	19	19
Zn demand per hop plant, g	0.81	0.81	0.81
TN demand for total hop plants, kg	37 600 - 225 700	4 400 - 26 500	210 - 1 240
TP demand for total hop plants, kg	11 500 - 69 200	1 400 - 8 100	60 - 380
Zn demand for total hop plants, kg	110 - 660	10 - 80	0.61 - 4

The results are based on dry hops use of 2 g and 12 g per L of beer produced. It is clear from the results that the smaller the use of dry hops quantity per L of beer produced, the lower the total hops plants need and as a result lower nutrients demand. Since the demand for dry hops is higher for Hartwall brewery compared to other breweries, it needs quite a large amount of TN, TP and Zn compared to the other two breweries.

7.6. Replacement of artificial fertilisers demand

Total annual WW generated by each brewery and their nutrients (TN, TP, and Zn) composition are summarized in Table 25.

Table 25. Summary of wastewater produced by each brewery with their nutrients (TN, TP, and Zn) composition.

Parameter (per year)	**Hartwall Oy**	**Sinebrychoff Oy**	**Laitilan Oy**
Wastewater, L	871 650 000	63 299 000	15 900 000
N present in WW of brewery, kg	27 831	NA	60
P present in WW of brewery, kg	18 030	1 740	209
Zn present in WW of brewery, kg	253	NA	NA

The calculation results of replacement of artificial N, P, and Zn fertilisers demand based on dry hops use of 2 g and 12 g per L of beer produced for each brewery is depicted in Table 26. The results are quite similar to the results of dry hops replacement. It translates that replacement of dry hops demand means the replacement of fertilisers demands that are required to yield dry hops demand.

The results of replacement of artificial fertilisers demand show that, if the dry hops use is 2 g/L of beer, then TP (also Zn for Hartwall brewery) recovery from WW of all three breweries can replace artificial P (also Zn for Hartwall brewery) fertilisers demand by more than 100 %. However, if the dry hops use is 12 g per L of beer produced, then the nutrients (TN, TP, and also Zn for Hartwall brewery) recovery from WW of all three breweries are not sufficient to produce the annual dry hops demand requiring the additional quantity of nutrients, and the results show that the replacement is less than 50% in all breweries except about 55 % of artificial P fertiliser replacement in the case of Laitilan brewery. Therefore, the results show that the replacement of artificial fertilisers depends on dry hops use per L of beer produced. Moreover, from the description of all three breweries, it can be noted that the replacement of fertilisers also depends on nutrient quantity in WW of breweries.

Table 26. Replacement of artificial N, P, and Zn fertilisers demand based on dry hops use of 2 - 12 g/L of beer for each brewery.

Parameter (per year)	**Hartwall Oy**	**Sinebrychoff Oy**	**Laitilan Oy**
Replacement of N fertiliser, %	74 - 12	NA	29 - 5
Replacement of P fertiliser, %	156 - 26	129 - 21	330 - 55
Replacement of Zn fertiliser, %	230 - 38	NA	NA

The produced fertilisers by breweries are either in surplus quantity than the actual demand or they are insufficient to meet the demand, thus requiring an additional need for nutrients based on the dry hops use of 2 g/L and 12 g/L of beer produced. This is illustrated in Table 27. In the table, the minus (-) sign represents the surplus quantity of nutrients in *kg* than the actual demand. And the plus () sign represents the additional need for nutrients in *kg*.

Table 27. Surplus of N, P, and Z fertilisers produced by each brewery's WW or additional need of them that is needed to produce dry hops to meet annual beer production of each brewery based on dry hops use of 2 -12 g/L of beer. The surplus quantity of nutrients and the need for additional nutrients are represented by the minus (-) and plus () signs respectively.

Parameter (per year)	**Hartwall Oy**	**Sinebrychoff Oy**	**Laitilan Oy**
Surplus N fertiliser / Additional need, kg	9 800 - 197 900	NA	150 - 1 180
Surplus P fertiliser / Additional need, kg	(-6 500) - 51 100	(-390) - 6 370	(-150) - 170

Surplus Zn fertiliser / Additional need, kg	(-140) - 410	NA	NA

From the calculation results, it has been found that a surplus quantity of only P fertiliser is available for all the breweries and also Zn fertiliser for Hartwall brewery when the dry hops use is 2 g/L of beer produced. However, if the dry hops use is 12 g/L, the additional N, P and Zn fertilisers are needed for the breweries.

7.7. Reduction in carbon footprint from N and P recovery

The calculation results of reduction in carbon footprint (CO_2e emissions) by recycling of WW (TN and TP recovery) of each brewery are illustrated in Table 28.

Table 28. Total emission reduction by N and P recovery from WW of each brewery based on dry hops use of 2 – 12 g/L of beer produced.

Parameter	**Hartwall Oy**	**Sinebrychoff Oy**	**Laitilan Oy**
Emissions from TN application, t of CO_2e	181 - 1 083	21 - 127	1 - 6
Emissions from TP application, t of CO_2e	8 - 48	1 - 6	0-04 - 0.26
Total emissions from TN and TP application, t of CO_2e	190 - 1 000	22 -133	1 - 6
Emission reduction from TN recovery, t of CO_2e	134	NA	0.28
Emission reduction from TP recovery, t of CO_2e	13	1.21	0.14

Total emission reduction from TN and TP recovery, t of CO_2e	146	1.21	0.43
Total emission reduction from TN and TP recovery, %	78 - 13	6 - 1	42 - 7

It has been found that, if dry hops use is 2 g/L of beer produced then CO_2e emission reduction can be about 78 %, 6 %, and 42 %, whereas if dry hops use is 12 g/L of beer produced then CO_2e emission reduction can be about 13 %, 1 % and 7 % from total emissions by N and P application for production of total dry hops demand by Hartwall, Sinebrychoff and Laitilan breweries respectively. It has been assumed that TN and TP present in the WW of each brewery are fully recovered to produce organic liquid fertiliser and are completely bioavailable.

7.8. Land use change

The calculated figure for the reduction in area demand by replacing soil-based hops farms with hydroponics hops farms is illustrated in Table 29. The results are based on dry hops use of 2 - 12 g/L dry hops.

Table 29. The total demand of land area for hydroponics farms to grow total needed hop plants.

Parameter	**Hartwall Oy**	**Sinebrychoff Oy**	**Laitilan Oy**
Beer production, million L	273	32	1.5
Total dry hops demand, t per year	546 - 3 276	64 - 384	3 - 18
Area demand for hydroponics farm, m^2	122 800 - 737 000	14 300 - 86 000	700 - 4 000

Area demand for soil-based farms, m^2	2 436 000 - 14 617 000	286 000 - 1 713 000	13 400 - 80 000
Reduction in area demand, m^2	2 313 000 - 13 880 000	271 000 - 1 627 000	12 700 - 76 000
Reduction in area demand, % of an acre	95	95	95

From the calculation results, it has been found that if a hydroponics farm is applied instead of a soil-based farm to grow hop plants that meet the annual beer production of Hartwall, Sinebrychoff, and Laitilan breweries, then the total demand of space or land area can be significantly reduced by about 95% in both cases of dry hops use of 2 g/L and 12 g/L of beer produced. In other words, results show that land use change (LUC) to the hydroponics farming system requires about 95% less space than that of soil-based farming for growing the same number of hop plants, which is a significant reduction in land area demand.

7.9. Visualisation of the circular economy model in breweries

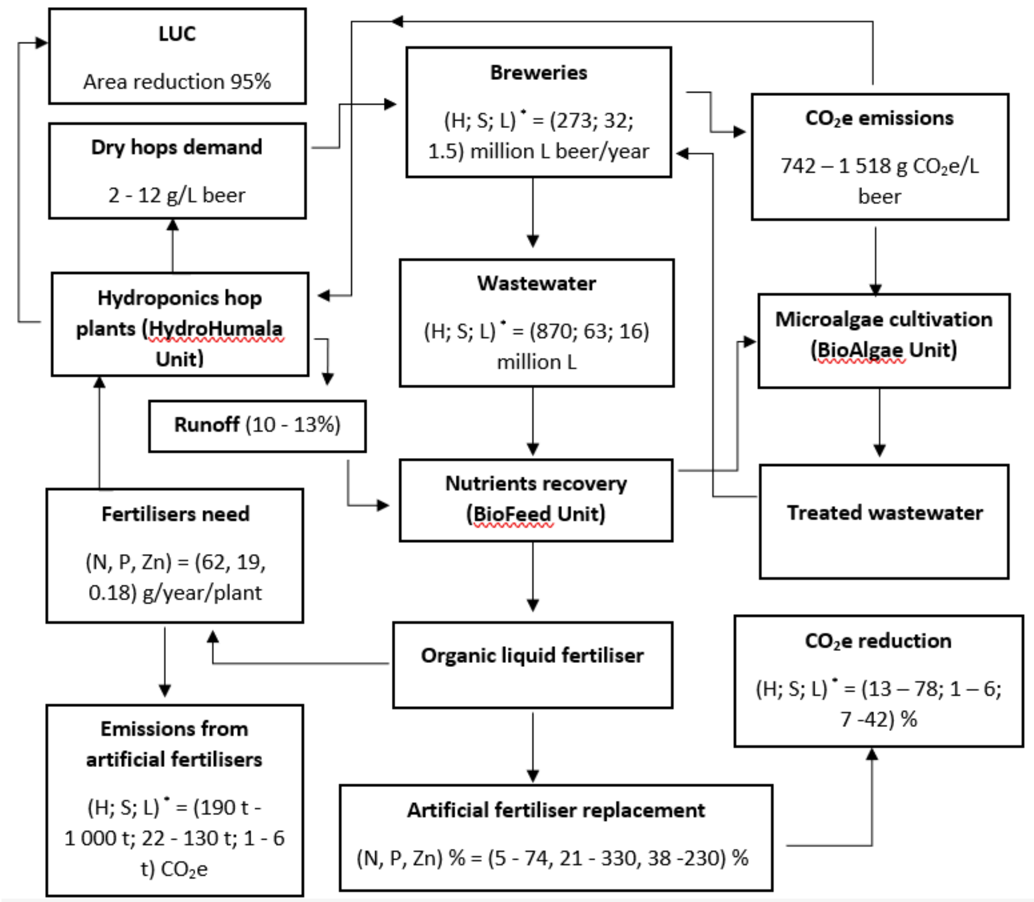
An ideal concept of this thesis is to apply the circular economic (CE) model in breweries. Recycling breweries WW and recovering nutrients present in it to produce liquid fertilisers for growing hop plants follow three principles of CE as defined by Ellen Macarthur Foundation (2022), which are: (1) eliminate waste and pollution; (2) circulate products and materials; and (3) regenerate nature. Further, the approach of the CE model can be enhanced if transportation is minimized to perform different circular activities such as recycling. The visualisation of the CE model in breweries and the overall synopsis of the results are presented in the flow diagram represented in *(H; S; L): (Hartwall; Sinebrychoff; Laitilan).

Figure *4*.

In the flow diagram, beer production of Hartwall (H), Sinebrychoff (S), and Laitilan (L) breweries along with their WW generation is given. WW generated from these three breweries proceed to the BioFeed unit where nutrients in WW are recovered to produce organic liquid fertiliser. The produced fertiliser from the BioFeed-system is utilised in the

HydroHumala unit to grow indoor hydroponics hop plants. The demand of artificial fertilisers (N, P, and Zn) is replaced by the produced organic fertiliser. About 90% of brewery WW nutrients can be recovered as fertiliser.

Dry hops demand for beer production is fulfilled by the hops yield from HydroHumala unit. The runoff from HydroHumala unit goes back to BioFeed unit for nutrient recovery and recycling this to the BioAlgae unit for microalgae cultivation. The BioAlgae unit also works as a biotechnological water purification system, from where the water can be recycled back to the brewery, i.e., CIP-tank for cleaning purposes.



*(H; S; L): (Hartwall; Sinebrychoff; Laitilan).

Figure 4. The visualization of the CE model in breweries and overall synopsis of the thesis results.

CO_2 emitted during the brewing process can be captured and supplemented to the HydroHumala unit for hop plants. CO_2 can also be directed to BioAlgae unit, but it is out of the focus of this thesis. CO_2 emissions from the brewing process of three case examples are not known from their environmental permits. The value of 740 - 1 518g of CO_2e emissions presented in Figure 4 is based on literature (Brewers Association). The demand for CO_2 for indoor hop plants is out of the scope this study. Therefore, further calculation on the reduction of carbon footprint by breweries by utilising their CO_2 emissions is not done in this study.

Total CO_2e emissions by application of artificial fertilisers (N and P) demand to produce required dry hops for each brewery is presented in the flow diagram. Then, the reduction in CO_2e emissions by the utilisation of recovered nutrients (N and P) to produce the required dry hops is presented. In addition, the reduction in land area due to LUC from soil-based farms to hydroponics farms for hops production is mentioned in the flow diagram. To enhance the approach of the CE model BioFeed, HydroHumala, and BioAlgae units are kept in the vicinity of the brewery so that all the circular activities can be done immediately with a minimum requirement of transportation, which will reduce greenhouse gas (GHG) emissions and costs from transportation.

7.10. Financial benefits

The economics of the breweries is directly affected by water usage and disposal in breweries, with rising costs for fresh water and WW management cost (Gertsen and Sønderby 2009, 4). Together with environmental benefits, brewers can achieve financial benefits in the following ways:

1) Local hops produced in the vicinity of the brewery may be cheaper than imported from overseas if it is a warm country where hops production can be done all round year without the need of extra heat and artificial light. However, if it is a cold country, then the cost for extra heat and artificial light might make production cost expensive.
2) As the demand for artificial fertilisers can be replaced from about 5% to 330% by producing own fertilisers, expenditure on buying fertilisers will be less.
3) When CO_2 produced from the brewery is utilised to grow indoor hydroponics hop plants, the additional cost needed to supplement CO_2 for the indoor hops farm will

be reduced. This further reduces CO_2 taxation, if the brewery is obliged to pay CO_2 taxation.

4) Fewer fees or no fees need to be paid to WWTP for discharging WW to the sewer as discharged WW after treatment will have very fewer organic compounds and nutrients load or no nutrients load at all if they are completely recovered.
5) If treated WW after producing organic liquid fertiliser is re-circulated for growing hydroponics hop plants or growing microalgae or cleaning purposes, then brewers need less amount of fresh water supply, and this may save huge costs that are needed for freshwater supply.

Above are the estimated financial benefits that breweries can achieve from different approaches upon implementing the concept of this thesis. The calculation of actual figures for financial benefits is out of the scope of this research.

8. Discussions

The nutrients present in the runoff from the HydroHumala unit can be recovered and thus can be recirculated into the system. However, for this, the exact elements present in the runoff solution must be known so that it can make sure the need for new nutrient salts with their quantity, and thus accurate and consistent nutrient formula is made. This process can be costly and time-consuming as it requires expensive testing constantly as well as continual reanalysing nutrient salt additions. It may be more beneficial and practical for very large-scale operations than for smaller scale (Clark 2017).

When the nutrients and all the organic compounds are recovered efficiently from WW, the nutrient load in the WW would be very low and thus it is less likely to pollute water sources even if it is discharged into the environment. Further, the reuse of treated WW that emerges from the BioAlgae unit can reduce the water footprint by saving millions of L of freshwater use. To estimate reduction in the water footprint, the volume of treated WW needs to be evaluated. This evaluation is out of the scope of this thesis.

There are nutrient discharge risks caused by fertiliser transportation. The Baltic Marine Environment Protection Commission highlights that the loading and unloading of fertilisers at the harbour and cleaning the holds of ships that carry fertilisers in the open sea can cause nutrient discharges, which are one of the major contributors to the eutrophication of the Baltic Sea. A spillage of only 0.5% is permitted for fertiliser shipments in one cargo. One cargo can contain about 5 000 t of fertiliser. According to estimates, a tenth (0.05%) of the cargo can end up in the sea as spillage. If the fertiliser contains 5% of P, then 125 kg of P ends up in the sea from a single ship and this is enough to generate 125 t of algae. (John Nurmisen Säätiö 2020) Therefore, becoming self-reliant on fertilisers reduces the shipment and thus can contribute to some extent to the conservation of the sea. However, the fertilisers needed for total hops growing are lower compared to the total fertiliser demand in Finland. Therefore, contributions to sea conservation can be insignificant if total fertiliser demand other than for hops growing is shipped as usual.

Self-reliance on fertilisers and local production of hops, cut down the import of fertilisers and tons of hops every year and consequently, it reduces GHG emissions from transportation of them. The estimation of GHG emissions from the shipment of hops and fertilisers is out of the scope of this study. However, a reduction in emissions only from transportation may not have a significant impact to decrease emissions from the overall hops production if GHG emissions from the growing phase of hops are large. There can be differences in GHG emissions during the growing phase depending on how and where hops are grown. Emissions from the growing phase of hydroponics hops and soil-based hops can be totally different. Similarly, emissions from the hops grown outdoors (hydroponically or soil-based) in warm countries and hops grown indoors hydroponically in a cold country like Finland for 300 d/year can be significantly different. In indoor hydroponics farming, there is a need for additional heating and artificial lighting. Energy usage by such heating and lighting can be intensive which can cause more GHG emissions in indoor farming compared to outdoor. The source of energy is also another factor that has an impact on GHG emissions. Energy usage of hydroponics farms and corresponding GHG emissions is not evaluated in this study. Further, the calculation of the reduction of carbon footprint by breweries by utilising their CO_2 emissions is not done in this study. This thesis is focused on the nutrient balance and could not include the emissions from the whole Life Cycle Assessment (LCA) of hops growing.

The financial benefits from growing local hops in indoor hydroponics systems cannot be predicted without knowing the actual cost of heating and artificial lighting needed for indoor growing systems. Due to the intensive use of energy, it can be speculated that indoor hops farming can be costly. Nevertheless, hops yield in hydroponics farming can be 20 times higher than that of soil-based farming (Clark 2017; Hauser and Shellhammer 2019; PennState Extension 2021), which may contribute to profitability. But a comprehensive study must be done on it to evaluate it.

9. Conclusions

The potentiality of three Finnish breweries has been evaluated and findings show that nutrients (TN, TP, and Zn) composition in their WW can produce dry hops from about 1 t to 1 200 t per year. Also, the potentiality of these nutrients to replace the annual demand of artificial fertilisers for growing hop plants to yield annual dry hops demand is evaluated. From the findings of this study, it can be concluded that the replacement of artificial fertiliser is dependent on the use of dry hops per L of beer produced, nutrient quantity in WW of breweries, and the quantity of beer production. The replacement potentiality can be further enhanced if the runoff solution from the hydroponics system (HydroHumala unit) is recirculated by knowing the exact nutrients present in it.

When the dry hops use is in a small quantity like 2 g/L of beer produced, then most of the nutrient's quantity in breweries' WW are sufficient to produce annual dry hops demand for beer production. The smaller quantity of dry hops used in beer means lower demand for them and higher replacement of fertiliser demand to grow hop plants. For example, findings show that in the case of Hartwall brewery, when the dry hops use is 2 g/L of beer produced, the necessity of buying artificial N, P, and Zn fertilisers can be replaced by about 74%, 156%, and 230% respectively. But when the dry hops use is 12 g/L of beer produced, the replacement of artificial N, P, and Zn fertilisers are about 12%, 26%, and 38% respectively. Similarly, in the case of Sinebrychoff brewery, replacement of artificial P fertiliser is about 129% and 21% when the dry hops use is 2 g/L and 12 g/L of beer produced respectively. And in the case of Laitilan brewery replacement of artificial N and P fertilisers are about 29 - 5% and 330 - 55% depending on the dry hops use of 2 - 12 g/L of beer produced respectively. The replacement of artificial N fertiliser in the case of Laitilan brewery is just 29% even when dry hops use is in a smaller quantity of 2 g/L of beer produced because N content in Laitilan's WW is small, which is only 4 mg/L of WW compared to 32 mg/L of WW of Hartwall brewery.

The environmental benefits that can be achieved from the implementation of this thesis work are reduction in carbon footprint by less CO_2e emissions of about 400 to 146 000 kg CO_2e from TN and TP recovery, that will otherwise be emitted by the production of artificial N and P fertilisers that are applied to produce hops; about 95% of less demand of land area by LUC from soil-based hops farm to hydroponics hops farm; fewer GHG emission by becoming self-reliant in hops and fertilisers demand, however it depends on how and where hops are grown (indoor or outdoor in hydroponics or in soil-based farming); reduction in spillage of fertilisers into the sea due to fewer shipment of them, thus less contribution towards the eutrophication of the sea, such as Baltic Sea; reduction in water footprint by reusing treated WW that generates after production of organic liquid fertiliser for cleaning purposes or growing hops or other plants. Even if treated WW is discharged into the environment it is less likely to pollute the water sources. Thus, it won't contribute to the pollution of water bodies. Additionally, non-renewable resources of fertilisers such as phosphate rock will be preserved when nutrient like P is recovered and reused as fertiliser. The achievement in environmental benefits contribute to climate change mitigation and helps in achieving seven SDGs of the UN which are *Goal 6: Clean Water and Sanitation, Goal 9: Industry, Innovation, and Infrastructure, Goal 11: Sustainable Cities and Communities, Goal 12: Responsible Consumption and Production, Goal 13: Climate Action, Goal 14: Life Below Water, and Goal 15: Life On Land.*

Breweries can get the financial benefits from the savings that are achieved by becoming self-reliant on dry hops demand or buying fewer of them, however, hops grown in indoor hydroponics systems can be costly due to intensive energy use. Further, savings can be made from buying fewer fertilisers, no need or less need of CO_2 supplements for indoor hops growing, paying less CO_2 tax, paying less fee, or no fee at all to the municipality for discharging treated WW, and less demand for fresh water supply.

Implementation of this thesis work can play a vital role in the paradigm shift of current breweries towards the sustainable practice of beer production and WW management. Breweries not only achieve environmental and financial benefits, but they can also become self-sufficient in beer production, by growing indoor hop plants throughout the year, which will be less dependent on climate change (conventional soil-based outdoor hops production is climate dependent). On top of that beer produced by such breweries will have brand value. From the customer's point of view, they might be more satisfied to have a beer that has a sustainable story to tell. Breweries can be an example to other manufacturing industries as well. They also enhance the sustainability of the city or the country they belong to and help in maintaining the green image of the city.

9.1. Limitations and future research

The limitations of this research work are that the analysis of hydroponics hops production potential and replacement of artificial fertilisers demand are based only on TN and TP present in the WW of Sinebrychoff and Laitilan breweries and TN, TP, and Zn present in the WW of Hartwall brewery. Also, the reduction in CO_2e emissions is based only on the replacement of N and P fertilisers. There might be the presence of other essential nutrients in the brewery WW which are necessary for the growth of hop plants. In the future, further research can be carried out by analysing other essential nutrients in the brewery WW. This analysis will give more precise results to conclude the capacity of all recovered nutrients from WW of breweries to produce hydroponics hops and replacement of artificial fertilisers demand with more essential nutrients content. In addition, the exact nutrients present in the runoff solution coming out from HydroHumala unit are not known. Future research on it helps to determine how much nutrients can be saved further by recirculating runoff solutions for growing hops.

The quantitative evaluation of water footprint reduction is not done in this research because the volume of treated WW after the production of organic liquid fertiliser from BioFeed unit is not known. Further research is needed to estimate it and a laboratory or pilot scale experiment might be needed to evaluate if this treated WW is suitable for growing hydroponics hops or other plants. In addition, the estimated CO_2 emissions only from a brewing process and the CO_2 consumption particularly by indoor hop plants are not evaluated. Future research can be done to determine the exact CO_2 emissions from the brewing process and supplement CO_2 needed for indoor hop plants.

Further study can be done on what is the total demand for fertiliser for growing total hops need in Finland and an estimation can be done on how much spillage will be prevented if become self-reliant on that fertiliser demand. Future research can also be done on the whole life cycle assessment (LCA) of breweries, indoor/outdoor hydroponics hops farm, and soil-based hops farm that includes emissions from energy consumption as well. This study will help to estimate the total carbon footprint of breweries and the sustainability of different farming practices. This estimation helps to understand how much total carbon footprint breweries can reduce by producing fertilisers from the recovery of nutrients in their WW and utilising that fertiliser to produce hops in indoor/outdoor hydroponics or soil-based farming.

Additionally, the evaluation of financial benefits with profitability calculations in figures is not done in this research. Financial analysis should focus on the total cost of production of indoor hydroponics hops. The study would be more thorough and interesting if the financial benefits can be estimated in figures based on the recycling WW of breweries. Future research on the comparison between overall financial costs for indoor hydroponics and outdoor soil-based hops farming is also recommended.

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