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Sustainability assessment of urine concentration technologies

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Matilda Gunnarsson

Abstract

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The majority of the nutrients in household wastewater are found in the urine and in order to facilitate the use the nutrients in the urine as fertilizer, the urine can be can be concentrated. To extract the nutrients from the urine, various technologies for urine concentration are being developed today. As the technologies are relatively new, urine concentration systems have not been installed on a larger scale. In this study, sustainability of three different urine concentration technologies was evaluated through a fictional case study for 2100 people that took inspiration from a planned residential area in Malmö, Sweden, where technology for urine concentration will be implemented in at least one of the buildings. The technologies were evaluated through a multi-criteria assessment (MCA), where different criteria within sustainability categories environment, technical, economic and health were determined based on the Sustainable Development Goals (SDGs). The technologies examined were alkaline dehydration, nitrification-distillation and ion-exchange using a pre-step of struvite precipitation. For the alkaline dehydration technology, fresh urine is added to an alkaline medium, in order to prevent nitrogen losses, and then dried. In the nitrification-distillation technology, stored urine is treated by first being stabilized by a partial nitrification and then distilled in order to reduce the volume. For the ion-exchange and struvite precipitation system, phosphorus is first precipitated from stored urine and nitrogen is then extracted through ion-exchange. The urine concentration technologies were assumed to be installed in semi-centralized treatment plants in basements in the residential area. The other household wastewater was assumed to be treated in the local wastewater treatment plant (WWTP). The results showed that all three urine concentration technologies may contribute to a significant increase in nitrogen recovery from the household sewer. However, this may come at the expense of increased annual costs for the population. Before it is possible to determine whether urine concentration can be an alternative as a complement to the existing wastewater treatment, further studies of the urine concentration technologies and their sustainability are required. However, this study indicated that urine concentration technologies perform well in many of the sustainability criteria examined and therefore have potential to contribute to the SDGs, especially regarding nitrogen recovery. This study can therefore be an incentive for further studies, where the sustainability of an implementation of urine concentration in Sweden is addressed.

Keywords: Wastewater treatment, urine concentration, alkaline dehydration, nitrification-distillation, ion-exchange, struvite precipitation, MCA

Department of Energy and Technology, Swedish University of Agricultural Sciences, Lennart Hjelms väg 9, SE-75651 Uppsala. ISSN 1401-5765

Referat

Hållbarhetsanalys av urinkoncentreringsteknik

Matilda Gunnarsson

Majoriteten av näringen i hushållsavloppsvattnet finns i urinen och för att underlätta användningen av växtnäringsämnena i urinen som gödningsmedel kan den koncentreras. För att utvinna näringen ur urinen utvecklas idag olika tekniker för urinkoncentrering. Då teknikerna är relativt nya har system för urinkoncentrering inte installerats i en större skala. Därför utvärderades hållbarheten för tre olika urinkoncentreringsmetoder genom en fiktiv fallstudie som innefattade 2100 personer. Fallstudien fick inspiration från ett planerat bostadsområde i Malmö, Sverige, där teknik för urinkoncentrering ska implementeras i minst en av byggnaderna. Teknikerna utvärderades genom en multikriterieanalys (MKA), där kriterier inom hållbarhetskategorierna miljö, teknik, ekonomi och hälsa valdes utifrån de Globala målen. De tekniker som utvärderades var alkalisk urintorkning, nitrifikations-destillering och jonbyte där struvitutfällning tillämpades som förbehandling. För den alkaliska urintorkningen tillförs färsk urin till ett alkaliskt medium, för att förhindra kväveförluster, och torkas sedan. I nitrifikations-destillerings tekniken behandlas lagrat urin genom att det först stabiliseras genom en partiell nitrifikation för att sedan destilleras för att reducera volymen. För systemet med jonbyte och struvitfällning, fälls först fosfor från lagrat urin ut och sedan utvinns kvävet genom jonbyte. Urinkoncentreringsteknikerna antogs anläggas i semi-centraliserade reningsverk i källare i bostadsområdet. Övrigt hushållsvatten antogs renas i det lokala avloppsreningsverket. Resultatet visade att samtliga av de tre teknikerna för urinkoncentrering kan bidra till en betydande ökning kväveåtervinning från hushållsavloppet. Dock kan detta komma på bekostnad av ökade årliga kostnader för de boende i området. Innan det är möjligt att avgöra om urinkoncentrering kan vara ett alternativ som ett komplement till den befintliga avloppsreningen i Sege Park krävs vidare studier av urinkoncentreringsteknikerna och deras hållbarhet. Däremot visade denna studie att urinkoncentreringsteknikerna presterar bra i många av de undersökta hållbarhetskriterierna och har därför potential att bidra till de Globala målen, främst när det gäller kväveåtervinning. Denna studie kan därför vara ett incitament för vidare studier som behandlar hållbarheten av en implementering av urinkoncentrering i Sverige.

Nyckelord: Avloppsvattenrening, urinkoncentrering, alkalisk urintorkning, nitrifikations-destillering, jonbyte, struvitfällning, MKA

Institutionen för energi och teknik, Sveriges lantbruksuniversitet (SLU), Lennart Hjelms väg 9, SE-75651 Uppsala. ISSN 1401-5765

Preface

This master thesis comprises 30 credits and concludes my studies at the Master's Programme in Environmental and Water Engineering at Uppsala University and the Swedish University of Agricultural Sciences (SLU). The supervisor was Jennifer McConville and the subject reviewer was Cecilia Lalander, Department of Energy and Technology, SLU. The examiner was Rickard Pettersson, Department of Earth Sciences, Uppsala University.

First I want to say thank you to my supervisor Jennifer for all the help and support throughout this thesis, and for always taking your time to answer my many questions. Then I also want to thank my subject reviewer Cecilia for valuable input and support in the writing and before the presentation of this thesis. Thank you to Jenna Senecal, Prithvi Simha and Chinmoy Kanti Deb in the Environmental Engineering Research Group at SLU as well for providing information regarding the alkaline dehydration technology.

Finally, thank you to my family and friends for being there for me during this thesis and throughout my studies. I could not have done this without you.

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Populärvetenskaplig sammanfattning

Hållbarhetsanalys av urinkoncentreringsteknik

Matilda Gunnarsson

Grödor förses med gödsel innehållandes näringsämnen som kväve och fosfor för att få en bra tillväxt. Grödorna konsumeras sedan av oss människor för att sedan, via toalettstolen, transporteras till ett reningsverk där det sker en rening av kväve och fosfor för att minska utsläppen av dessa växtnäringsämnen. En viss koncentration av kväve och fosfor finns dock kvar i det behandlade avloppsvattnet som släpps ut till närliggande vattendrag, vilket bidrar till övergödning. Genom att utvinna näringen från hushållsavloppet och använda den som gödsel kan det bidra till ett mer cirkulärt samhälle samtidigt som den negativa påverkan på miljön minskar.

Slam från reningsverk i Sverige kan vara certifierat och tillåts spridas på åkermark om det uppfyller vissa kvalitetskrav. Halten fosfor i slammet är hög, men enbart en liten del av kvävet hamnar i slammet. I Sverige har ett förslag om förbud mot spridning av avloppsslam förts fram av regeringen som potentiellt kan förbjuda användningen av slam som gödsel. Ett av förslagen förespråkar ett totalförbud, men ett annat förslag inkluderar undantag som kan skapa en öppning för innovativa tekniker för näringsutvinning från avloppsvattnet.

Den del av avloppet från hushåll som innehåller mest näringsämnen är urin som innehåller 80-90% av kvävet och 50-80% av den fosfor som finns i toalettavloppsvattnet. Urin innehåller samtidigt mycket vatten som gör att koncentrationen av kväve och fosfor i urin är låg. Genom att koncentrera urinen kan transport och användning av urin som gödsel förenklas. Detta kan ske antingen genom att vatten förs bort från urinen eller att näringsämnen utvinns från urinen. Olika tekniker har utvecklats för urinkoncentrering, men teknikerna är under utveckling och ännu inte optimerade.

Hållbarheten med avseende på olika hållbarhetskriterier för tre olika metoder för urinkoncentrering utvärderades i en fiktiv fallstudie för Sege Park, ett område i Malmö där 700 nya bostäder ska byggas. Studien antogs omfatta 2100 personer. Metoderna som utvärderades var alkaisk urintorkning, nitrifikations-destillering och struvitfällning efterföljt av jonbyte. Alkalisk urintorkning är en metod där färsk urin tillsätts till ett basiskt medium för att stabiliseras och därmed undvika kväveförluster vid den efterföljande torkningen. Vid nitrifikations-destillering stabiliseras lagrat urin genom en nitrifikationsprocess för att sedan koncentreras genom destillering. Vid struvitfällning tillsätts magnesium till lagrat urin för att fälla ut fosfor från urinen och jonbyte används för att utvinna kvävet. Den kväve och fosforfria lösningen efter struvitutfällningen behöver sedan vidare behandling och antogs i denna studie behandlas i avloppsreningsverket. Gemensamt för alla metoder var att kväveåtervinningen var markant högre jämfört med det konventionella systemet. Däremot bidrog alla system till ökade årliga kostnader för de boende i området.

För skalan som omfattas i studien hade inte urinkoncentrering en effekt på koncentrationen av kväve och fosfor i utsläppen från avloppsreningsverket. Därför undersöktes även en uppskalning av installationen av urinkoncentreringstekniker, vilken visade på att urinseparering kan bidra till minskade utsläpp, främst av kväve. Det undersöktes även hur mycket av det urin som produceras i Malmö som behöver behandlas med urinkoncentrering för att täcka gödselbehovet för åkermarken där. Resultatet visade att redan om hälften av urinen behandlas med urinkoncentrering kan majoriteten av gödselbehovet täckas.

Acronyms and abbreviations

Cd - Cadmium

K - Potassium

MCA - Multi-Criteria Analysis

N - Nitrogen

NFS 2016:6 - Regulations on treatment and control of discharges of wastewater from urban areas

P - Phosphorus

SDG - Sustainable Development Goal

SuSanA - Sustainable Sanitation Alliance

WHO - World Health Organization

WWTP - Wastewater Treatment Plant

Contents

1 Introduction

The population is growing and cities are expanding, which generates larger streams of wastewater. In turn, this increases the load of wastewater, both volume and pollutants such as nutrients, to the wastewater treatment plants (WWTP). Nitrogen and phosphorus are eutrophying nutrients and therefore there are limit values for the emissions of these nutrients (Swedish EPA 2016). Nitrogen and phosphorus are partially removed from the wastewater at the WWTP. The remaining nitrogen and phosphorus are discharged to the recipient. The eutrophying emissions are likely to increase when cities are growing, which can have negative effects on the recipient and thus on the Sustainable Development Goal (SDG) 14 (Life below water). In order to avoid an increase or to even decrease the concentration of nutrients in the effluent from the WWTP, more energy can be needed for the process (Åmand et al. 2016). At the same time, nitrogen and phosphorus are nutrients that are used in agriculture, where crops are supplied with N and P rich commercial fertilizers (The Swedish Board of Agriculture 2021). The nutrients are taken up by plants and then removed from the fields during harvest, which in turn is compensated for by applying more commercial fertilizer. The crops are consumed by humans and the containing nutrients are then excreted and sent to a WWTP plant. This linear system also leads to soil nutrient stripping (Harder et al. 2019). Further, according to Steffen et al. (2015) both the biogeochemical flows phosphorus and nitrogen are outside the planetary boundaries as well as the safe operating space. The soil nutrient stripping and the overshoot of the planetary boundaries can argue that it is important to expand the use of human excreta as fertilizer to enable a more closed loop society in line with SDG 12 (Responsible consumption and production).

The majority of the nutrients found in toilet wastewater comes from human excreta and particularly from the urine fraction (Fumasoli et al. 2016). Approximately 80-90% of the nitrogen, 50-80% of the phosphorus and 80-90% of the potassium in human excreta can be found in the urine (Vinnerås 2001). Still, the nutrient concentration in urine can be considered low. About 95% of urine is water and less than 1% is nitrogen (Vinnerås et al. 2006). This can be compared to urea and ammonia nitrate that are commonly used fertilizers and contain 46 and 35% nitrogen, respectively. By removing the water or extracting the nutrients, the volume is reduced, facilitating transport and the nutrient reuse, for example by enabling the use of the same machinery as what is used for commercial fertilizer (Senecal 2020).

One way of dealing with the low nutrient concentration in urine, and facilitating the collection and transportation, is to concentrate the nutrients in the urine. Today new technologies are under development for urine concentration, where the focus is to recover the nutrients from the urine (Etter et al. 2015, Simha et al. 2020a, Tarpeh et al. 2017). However, it is uncertain if the nutrient recovery may be at the expense of other factors of sustainability and therefore this study aimed to assess the sustainability of three different urine concentration technologies.

1.1 Aim

The aim of this study was to investigate the sustainability of three different technologies for urine concentration from a Swedish perspective, by performing a multi-criteria assessment (MCA), with the intention to evaluate if urine concentration can be a future wastewater management that can contribute to reaching the SDGs connected to the different criteria investigated.

1.2 Research question

In terms of the examined criteria, what are the advantages and the disadvantages of the different urine concentration technologies and can urine concentration be a sustainable alternative as a complement to existing wastewater management from a Swedish perspective?

1.3 Scope

In this study, the evaluation of urine concentration technologies from a Swedish perspective was the main focus and, in order to have a complete wastewater treatment system, they were evaluated as add-ons to the existing wastewater treatment in Malmö. Three different options for urine concentration were evaluated, where blackwater and greywater were assumed to be transported to the WWTP and the urine was assumed to be diverted and transported to semi-centralized treatment plants within the residential area. In order to define a baseline for the assessment, a conventional system, where all the household wastewater was assumed to be treated at a WWTP, was also included. Nutrient recovery was aimed at nitrogen and phosphorus recovery, excluding other important nutrients such as potassium and micronutrients. In addition, the method for the assessment was a MCA, where criteria within the categories environment, technical, economic and health are evaluated. The social aspects were not addressed.

2 Background

2.1 SDGs and Sustainable sanitation

The Sustainable Development Goals (SDGs) are a part of the 2030 Agenda for Sustainable Development that was adopted in 2015. The SDGs consist of 17 goals for a sustainable present and future, where SDG 6 directly targets sanitation. However, according to the Sustainable Sanitation Alliance, SuSanA (2017), sustainable sanitation can have a considerable impact on the other SDGs as well because their definition of sustainable sanitation is reflected in several SDGs. Their definition of a sustainable sanitation system does not only include protecting human health, but also the environment. Further, sustainable sanitation also has to be *economically viable*, *socially acceptable* as well as *technically and institutionally appropriate* (SuSanA 2017).

2.2 Household wastewater

Household wastewater consists of greywater and blackwater and contains nutrients, such as nitrogen, phosphorus and potassium, as well as metals and pathogens (Swedish EPA 1995). Greywater is the wastewater from the kitchen, laundry and bathroom. It also constitutes the largest part of the household wastewater (Vinnerås 2001). However, the wastewater from the toilet is not included in the greywater and is instead denoted as blackwater. The blackwater consists of urine, faeces and flush water and is the most nutrient dense fraction of the wastewater (Vinnerås 2001, Swedish EPA 1995). Generally in

Sweden, the conventional toilet has one bowl and one pipe in which human excreta, toilet paper and flushwater are collected and transported. The household wastewater (black- and greywater) are mixed and transported to a wastewater treatment plant (WWTP) where it is treated.

In Sweden, an average person excretes about 550 kg urine and 51 kg faeces, consumes about 36500 kg greywater and 9 kg toilet paper each year (Vinnerås et al. 2006). According to Svenskt Vatten (2017), the amount of flush water used per person and day is 30 L, which adds up to about 11000 kg each year. For the nitrogen, phosphorus and potassium content of the different fractions, Swedish design values have been suggested in a study by Vinnerås et al. (2006) (Table 1). Based on the numbers presented in Table 1, the household wastewater consists of solely one percent urine. At the same time, the majority of nutrients in the household wastewater can be found in this fraction.

Table 1: Produced wet mass of wastewater per person and year for the different fractions (Vinnerås et al. 2006, Svenskt Vatten 2017).

	Wet mass	N	P	K
Urine (kg/year)	550	4.0	0.4	1.0
Faeces (kg/year)	51	0.6	0.2	0.4
Toilet paper (kg/year)	9	-	-	-
Greywater (kg/year)	36500	0.5	0.2	0.4
Flushwater (kg/year)	11000	-	-	-

2.3 Urine diversion

Urine can be diverted at source using a urine diverting toilet. Urine diversion is used to collect the urine separately from the faeces that have a high concentration of pathogens (Vinnerås 2001). In a Urine-Diverting Flush Toilet water is used to flush both faeces and urine (Tilley et al. 2014). Urine diverting toilets are designed to minimize the dilution of the urine with flushwater (Gundlach et al. 2021, Tilley et al. 2014). This system requires different piping for the collection and transporting of urine to a storage tank, while the blackwater, containing faeces and flushwater is transported to treatment such as WWTP (Tilley et al. 2014). According to Gundlach et al. (2021), installation of urine diverting *NoMix* toilets has been limited because of the designs. It was found in a study by Lienert & Larsen (2010) that the *NoMix* toilets required further development since the design caused problems for 60% of the users. A new design for *NoMix* toilets has since been developed, where the *teapot effect* (that relates the attachment of a fluid to a surface to different parameters) is used (Gundlach et al. 2021). Urine is collected with a minimal amount of water without requiring a user behavior change.

2.3.1 Urine storage

There are some aspects that have to be taken in consideration when designing a urine storage tank. To avoid leakage of urine to the groundwater and vice versa, the material should be watertight (von Münch & Winker 2011). In the case of constructing a permanent storage tank, either plastic or concrete can be used (Tilley et al. 2014). In order to calculate the required storage volume, Equation 1 can be used (von Münch & Winker 2011).

$$V_{storage} = N_{users} \cdot p_{urine} \cdot t_{storage} \cdot f_{timefraction} \tag{1}$$

where, N_{users} is the number of people using the system, p_{urine} is the volume urine produced per person and day, $t_{storage}$ is the storage time and $f_{timefraction}$ is the proportion of the day that the urine diverting toilet is used.

2.3.2 Urea hydrolysis

Urea hydrolysis is the process in which the urea in the urine is degraded to ammonium and ammonia by the enzyme urease, which also leads to an increase of the pH (Chipako & Randall 2020, Udert et al. 2003). Urea is hydrolysed in the pipes and in the storage tank (Senecal 2020, Udert et al. 2003). Most of the urease is in the pipes due to formation of biofilm and fecal cross contamination (Senecal 2020). The extent of the urea hydrolysis during pipe transport depends on the length of the pipe and the effectiveness of the biofilm that is built up in the pipe (Senecal, personal communication). Extended storage time enables complete urea hydrolysis (Tarpeh et al. 2017). According to Udert et al. (2003) complete urea hydrolysis can be performed within a few days in the urine storage tank.

2.4 Urine concentrating technologies

There are mainly two categories for urine concentration (Harder et al. 2019). The first involves concentrating the nutrients by removing the liquids to obtain concentrated liquids, slurries or powders that can be used as fertilizers. In the other category, selected nutrients are recovered from the urine and result in a concentrate of the selected nutrient. However, using technologies from this category, waste products are also generated that have to be treated. This thesis focuses on three different systems for urine concentration.

2.4.1 Alkaline dehydration

Alkaline dehydration belongs to the first category of urine concentration. The method of drying fresh urine in an alkaline medium is investigated by researchers at SLU. The urine is collected from urine diverting toilets or urinals and has a potential of being treated at a household level (Senecal & Vinnerås 2017) or to be semi-centralized if a so called limebox, that adds MgO to the urine, is installed in the toilet (Senecal, personal communication). According to Simha et al. (2021) the MgO addition prohibits the urea hydrolysis during the pipe transport.

The fresh urine is added to an alkaline media with a pH above 10 to prevent hydrolysis of urea and dried. The mass reduction of the urine is over 90%, leaving a concentrate of nutrients in the alkaline media (Simha et al. 2020a). The nutrient recovery from the urine is complete, except for nitrogen. However, it has been demonstrated that over 90% of the nitrogen in the urine can be recovered when dried at 60 °C and at high drying rates (Simha et al. 2020b). From laboratory pilot set-ups it has been demonstrated that the system generates a dry and nutrient dense powder (Simha et al. 2020a). The powder has, after a four days storage at 20 °C, a sufficient pathogen inactivation to use as a fertilizer in Sweden (Senecal et al. 2018). The system has a medium energy consumption of 1 kWh/L urine (Senecal, personal communication).

A pilot field testing was performed in 2019 by Simha et al. (2020c). The system for the field test was designed to dehydrate 30 L urine per day and consisted of three closed plastic boxes, containing an alkaline media (Figure 1). Urine was supplied to the first and third drying box (and to the middle box at an overflow since the drying boxes were interconnected). Hot air was supplied by fans placed on the boxes and the humid air was removed using a dehumidifier. The field test set-up was optimised only for a high dehydration rate, which resulted in a high energy consumption.

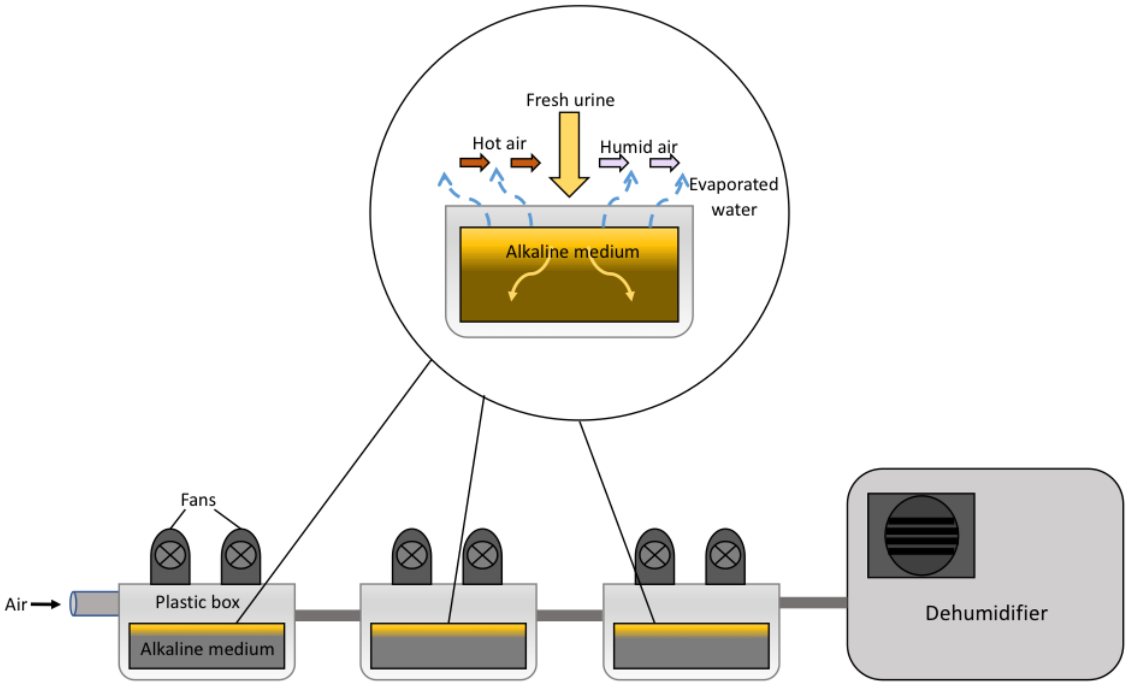

Figure 1: Schematic representation of the alkaline dehydration set-up for the pilot field study.

2.4.2 Nitrification-distillation

The nitrification-distillation method is another example of the first category where the liquid is removed from the urine (Etter et al. 2015). This method of urine concentration was developed by researchers at Eawag and in the VUNA Project that aimed to recover nutrients from urine. In the nitrification-distillation system, urine is diverted in urine diverting toilets or urinals and collected in a storage tank (Etter & Udert 2015). From the storage tank the urine is pumped to a nitrification column (Figure 2). Nitrification is used to stabilize the nitrogen in the urine to avoid the loss of nitrogen as well as malodor. Researchers have found that the nitrification rate (the amount of ammonium converted to nitrate) varies from 100-800 mg/L reactor volume and day (Etter & Udert 2015). To obtain an optimal nitrification, a steady supply of urine and a pH within the range 5.8-6.5 are essential for process stability (Etter et al. 2015, Fumasoli et al. 2016). This is because an overloading of urine can generate an accumulation of nitrite and an underloading of urine can generate a dangerous low pH for the bacteria performing the nitrification. According to Etter et al. (2015) careful process control can enable a stable urine supply and pH. From the nitrification columns the urine is transported, via a sealed intermediate storage tank, to the distiller (Etter & Udert 2015). Distillation is used to evaporate the water from the urine and is performed by a vacuum distiller (Etter & Udert 2015). The distillation process fulfills the pasteurisation requirements and results in complete pathogen inactivation according to Etter et al. (2015). The urine can be treated locally at a treatment plant, but theoretically the technology may also be applied at household level (McConville et al. 2020).

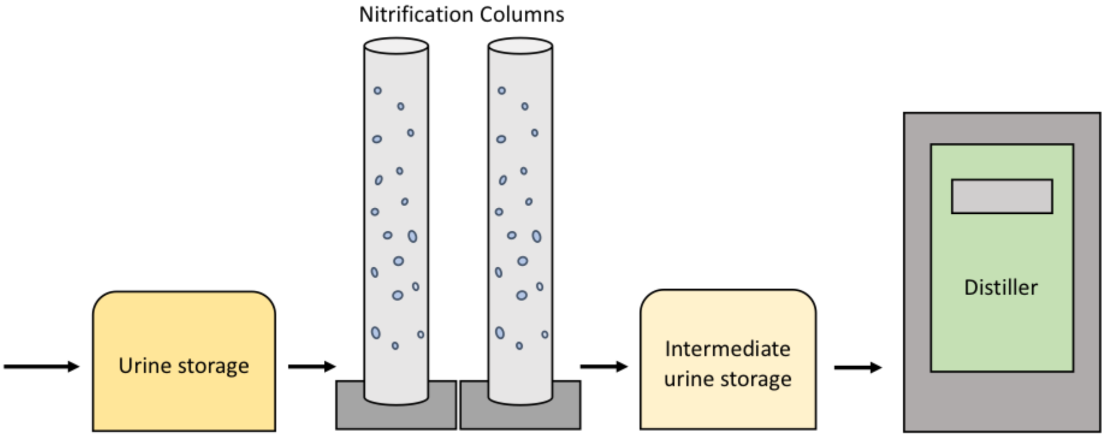

Figure 2: Schematic representation of the nitrification distillation set-up.

According to Etter et al. (2015), the nitrification-distillation method recovers 99% of the nitrogen and has a complete recovery of all the other nutrients in the urine. Furthermore, it removes 97% of the water (Etter et al. 2015). The average energy consumption for one liter of urine is about 150 Wh (Etter & Udert 2015). The final products are distilled water and a concentrated liquid containing a high amount of nutrients, which makes it suitable to use as a fertilizer (Fumasoli et al. 2016). In 2018, the Swiss Federal office of Agriculture licensed the concentrate nutrient solution for use on all crops and the fertilizer goes under the name Aurin (McConville et al. 2020).

2.4.3 Ion-exchange and struvite precipitation

The ion-exchange method as well as the struvite precipitation method recovers selected nutrients (nitrogen for ion-exchange and mainly phosphorus for the struvite precipitation) and therefore they belong to the second category of urine concentration technologies (Etter & Udert 2015, Tarpeh et al. 2017). Urine is diverted and collected separately and stored in sealed containers to keep the urine composition constant by preventing nitrogen losses due to ammonia volatilisation (Tarpeh et al. 2018a). During storage, urea is converted by hydrolysis to ammonium that has a positive charge. Ammonium adsorb to the negatively charged ion-exchange resins (Tarpeh et al. 2017). When exhausted, the resin can be used as a fertilizer as demonstrated in a study by Beler-Baykal et al. (2011) where clinoptilolite was used and the old resin was changed and used as a fertilizer. However, depending on the resin, it can also be regenerated and thereby used again. In a later study performed by Tarpeh et al. (2018a), Dowex Mac 3 that has an adsorption density of around 4 mmol N/g, was used as resin and was regenerated using sulfuric acid. The result from the study showed resin generation efficiencies over 90% that were consistent over ten cycles. With this setup, a total nitrogen recovery of over 99% has been achieved in laboratory trials by Tarpeh et al. (2018b).

In this thesis, the method using Dowex Mac 3 as resin was evaluated. The suggested implementation of the ion exchange technology is a continuous flow column set-up according to Tarpeh et al. (2017). The energy consumption for the process is low and mainly depends on the energy demand of the pumps (Kavvada et al. 2017). During the process only nitrogen is captured from the urine, leaving other important nutrients such as phosphorus in the residuals streams. For phosphorus recovery and disinfection, additional steps are needed according to Tarpeh et al. (2018a). To enable phosphorus recovery, a treatment step with struvite precipitation can be applied and the residual streams could be treated in a WWTP (Tarpeh et al. 2017) (Figure 3).

Struvite ($MgNH_4PO_4 \cdot 6\,H_2O$) is precipitated from urine by adding a magnesium source and separated from the liquid by filtering (Antonini 2013, Etter & Udert 2015). The dried product is a powder that may be used as a fertilizer (McConville et al. 2020). Studies have shown that with struvite precipitation, over 90% of the phosphorus in the urine could be removed (Antonini 2013, Etter & Udert 2015). Furthermore, Antonini (2013) performed a study on nutrient recovery with struvite precipitation combined with ammonia striping. It was found that less than 1 kWh per 50 L urine was used for struvite precipitation. For the pathogen inactivation from the struvite fertilizer product, drying at a low relative humidity and at temperatures above 35 °C is recommended; the drying temperature should however be under 40-55 °C to avoid struvite decomposing (Decrey et al. 2011). According to Decrey et al. (2011), urine and struvite storage could also result in pathogen inactivation.

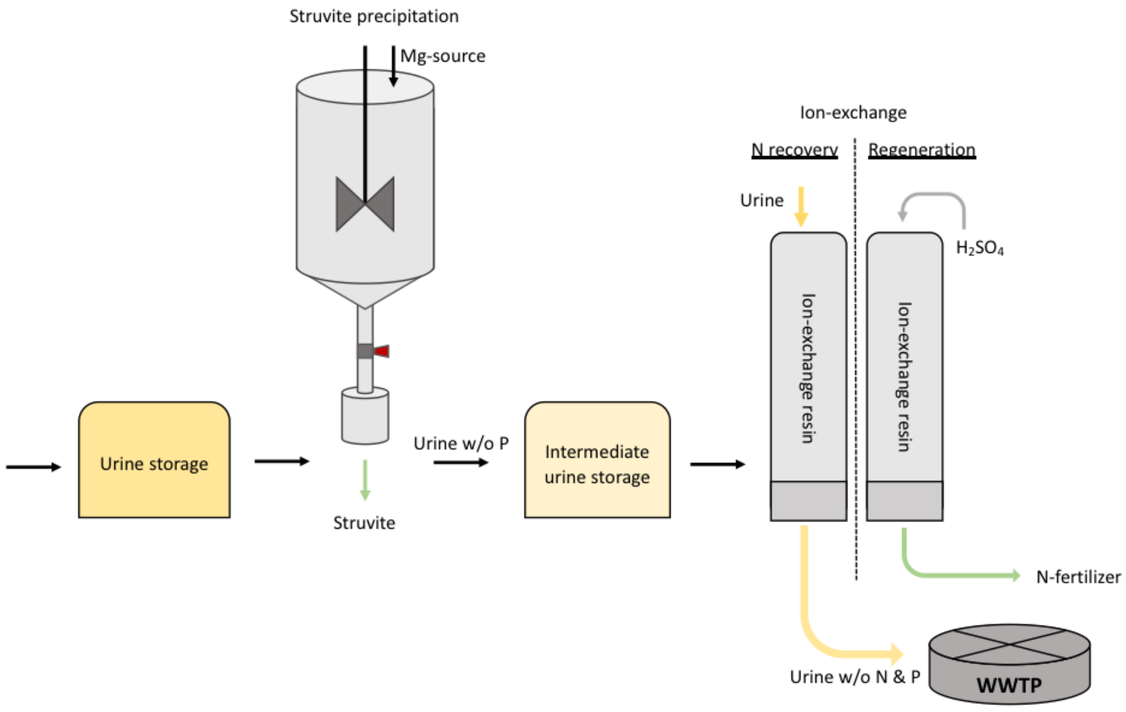

Figure 3: Schematic representation of the ion-exchange system set-up with struvite preprecipitation.

3 Method

This study was structured as a fictional case study for Sege Park in Malmö, Sweden, and investigated if applying urine concentration technologies could contribute to different SDGs connected to the criteria investigated. In order to assess the different urine concentration technologies, a MCA was used. Criteria for the MCA were assigned based on the SDGs and the data available from previous studies concerning the urine concentration technologies investigated. The study examined if the application of urine concentration technologies could contribute to making Malmö a more sustainable city by recovering nutrients from urine (SDG 6.3, 9 and 12) and reducing the nutrient emissions to Öresund (SDG 14). The study also examined if the investigated urine concentration technologies would be affordable for the habitants of Malmö (SDG 6.2), and if they would be space (SDG 11) and energy efficient (SDG 9). Finally, in order to have a safe working environment, it is essential for the technologies and the concentrated product to be safe to manage (SDG 3 and 8). Information and data for the different urine concentration technologies were obtained from research articles, where the technologies and their performance had been addressed. Data from the literature was used to perform calculations in order to investigate the performance of the different urine concentration technologies for the selected criteria in the MCA.

3.1 Sege Park

Sege Park is located in Malmö, Sweden, and is an area where 700 new homes will be constructed during the period 2021-2025 (Malmö Stad Stadsbyggnadskontoret 2017, Malmö Stad 2021, 2015). The new homes will mainly be in apartment buildings, but also in terraced houses, and both consist of newly built houses as well as renovated buildings. The new buildings will be 2-6 floors, mostly between 3-5 floors (Malmö Stad Stadsbyggnadskontoret 2017). The ambition for this area is to be a testbed for the installation of urine diversion in at least one of the buildings, with the aim of recovering nutrients and reducing nutrient emissions (Malmö Stad 2015). This thesis was inspired by the new area Sege Park. However, the resulting impact of the implementation would be small and therefore a fictional case study was examined, where it was assumed that urine concentration technology was applied in all new buildings in Sege Park. In the study, it was therefore assumed that urine concentration technologies would be installed in all 700 new homes, and that the average household consisted of three persons (in total 2100 persons).

The assumed composition of the household wastewater from Sege Park is presented in Table 1. The proportion of the time that would be spent at home was assumed to be 2/3 of the day because, according to von Münch & Winker (2011), it is a commonly used design criteria. From this information the mass of faeces and urine produced, and the corresponding mass of the nutrients, was multiplied with a factor of 2/3. However, it was assumed the washing, dishing and showering was performed at home and therefore all of the greywater produced by the population of Sege Park was assumed to be produced in the residential area.

3.2 Systems and system boundary

The baseline in this study was a conventional system (Figure 4). The conventional system included a standard toilet and the household wastewater (blackwater and greywater) was assumed to be transported to Sjölunda Wastewater Treatment Plant for treatment using the conventional municipal wastewater grid. The sludge produced at Sjölunda WWTP is REVAQ-certified and can therefore be used as fertilizer (VA SYD 2019). In this study, all of the sludge produced at the WWTP was assumed to be applied as fertilizer.

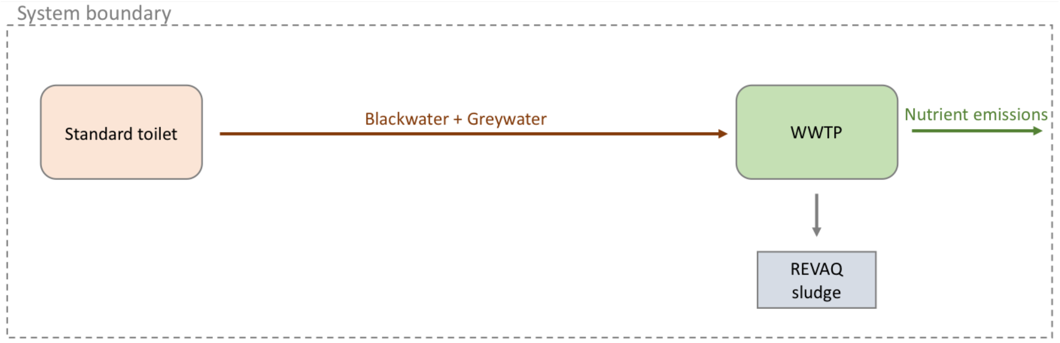

Figure 4: A schematic illustration of the baseline system (the conventional system) where a standard toilet is used and the household wastewater, including urine, is treated at Sjölunda Wastewater Treatment Plant.

For the criteria energy demand, a system expansion was used in order to calculate the energy demand corresponding to commercial N and P fertilizer production that was assumed to be replaced with the fertilizer produced by urine concentration (Figure 5).

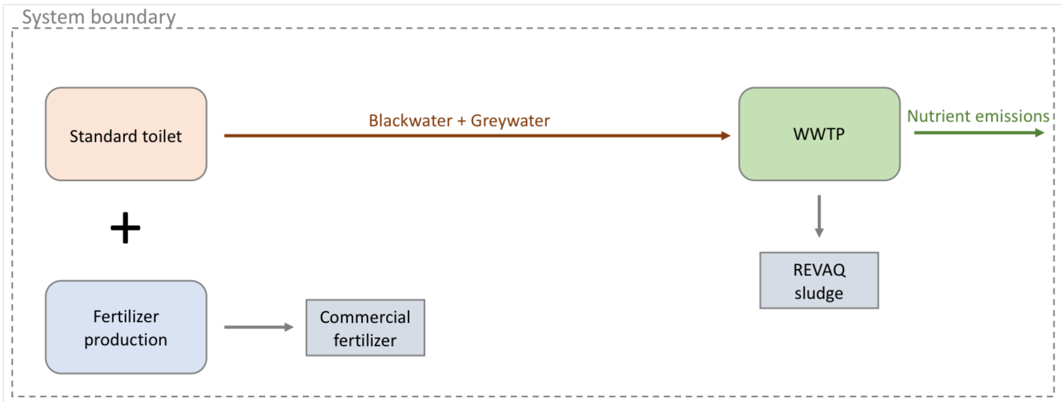

Figure 5: A schematic illustration of the system expansion for the conventional system where commercial fertilizer production is included.

The urine concentration technologies investigated were alkaline dehydration, nitrification-distillation and ion-exchange with struvite pre-precipitation. For the urine concentrating technologies, it was assumed that the urine was diverted by urine diverting toilets and transported to a semi-centralized treatment plant in the residential area (Figure 6). The alkaline dehydration system included a limebox in the toilet that added MgO to the urine in order to prevent urea hydrolysis. The blackwater, urine excluded, was assumed to be transported to Sjölunda WWTP for treatment using the conventional municipal wastewater grid. For the ion-exchange system, the urine treatment generated a rest product that was assumed to be transported to the WWTP as well. All urine concentration systems included the nitrogen and phosphorus recovery from the urine concentration technologies as well as the REVAQ sludge.

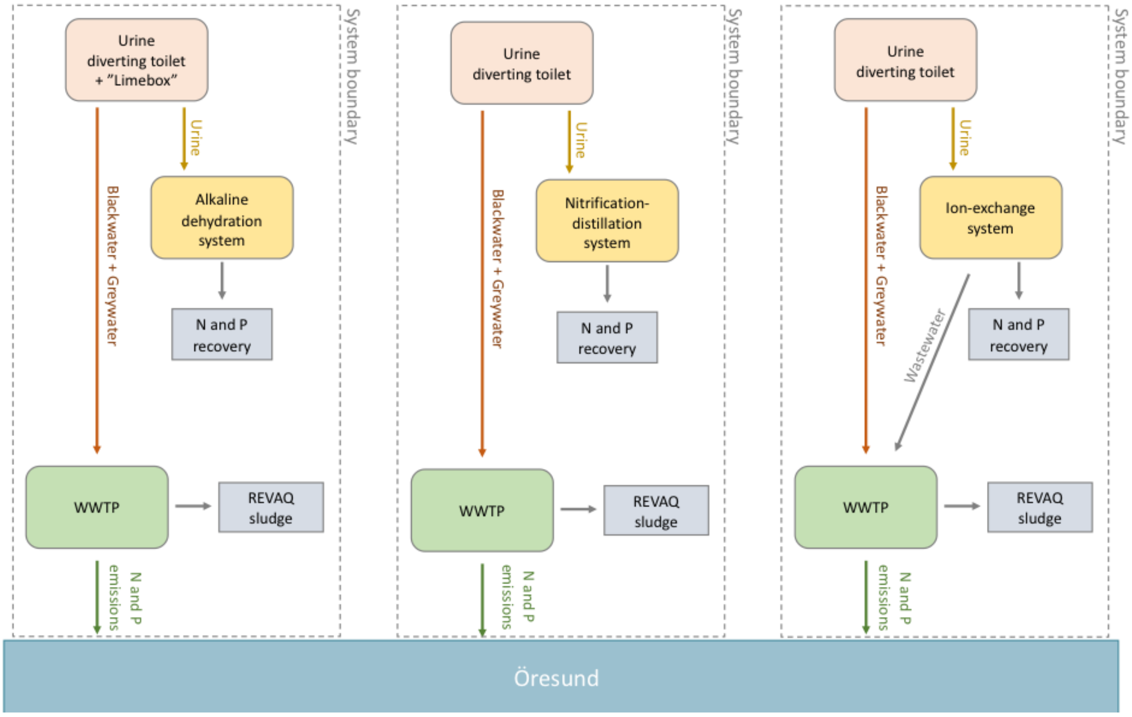

Figure 6: A schematic illustration of the different urine concentration systems where a) is the alkaline dehydration system, b) is the nitrification distillation system and c) is the ion exchange system.

3.3 Multi-criteria assessment

Multi-criteria assessment (MCA) is a tool for evaluating the sustainability of different systems by investigating different criteria. The MCA can give perspectives of the systems and shows advantages and disadvantages (Lennartsson et al. 2009). However, the method does not give a complete assessment of the sustainability and are sometimes more suitable for comparing different systems performing the same task rather than providing information about the total anthropogenic impact (Hellström et al. 2000). Kvarnström et al. (2004) divided criteria for sustainability assessment in five categories; health, environment, economy, technical function and socio-culture. In order to perform the assessment, different criteria are decided within the categories. The criteria may be assessed quantitatively or qualitative. Indicators are assigned to measure the investigated criteria (Hellström et al. 2000).

The categories investigated in the MCA in this study were environment, technical function, economic and health. In deciding the criteria for the MCA, inspiration was taken from SuSanA (2017) and the SDGs and their targets (Figure 7).

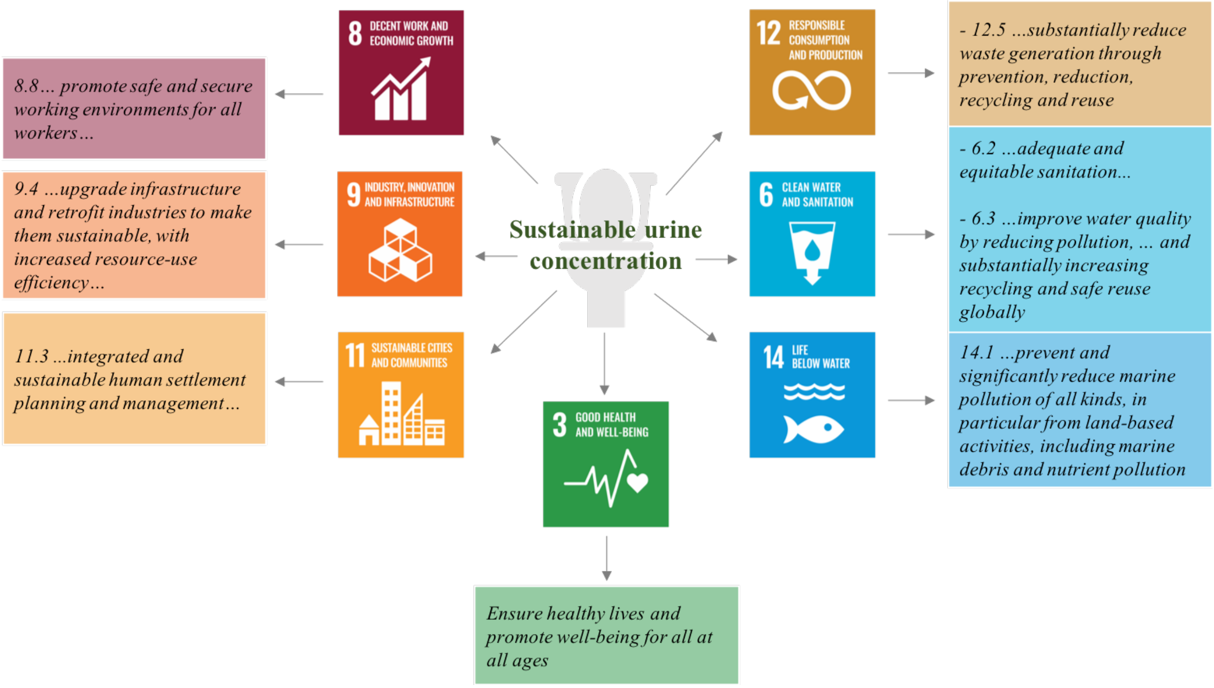

Figure 7: A schematic representation of the SDGs and the specific targets that the criteria for the MCA were derived from in order to investigate the sustainability for the different urine concentration technologies.

Based on the SDGs and their targets, the criteria in Table 2 were decided to be examined. The assessment mainly focused on the environment, where three criteria were examined. For the other categories one criteria each was investigated. Each criteria was assigned at least one indicator.

Table 2: The criteria and their respective indicators investigated the MCA.

Category	**Criteria**	**SDG**	**Analysis**	**Indicator**
Environment	Eutrophying emissions	14	Quantitative	Concentration of N in WWTP emissions (mg/L)
				Concentration of P in WWTP emissions (mg/L)
	Nutrient recovery	6, 9, 11, 12	Quantitative	% N-recovery from total household wastewater
				% P-recovery from total household wastewater
	Energy demand	9	Quantitative	% of annual apartment energy demand for urine concentration
Technical	Space efficiency	11	Quantitative	Space required in residential area (m2/household)
Economic	Cost and affordability	6	Quantitative	Annual cost per household (SEK/year)
Health	Working environment	3, 8	Semi-quantitative	Additional risk with urine concentration

3.3.1 Performance

The performance for each indicator was evaluated and then graded on a five-point scale, where 5 represents very good and 1 very poor. The grading scale is presented per indicator. The scale and its limits were decided based on relevant data such as threshold values or other information that provides perspective on the indicator. The performance was also given a corresponding color for visual understanding of the grading. The scale is defined below:

Green: 5 - Very good

Lime: 4 - Good

Yellow: 3 - Neither good nor bad

Orange: 2 - Poor

Red: 1 - Very poor

3.3.2 Eutrophying emissions

Data for the wastewater volume and nutrient concentrations in the influent to and effluent from Sjölunda WWTP were collected from available environmental reports for Sjölunda WWTP from the years 2015, 2016 and 2019 (VA SYD 2015, 2016, 2019). The nitrogen and phosphorus removal in the WWTP was calculated using data for incoming and outgoing concentrations for each year. The calculations were performed for each of the three years to investigate the resulting percentage change in the concentration of the emissions. The change was found to be very small between the years and therefore the result of the most recent data (2019) was used for the performance evaluation.

Since Sege Park is a new residential area, it generates additional wastewater to what is already treated in the WWTP. The composition of the additional fraction of wastewater from Sege Park was calculated based on the assumed composition of household wastewater and assumed proportion of time spent at home in 3.1. Assumptions for the calculations are summarized in Appendix A.

The volume wastewater produced in Sege Park was calculated by transforming the mass of the wastewater fractions produced per person and day to the volume in liters and multiplying it with the population in Sege Park. For urine and greywater, it was assumed that the mass could be directly transformed to volume. The density used for faeces and toilet paper were 1,075 kg/L and 1,4 kg/L, respectively. The calculations for the conventional system included the volume and the mass of nitrogen and phosphorus from all fractions. By using alkaline dehydration and nitrification-distillation systems the nitrogen and phosphorus in the urine were assumed to not be treated at the WWTP. Therefore, the volume of urine and the nutrients in the urine were excluded from the calculations of wastewater volume and nutrients produced in Sege Park. However, for the ion-exchange system the volume wastewater as well as nitrogen and phosphorus concentration in the wastewater was calculated differently, since the wastewater from the ion-exchange system was assumed to be treated at Sjölunda WWTP. The volume reduction of the urine for the ion-exchange system was assumed to be small and was therefore considered negligible. Nevertheless, the nitrogen and phosphorus in the urine were reduced with 99 and 93%, respectively. These numbers are based on the potential nutrient removal through the use of struvite precipitation and ion-exchange and are based on studies from Etter et al. (2015) and Tarpeh et al. (2018b).

The resulting concentration of nitrogen and phosphorus the influent to Sjölunda WWTP was calculated as:

$$c_{in} = c_{Sege\ Park} \cdot f_{Sege\ Park} + c_{ER} \cdot f_{ER} \tag{2}$$

where, $c_{Sege\ Park}$ is the nutrient concentration in the wastewater from Sege Park, $f_{Sege\ Park}$ is the fraction from Sege Park of the total incoming wastewater to Sjölunda WWTP, c_{ER} is the incoming concentration and f_{ER} is the fraction of incoming wastewater from the rest of the city according the environmental reports. The resulting concentration of the eutrophying emissions from the WWTP for the different systems was calculated using the phosphorus and nitrogen removal efficiencies in the WWTP.

For the nitrogen emission, the grading of the performance was decided based on the 2019 annual mean emissions from Sjölundas Wastewater Treatment Plant, which was 12 mg/L (VA SYD 2019) and the regulations in NFS 2016:6 (Swedish EPA 2016). According to the regulations the highest annual mean nitrogen concentration allowed in the effluent is 10 mg/L for a WWTP treating wastewater from >100,000 people. As of today, the effluent from Sjölunda exceeds the allowed concentrations, but it fulfills the regulations by having >70% annual nitrogen removal efficiency. The nitrogen concentration in the wastewater to Sjölunda WWTP was around 42 mg/L for the conventional system and the percentage removal at Sjölunda WWTP was calculated from this value. According to Åmand et al. (2016) Swedish treatment plants may face stricter requirements for nitrogen and phosphorus emissions in the future. What these requirements will look like is uncertain, but limit values of 5-6 mg N/L for nitrogen has been mentioned. Based on this information the performance was graded accordingly:

5 - Very good: Annual mean nitrogen removal efficiency >85% corresponding to a concentration of <6.3 mg/L in the effluent from the WWTP.

4 - Good: Annual mean nitrogen removal efficiency 76-85% corresponding to a concentration of 8.4-10.0 mg/L in the effluent from the WWTP.

3 - Neither good nor bad: Annual mean nitrogen removal efficiency 70-75% corresponding to a concentration of 10.1-12.6 mg/L in the effluent from the WWTP.

2 - Poor: Annual mean nitrogen removal efficiency 50-69% corresponding to a concentration of 12.7-21.0 mg/L in the effluent from the WWTP.

1 - Very poor: Annual mean nitrogen removal efficiency <50% corresponding to a concentration of >21.0 mg/L in the effluent from the WWTP.

For phosphorus, the threshold value for the effluent from Sjölunda Wastewater Treatment Plant has a monthly mean of 0.3 mg/L and the phosphorus removal was 94% in 2019 (VA SYD 2019). Based on the method and chemicals used for the phosphorus removal, the phosphorus removal varies between 80-98% (Svenskt Vatten & Naturvårdsverket 2013). However, for thresholds below 0.2 mg/L additional steps with ultra or nano filtration is required. According to Åmand et al. (2016), 0.2 mg/L might also be future limits of phosphorus concentration in effluents from Swedish WWTPs. Based on this information the performance in the MCA was graded as follows:

5 - Very good: Annual mean concentration of phosphorus in effluent from the WWTP is <0.2 mg/L (>96% removal efficiency).

4 - Good: Annual mean concentration of phosphorus in effluent from the WWTP is 0.20-0.27 mg/L (>95% removal efficiency).

3 - Neither good nor bad: Annual mean concentration of phosphorus in effluent from the WWTP is 0.28-0.34 mg/L (>93% removal efficiency).

2 - Poor: Annual mean concentration of phosphorus in effluent from the WWTP is 0.35–0.50 mg/L (>90% removal efficiency).

1 - Very poor: Annual mean concentration of phosphorus in effluent from the WWTP is >0.50 mg/L (<90% removal efficiency).

3.3.3 Nutrient recovery

Nutrient recovery for the conventional system was calculated based on the nitrogen and phosphorus in the REVAQ-sludge. Assumptions used in the calculations are summarized in Appendix A. Sjölunda WWTP has a 94% phosphorus removal efficiency (VA SYD 2019) and it was assumed that all of the precipitated phosphorus ended up in the sludge. As for the nitrogen recovery, about 20-30% of the nitrogen in the wastewater ends up in the sludge and only half of the 20-30% is preserved in the sludge after dewatering (Jönsson 2019). From this information, the nitrogen recovery for the conventional system was assumed to be 15%.

For the urine concentration systems the percentage recovery from the faeces and greywater in the WWTP was assumed to be the same as for the conventional system. The nutrient recovery for the urine concentration technologies was calculated using the potential maximal recovery for the different technologies. The reason for using the potential recovery was to give a fairer comparison between the different technologies, since they are at different stages of development and have not yet been optimized. For the recovery calculations it was also assumed that no nitrogen was lost in the pipe transport nor in the urine storage tank due to sealed storage and non-leaking pipes.

Regarding nitrogen recovery, the Swedish EPA (2013) suggested a target of a minimum of 10% return to agricultural land before 2018. Based on the suggested target and considering that the biogeochemical flows of nitrogen has exceeded the planetary boundaries according to Steffen et al. (2015), the system performance in the MCA for recovery of nitrogen were decided accordingly:

5 - Very good: Nitrogen recovery from total household wastewater is >50%.

4 - Good: Nitrogen recovery from total household wastewater is 30–50%.

3 - Neither good nor bad: Nitrogen recovery from total household wastewater is 10-29%.

2 - Poor: Nitrogen recovery from total household wastewater is 1-9%.

1 - Very poor: Nitrogen recovery from total household wastewater is <1%.

Targets for phosphorus recovery for the purpose of returning nutrients to agricultural land was suggested to be at least 40% before 2018 by Swedish EPA (2013) and 60% Government Offices of Sweden (2020). Based on these values and taking into account the latest suggestion, the system performance in the MCA for recovery of phosphorus were decided accordingly:

5 - Very good: Phosphorus recovery from total household wastewater is >90%.

4 - Good: Phosphorus recovery from total household wastewater is 70–90%.

3 - Neither good nor bad: Phosphorus recovery from total household wastewater is 50–69%.

2 - Poor: Phosphorus recovery from total household wastewater is 30–49%.

1 - Very poor: Phosphorus recovery from total household wastewater is <30%.

3.3.4 Energy demand

The energy demand was calculated based on energy input required to treat the urine produced in Sege park with the different urine concentration technologies. Manufacturing of the chemicals or material was not taken into consideration. The energy consumption for the conventional system was calculated using data for the energy demand for nitrogen removal in the WWTP and also for the production of equal amounts of N and P, in the form of commercial fertilizers, as recovered from the urine concentration systems. Assumptions and data for the calculations are summarized in Appendix A. Based on the data and the volume of urine produced in Sege Park, the energy consumption for the different urine concentration technologies were calculated.

In order to calculate the energy demand of the fertilizer production, data for the average energy demand for N and P fertilizer production in Europe from a study by Maurer et al. (2003) was used. For the nitrogen removal in the WWTP, an average value for the energy demand of aeration and addition of external carbon source were calculated based on data collected from Maurer et al. (2003) as well as Kavvada et al. (2017). These calculations are described in Appendix A.

According to Vattenfall (2020), the energy consumption for an apartment is around 2400-4800 kWh per year, depending on the size. From these values, the medium energy consumption per apartment and year (3600 kWh) was compared with the medium energy demand per household and year for the different urine concentration technologies. The grading used for the MCA is presented below:

5 - Very good: The annual energy consumption is <10% of the apartment energy consumption.

4 - Good: The annual energy consumption is 10–19% of the apartment energy consumption.

3 - Neither good nor bad: The annual energy consumption is 20–29% of the apartment energy consumption.

2 - Poor: The annual energy consumption is 30–49% of the apartment energy consumption.

1 - Very poor: The annual energy consumption is >50% of the apartment energy consumption.

3.3.5 Space efficiency

The space required per unit was decided based on literature values and assumptions when data was missing. The nitrification-distillation technology requires 5 m^2 for one reactor and a total of 10 m^2 per unit (Etter & Udert 2015). From this information, it was assumed that the space required for the urine concentration technology set up would be twice the space of the reactor. The alkaline dehydration technology was assumed to require about 3 m^2 per reactor based on a field study performed by Simha et al. (2020c). The total area required was then assumed to be 6 m^2 per unit based on the previous assumption that the urine concentration set up would need twice the space of the reactor. Based on the treatment capacity, 70 units were needed for both the nitrification-distillation and the alkaline dehydration system to treat the urine from Sege Park. For the ion-exchange system, no data was found concerning the space required for this set-up. Therefore, considering the amount of components, it was assumed that it would require about the same space as the nitrification-distillation system, thus 10 m^2 per unit. A hypothetical ion-exchange system was designed for this study and assumed to be able to treat 100 L of urine per day, thus only 22 units were assumed to be required.

The criteria was evaluated based on the space required in the residential area and the fact that the urine concentration could compete with space needed for parking windows in e.g. underground parking garages. The grading of the space efficiency was then decided considering the sustainability strategy from Malmö Stad (2015) for the area, which suggests that parking space for maximum 0.5 cars per household will be provided. According to Malmö Stad Stadsbyggnadskontoret (2017), parking will mainly be provided in a planned parking garage, but underground parking is also included in the plan. Given that a standard parking window is 12.5 m^2 and that each household requires 0.5 parking window, the space for parking was assumed to be 6.25 m^2 per household. Based on this information the performance for the different systems in the MCA was decided accordingly:

5 - Very good: Space required per household is $<$10% ($\leq$ 0.6 m^2) of household parking window

4 - Good: Space required per household is 10-20% ($\leq$ 1.3 m^2) of household parking window

3 - Neither good nor bad: Space required per household is 21-30% ($\leq$ 1.9 m^2) of household parking window

2 - Poor: Space required per household is 31-40% ($\leq$ 2.5 m^2) of household parking window

1 - Very poor: Space required per household is $>$40% ($>$2.5 m^2) of household parking window

3.3.6 Cost and affordability

The cost estimation was based on the cost of the components and the operation and maintenance (O&M) cost for each system. Additional cost for installation was not considered since the urine concentration technologies are under development and have not yet, to the best of our knowledge, been applied at larger scale at the time of this study. Neither was a safety factor for fluctuations of the volume urine taken in consideration for the fictional systems. Furthermore, the systems have not yet been optimized and were therefore not optimized in this study either. Hence, the estimations have a large uncertainty and should therefore rather be seen as a tool for comparing the cost between the systems than the actual cost for the systems.

The cost estimation was performed with the conventional system as a baseline. It was also assumed that the additional cost for the urine piping was negligible when constructing a new area. In addition, the piping costs would be approximately the same for the urine concentration systems in any case. Design parameters and assumptions for the different systems are summarized in Appendix B. For the alkaline dehydration technology, the cost was estimated based on the system set-up for the field study in Finland performed by Simha et al. (2020c). It was assumed that it would give an idea of the cost for the system in this thesis. The nitrification-distillation set-up was assumed to be the one presented by Etter & Udert (2015) where the costs for the different components also were presented. The treatment capacity of the system was decided based on an assumed nitrification rate of 450 mg N/L reactor and day and the nitrogen concentration in the urine decided based on the values in Table 1. The ion-exchange system was in this study designed to treat 100 L urine per day and included weekly regeneration. The set-up took inspiration from relevant literature and for further information (Table 21).

The annuity method was used to calculate the annual costs (C_a) according to

$$C_a = C_c \cdot \frac{p}{1-(1+p)^{-n}} + C_{O\&M} \tag{3}$$

where, C_c is the capital cost, p is the discount rate, n is the lifetime in years and $C_{O\&M}$ is the O&M costs (Kärrman et al. 2017). The lifetimes were estimated based on Svenskt Vatten (2015) and from the lifetime the corresponding discount rate was assumed according to the rates suggested by Söderqvist (2006). The costs were assumed to be shared by the residents of Sege Park.

The performance grading in the MCA was based on the usage fee in Malmö that was 3100 SEK per year in 2020 and the average usage fee in Sweden that was 4900 SEK per year in 2020 for a standard apartment according to Svenskt Vatten (2020a). The conventional system was set as a baseline and the additional costs for the urine concentration technologies were evaluated as follows:

5 - Very good: Additional annual costs of <500 SEK/household

4 - Good: Additional annual costs of 500-1500 SEK/household

3 - Neither good nor bad: Additional annual costs of 1501-2500 SEK/household

2 - Poor: Additional annual costs of 2501-3500 SEK/household

1 - Very poor: Additional annual costs of >3500 SEK/household

3.3.7 Working environment

All systems were assumed to be safe to use for the population in Sege Park because the only difference at the household level for the different systems investigated was the toilet. The use of the recovered nutrients as fertilizer was assumed to be safe after four days of storage for the alkaline dehydration technology (Senecal et al. 2018). The use of the concentrate of nutrient from the nitrification-distillation technology was also assumed to be safe, because the technology has a complete pathogen inactivation due to the distillation (Etter & Udert 2015). For the ion-exchange system, based on Swedish EPA (2013) report, it was assumed that the urine was stored for 30 days prior to the treatment in order to be safe to use on the fields. Therefore, the health assessment focuses on the health risks operating the different systems.

To evaluate the performance for the health of the workers a Semi-quantitative risk assessment was used. The method is described in the manual *Sanitation Safety Planning* by WHO (2016) and is based on a relation between the severity (S) and the likelihood (L) that defines the level of the risk. The likelihood scale goes from *very unlikely*, where the hazard has not occurred before and not likely to happen within the next year, to *almost certain*, where the hazard has been reoccurring in the past and is highly probable to occur within the following year almost regardless of the circumstances. The severity is defined from *insignificant*, where the hazard causes no or almost no negative health effects, to *catastrophic*, where the health effects are serious and may even be life-threatening. The relation is presented in Table 3, which is a version of the one presented in the manual, but the risk level low is divided into low and very low creating five risk levels instead of four.

Table 3: Modified matrix for semi-quantitative risk assessment from the manual *Sanitation Safety Planning* by WHO (2016).

			Severity [S]				
			Insignificant	Minor	Moderate	Major	Catastrophic
			1	2	4	8	16
Likelihood [L]	Very unlikely	1	1	2	4	8	16
	Unlikely	2	2	4	8	16	32
	Possible	3	3	6	12	24	48
	Likely	4	4	8	16	32	64
	Almost certain	5	5	10	20	40	80
Risk score R=L·S			<4	4-6	7-12	13-32	>32
Risk level			Very low	Low	Medium	High	Very high

The risks concerning the maintenance and operation of the wastewater treatment for the different technologies were evaluated and hazardous events were identified through a literature study. Hazards for the urine concentration systems were identified from the chemicals used, system maintenance, process failure and the pathogen reduction in the recovered concentrate of nutrients that were described in studies concerning the different technologies (Etter & Udert 2015, Tarpeh et al. 2018a, Senecal 2020, McConville et al. 2020). The risks associated with the process chemicals were identified through chemical data sheets. Information about the hazardous events connected to the wastewater treatment at the WWTP were collected from a summary by IVL (2020) and they apply to all systems, since the systems for urine concentration also were connected to the WWTP. The basis for the risk analysis can be found in Appendix C.

The likelihood and severity of the hazardous events were determined according to the manual by WHO (2016) and then the risk level was determined by the risk score according to Table 3. The conventional system was set as a baseline for the performance evaluation. Therefore, the performance was decided considering the additional risk associated with the urine concentration technologies. The performance of the urine concentration technologies was determined accordingly:

5 - Very good : Of the risks connected to urine concentration no risk levels are high or very high and the total risk score is <20% of the conventional system's risk score.

4 - Good : Of the risks connected to urine concentration $\leq$1 risk level is high, no risk levels are very high and the total risk score is <40% of the conventional system's risk score.

3 - Neither good nor bad : Of the risks connected to urine concentration $\leq$3 risk levels are high, no risk levels are very high and the total risk score is <60% of the conventional system's risk score.

2 - Poor : Of the risks connected to urine concentration $\leq$6 risk levels are high, no risk levels are very high and the total risk score is <80% of the conventional system's risk score.

1 - Very poor : Of the risks connected to urine concentration >6 risk levels are high, >0 risk levels are very high and the total risk score is >80% of the conventional system's risk score.

3.4 Wider implementation

A wider implementation of the systems for urine concentration were investigated for three different criteria as a type of sensitivity assessment. The criteria investigated were eutrophying emissions, nutrient recovery and space efficiency. The criteria eutrophying emissions was chosen in order to investigate what effect a wider implementation could potentially have on the nitrogen and phosphorus emissions from the WWTP, because the fraction wastewater Sege Park represented of the total wastewater treated at the WWTP was too small to make a difference. For nutrient recovery, a wider implementation was investigated in relation to the fertilizer demand in Malmö in order to see how much of the fertilizer demand that could potentially be met by fertilizer produced from urine concentration. The space requirement was investigated since in new areas, urine concentration can be planned for and placed in the basements. However in existing buildings, there may not be room in the basement and the technology therefore needs to be placed elsewhere.

Eutrophying emissions

The nitrogen and phosphorus emissions resulting from having different fractions of the population connected to a urine diverting sanitation system were calculated and plotted. The nitrogen and phosphorus concentration in the influent to the WWTP as well as the volume wastewater treated at the WWTP from VA SYD (2019) were used for the calculations. Based on the characteristics of the wastewater in Table 1, it was assumed that urine diversion would result in a 79% removal of nitrogen from the wastewater at the residential area for the alkaline dehydration and nitrification-distillation technology and 78% nitrogen removal for ion-exchange with struvite precipitation. For the phosphorus removal from the wastewater produced in Sege Park, a 49% removal for the alkaline dehydration and nitrification-distillation technology and a 46% removal for ion-exchange with struvite precipitation were assumed to occur in the residential area. The nitrogen and phosphorus removal efficiencies at the WWTP were assumed to be 70 and 94%, respectively.

Fertilizer demand

To calculate the proportion urine produced in Malmö that would be required to cover the fertilizer demand, the area of available agricultural land was multiplied with the amount fertilizer required per ha. In Malmö there are 4588 ha agricultural land (Malmö Stad 2020) and the average fertilizer demand per ha was assumed to be the same as in Skåne, 8 kg P per ha and 122 kg N per ha (SCB 2020a). It was assumed that the recovered nitrogen and phosphorus had the same fertilizer capacity as commercial fertilizer. Based on the nitrogen and phosphorus content in urine, according to Table 1, and the population in Malmö (347,949 persons at the end of 2020 according to Malmö Stad (2020)), the proportion of urine produced in Malmö that required to be treated with urine concentration in order to cover different proportions of the fertilizer requirement in Malmö was calculated. The calculations were performed for four different recovery rates.

Space requirement

If urine concentration were to be applied to existing infrastructure, there may not be enough space in the basement of the building and therefore the treatments would need to be placed outside, in for example a building constructed on a parking lot. Or it may be possible to fit into parking space in underground parking garages. Therefore, it was investigated how many parking windows each technology required if they were to be applied at the homes for half of the population in Malmö, 173,975 persons at the end of 2020 (Malmö Stad 2020). The calculations for the space required per person were based on the same data and assumptions as in 3.3.5. For the calculations, the space requirement for the different urine concentration technologies were multiplied with half of the population. Then the total area was divided by the area for a parking window (12.5 m^2) in order to determine how many parking windows that would be required.

4 Results and discussion

The results are presented and discussed per criteria. A summary of all results for the urine concentration technologies is found in 4.7.

4.1 Eutrophying emissions

The concentration in the effluent from the WWTP did not vary from that achieved today (Table 4). The Sege Park wastewater fraction was too small (only 0.25% of the total wastewater treated at the WWTP) in order to make a difference by itself. The application of urine concentration technologies would therefore have had a negligible reduction of the eutrophying emissions at this scale. The result was expected and therefore the impact of a wider application was investigated in 4.8. However, it is worth mentioning that only through urine diversion 75% of the nitrogen and over 40% of the phosphorus in the wastewater from Sege Park may be removed before reaching the WWTP.

Table 4: Annual average concentration of nitrogen and phosphorus in the effluent from Sjölunda.

Technology	Conventional system	Alkaline dehydration	Nitrification-distillation	Ion-exchange
N (mg/L)	12.0	12.0	12.0	12.0
Performance	**3**	**3**	**3**	**3**
P (mg/L)	0.3	0.3	0.3	0.3
Performance	**3**	**3**	**3**	**3**

4.2 Nutrient recovery

The phosphorus recovery for the different technologies was very similar. Meanwhile, looking at the nitrogen recovery there was a large difference between the urine concentration technologies and the conventional system (Table 5). However, it is important to keep in mind that the recovery efficiency might be reduced because the maximum recovery was used for the calculations and applying the system on a larger scale could generate nitrogen losses during transport, storage and urine concentration. For the alkaline dehydration system, too high drying temperature would result in nitrogen loss (Simha et al. 2020c). Nevertheless, the urine concentration recovery capacity could drop to almost 65% and still recover 50% of the nitrogen in the household wastewater and thereby still have a very good performance. The phosphorus recovery was not as sensitive to the operation conditions as the nitrogen recovery, because phosphorus is not as volatile as nitrogen.

However, for struvite precipitation Antonini (2013) described a difficulty to recover all the struvite from the filter, which may lead to reduced recovery.

Table 5: Potential annual nitrogen and phosphorus recovery for the different systems. The numbers in parentheses represent the recovery of the urine concentration technology.

Technology	Conventional system	Alkaline dehydration	Nitrification-distillation	Ion-exchange
N (%)	15	78 (74)	79 (75)	79 (75)
Performance	**3**	**5**	**5**	**5**
P (%)	94	97 (44)	97 (44)	96 (41)
Performance	**5**	**5**	**5**	**5**

Since the wastewater from Sege Park was a very small part of the total wastewater treated at the WWTP, applying urine concentration would probably not affect the quality of the sludge. An expanded implementation of urine concentration systems could however have an effect on the quality of the sludge. This is further discussed in 4.8. Furthermore, a potential ban on use of wastewater sludge has been proposed in Sweden Government Offices of Sweden (2020). If accepted, the use of Revaq-sludge in agriculture might not be allowed. In addition, one of the proposals was a total ban on the spread of all sludge from sewage and this would also include the product from urine concentration. In that case, all systems investigated in this study would have had zero recovery. On the other hand, a ban with certain exceptions has also been proposed and in that case, urine concentration may be an exception. The potential ban, depending on what form it takes, may therefore also be an incentive to further investigate implementation of urine concentration. However, the phosphorus recovery from the urine concentration systems was only around 40% without the recovery from the sludge. This recovery did not reach the 60% proposed by Government Offices of Sweden (2020) by itself. Furthermore, the MCA performance for the phosphorus recovery would also have been graded as poor.

4.3 Energy demand

The performance for urine treatment was very good for most of the technologies when compared to the energy demand for an apartment. For the alkaline dehydration system however, the energy demand was significantly higher than for the other systems (Table 6).

Table 6: The annual medium energy demand needed to treat the urine from one household in Sege Park for the different urine concentration and conventional technologies compared with the annual medium energy demand for an apartment in Sweden.

Technology	Conventional system	Alkaline dehydration	Nitrification-distillation	Ion-exchange
Energy demand per household (kWh/year)	136	1100	165	23
% of apartment demand	4	31	5	1
Performance	**5**	**2**	**5**	**5**

The energy consumption for the alkaline dehydration technology was based on a field study and laboratory testing (Senecal 2020). The energy consumption could have been reduced by recovering heat from e.g. exhaust air. An automatized system could also have reduced the energy consumption for the alkaline dehydration by adjusting the system according to the incoming urine volume, something which was not not done in the field study (Senecal 2020). The nitrification-distillation technology used a vacuum distiller that had been optimized (Etter & Udert 2015) and the performance would probably have been the same in the Sege Park set-up. However, the nitrogen concentration in the urine was lower in the pilot-system described in Etter & Udert (2015) than in the Swedish design values, which might have resulted in a higher energy demand for the nitrification columns, due to a need for increased aeration, if they were to be installed in Sege Park. An increased energy demand for the nitrification-distillation technology may also have affected the performance of the system. The ion-exchange system with struvite precipitation is likely to have a lower energy demand than the other systems, but since data was difficult to find the consumption assumed in this study was very approximate. Moreover, the calculations did not take into account the further treatment of the nitrogen and phosphorus free urine at the WWTP. This may have increased the energy demand for the ion-exchange technology.

Sensitivity analysis

The household energy consumption accounts for 25% of the total energy use within Sweden (SCB 2020b). Generally an apartment consumes significantly less energy than a detached house (Vattenfall 2020). If the urine concentration technologies instead were compared to the average household consumption in Sweden, the alkaline dehydration system would consume 10% of the household demand and if the percentage of the grading was kept, the grading would have been good (on the verge of very good) instead.

4.4 Space efficiency

For the space efficiency criteria, all systems were graded as good to very good (Table 7). None of the systems have been optimized. Optimisation may have affected the appearance of the treatment units as well as the space they would require. Moreover, the performance may vary between different residential areas because it depends on the availability of space, which may also vary. Therefore, it is important to consider the prerequisites, for example if the buildings have available space in the basement or if the urine concentration should be placed in a separate building.

Table 7: The space requirement in the residential area per household for the different systems.

Technology	Conventional system	Alkaline dehydration	Nitrification-distillation	Ion-exchange
Space required (m^2/household)	0	0.6	1.0	0.3
Performance	**5**	**5**	**4**	**5**

For the alkaline dehydration technology, the dehydration can be performed directly in the toilet (Senecal 2020). The alkaline dehydration system would in that case not have required any space in the residential area. Nevertheless, this would not have affected the performance because it would still have received a 5. It would also have moved the service chain from a semi-centralized WWTP to the household level, which could potentially generate more work for the household and affect the acceptance. For the nitrification-distillation technology, the performance was dependent on the nitrification rate, where a higher nitrification rate resulted in a higher treatment capacity. A higher nitrification rate may therefore have resulted in less space requirement and a higher grading in the MCA. Meanwhile, the opposite was true for a lower nitrification rate. In addition, according to Etter & Udert (2015), the capacity of the distiller was much higher than the capacity of the nitrification columns (two orders of magnitude). Therefore, the same distiller may have been used in connection to more nitrification columns than in the system set-up evaluated in this study. This may also have reduced the space requirement. Considering the ion-exchange system, the space required was based on an assumption that it required about the same space per unit as the nitrification-distillation technology, which provided the result an uncertainty.

4.5 Cost and affordability

The result indicated that the capital costs were highest for the nitrification-distillation technology, the O&M cost was highest for the alkaline dehydration technology and the profit from sold fertilizer was the same for all systems (Figure 8).

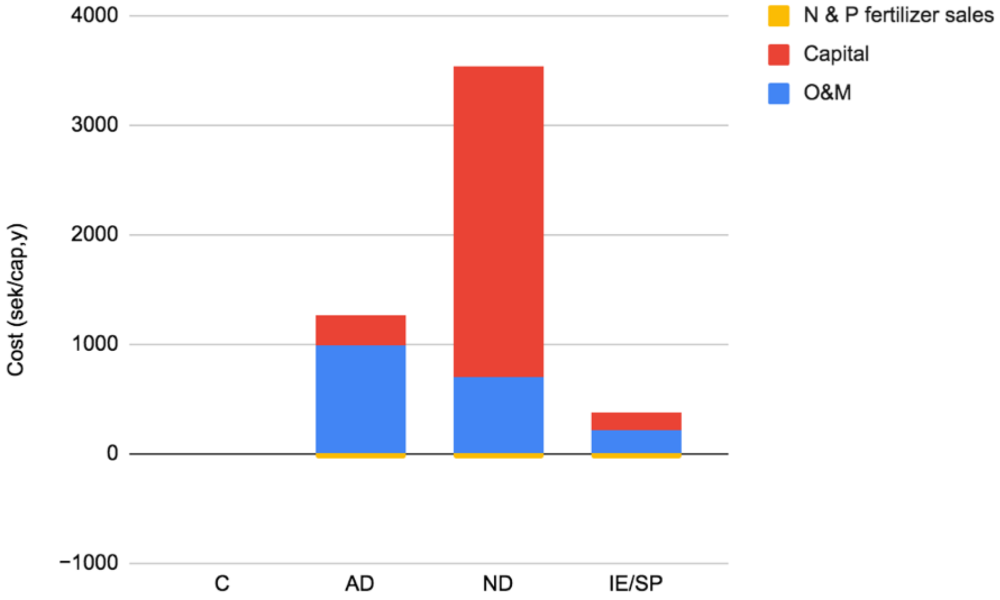

Figure 8: The annual costs per person and year for the different systems, where C represents the conventional system, AD the alkaline dehydration system, ND the nitrification-distillation system and IE/SP the ion-exchange and struvite precipitation system.

The performance was graded based on additional costs to the conventional system, which therefore did not receive a grade. The ion-exchange was graded as good, meanwhile the alkaline dehydration technology was graded as poor and the nitrification-distillation technology was graded as very poor (Table 8).

Table 8: Additional costs to the conventional system for the different urine concentration systems.

Technology	Conventional system	Alkaline dehydration	Nitrification-distillation	Ion-exchange
Additional costs (SEK/household)	-	2700	7100	1000
Performance	**-**	**2**	**1**	**4**

It is important to keep in mind that the cost estimations were rough estimates and that the compared systems were at different levels of development. The costs for the alkaline dehydration and ion-exchange systems were calculated based on components, while the cost for the nitrification distillation set-up was thoroughly described in literature. As mentioned earlier the distiller may also have been used for several more nitrification columns. Reducing the amount of distillers would also have had a significant impact on the cost, since the distiller was the most expensive component.

Furthermore, the cost estimations were based on the production of one unit, but when applied on a larger scale the price per unit is likely to reduce (Etter & Udert 2015). For the alkaline dehydration and the nitrification-distillation systems, the treatment capacity was less than one third of the assumed capacity for the ion-exchange system and therefore over three times more treatment units were required for these systems and this may explain the price difference. The service cost was also based on the number of units, which resulted in higher O&M costs for the alkaline dehydration and nitrification-distillation technologies. The O&M cost for the alkaline-dehydration would also have been reduced if the energy consumption was reduced.

Both the alkaline dehydration system and the nitrification-distillation system recovered all the nutrients in the urine (Simha et al. 2020a, Etter et al. 2015), while the ion-change system mainly recovered nitrogen and phosphorus leaving other important nutrients as potassium in the effluent. In order to enable a higher potassium recovery, an additional treatment step would have been required according to Tarpeh et al. (2018b), which also would have entailed additional costs. In this study, only the nitrogen and phosphorus recovery was investigated and therefore the ion-exchange system was designed based on that.

The installation cost and additional components for robustness in case of higher flows were not included in the cost estimation. The reason for the exclusion was lack of data available. These are important factors for the final system and also, the corresponding costs are important for accurate cost estimation and should therefore be further investigated before an eventual implementation.

4.6 Working environment

The hazardous events identified for the conventional systems were mostly related to the work at a WWTP. The risk level was defined as high for almost all of the investigated hazardous events (Table 9). The hazards presented were also valid for the urine dehydration technologies. Note that the risk assessment was performed principally to identify potential risks with the different urine concentration systems and in order to compare the systems to each other, rather than giving a deeper risk assessment. Emphasis was placed on making a consistent assessment, because changes in the severity may have contributed to significant changes in risk score since the severity in Table 3 increases by a factor of two. Some factors and chemicals needed in these technologies might not have been included in the assessment.

Table 9: Semi-quantitative risk assessment for the biological, chemical and physical hazards for workers at a WWTP.

Conventional system									
Hazard identification				**Existing controls**		**Risk assessment**			
#	Hazardous event	Hazard	Exposure route	Control description	Control validation	L	S	R	Lvl
1	Exposure to aerosols	Pathogens	Inhalation, ingestion	Working equipment, adequate ventilation, hygiene	Ventilation, staff safety education	4	4	16	H
2	Exposure to hydrogen sulfide	Toxic gases	Inhalation	Working equipment, adequate ventilation	Ventilation, staff safety education	4	2	8	M
3	Exposure to noise from machines	Hearing-impairing noise	Noise	Ear protection	Staff safety education, measures if exceeding limits	3	8	24	H
4	Heavy lifts and poor working positions	Body injury	Heavy lifts and poor working positions	Rules against performing heavy lifts alone	Staff safety education, lifting aid	4	8	32	H
5	Exposure to chemicals e.g. precipitating chemicals	Exposure to chemicals	Inhalation, skin contact	Working equipment	Staff safety education	3	8	24	H
6	Risk of falling	Body injury	Fall from height, level differences	Working equipment	Staff safety education	3	8	24	H
7	Methane accumulation	Body injury, loss of life	Explosion	Protective equipment, zones	Staff safety education, ventilation	1	16	16	H
8	Falling into basin	Body injury, loss of life	Falling, drowning	Guardrail, coverage, no solo work	Staff safety education, maintenance of guardrail	1	16	16	H

For the alkaline dehydration system four potential risks were identified. The highest risk level for the additional risks connected to the alkaline dehydration system was defined as high (Table 10).

Table 10: Semi-quantitative risk assessment for the alkaline dehydration technology.

Alkaline dehydration									
Hazard identification				**Existing controls**		**Risk assessment**			
#	Hazardous event	Hazard	Expostutre route	Control description	Control validation	L	S	R	Lvl
See Table 9									
Additional risks urine concentration									
1	Inhalation of ammonia vapors during urine drying	Toxic vapors	Inhalation	Adequate ventilation	Performing ventilation maintenance	3	2	6	L
2	Changing the alkaline substrate	Pathogens	Ingestion	Working equipment, rapid pathogen reduction	Staff safety education	1	4	4	L
3		Exposure to chemicals	Skin contact	Working equipment	Staff safety education	3	8	24	H
4	Exposure to urine during pipe maintenance	Pathogens	Ingestion	Working equipment	Staff safety education	3	4	12	M

For the nitrification-distillation system five additional risks were identified, of which three were found to have a high risk level (Table 11).

Table 11: Semi-quantitative risk assessment for the nitrification-distillation technology.

Nitrification-distillation									
Hazard identification				**Existing controls**		**Risk assessment**			
#	Hazardous event	Hazard	Exposture route	Control description	Control validation	L	S	R	Lvl
See Table 9									
Additional risks urine concentration									
1	Exposure to accumulated ammonia vapors if urine storage needs to be opened	Toxic vapors	Inhalation	Working equipment including mask with ammonia filter and googles	Staff safety education	2	8	16	H
2	Exposure to accumulated nitrite	Toxic vapors, strong acid	Inhalation	Working equipment, even supply of urine, constant pH	Staff safety education, process monitoring	2	8	16	H
3	Explosion caused by ammonium nitrite	Body injury, loss of life	Explosion	Operation temperature considerably lower than critical temperatures	Process monitoring	1	16	16	H
4	Handling concentrated urine	Pathogens	Ingestion	Heat treatment	Process monitoring	1	1	1	VL
5	Exposure to urine during pipe maintenance	Pathogens	Ingestion	Working equipment	Staff safety education	2	4	8	M

For the ion-exchange system six potential additional risks were identified. Of the potential hazards, two risk levels were classed as high (Table 12).

Table 12: Semi-quantitative risk assessment for the ion-exchange technology.

Ion-exchange									
Hazard identification				**Existing controls**		**Risk assessment**			
#	Hazardous event	Hazard	Exposture route	Control description	Control validation	L	S	R	Lvl
See Table 9									
Additional risks urine concentration									
1	Exposure to accumulated ammonia vapors if urine storage needs to be opened	Toxic vapors	Inhalation	Working equipment, including mask with ammonia filter, adequate ventilation	Staff safety education	2	8	16	H
2	Exposure to struvite during collection	Pathogens	Ingestion	Working equipment	Staff safety education	1	4	4	L
3		Exposture to chemicals	Inhalation, skin contact	Working equipment	Staff safety education	3	2	6	L
4	Exposure to sulfuric acid during regeneration	Strong acid	Inhalation, skin contact	Working equipment, adequate ventilation	Staff safety education	3	8	24	H
5	Exposure to pathogens collection of fertilizer product	Pathogens	Ingestion	Working equipment	Staff safety education	1	4	4	L
6	Exposure to urine during pipe maintenance	Pathogens	Ingestion	Working equipment	Staff safety education	2	4	8	M

In the MCA, the conventional system was set as a baseline and was therefore not assigned a performance grading (Table 13). The alkaline dehydration technology was graded as good and both the nitrification-distillation and the ion-exchange technology were graded as neither good nor bad. The result would have been affected if the grading had been performed in a different way, for example if the highest risk score had defined the final performance. Then all systems would have had a poor performance. However, as mentioned in 3.3.7, the semi-quantitative risk assessment was used as a tool for internal comparison between the urine concentration systems and the grading used in this study may in this case provide clearer comparison. A more quantitative risk assessment could however provide a more in-depth analysis that may change the result. Additional risks could also be identified when these systems are brought to scale, since the urine concentration technologies are still innovations and all risks may not yet have been identified.

Table 13: Additional risks for the different urine concentration systems.

Technology	Conventional system	Alkaline dehydration	Nitrification-distillation	Ion-exchange
Number additional risk score $\geq$H	-	1	3	2
% of risk score for the conventional system	-	29	36	39
Performance	**-**	**4**	**3**	**3**

4.7 Performance matrix

The conventional system was graded as very good for all criteria except for eutrophying emissions and for the N recovery in nutrient recovery, where it was graded as neither good nor bad (Table 14). The performance for the economic and health category was not graded, because it was set as the baseline as it was also included in the urine concentration systems. The alkaline dehydration system had a poor performance for the energy demand and the annual cost, but performed better than the other systems in the health category. The nitrification-distillation system had a very poor performance for the annual cost. The ion-exchange system did not have a poor performance in any of the criteria investigated.

Table 14: Performance matrix for the MCA where CS is the conventional system, AD is the alkaline dehydration system, ND is the nitrification-distillation system and IE is the ion-exchange/struvite precipitation system.

Category	**Criteria**	**SDG**	**Indicator**	**Performance**			
				CS	**AD**	**ND**	**IE**
Environment	Eutrophying emissions	14	Concentration of N in WWTP emissions (mg/L)	3	3	3	3
			Concentration of P in WWTP emissions (mg/L)	3	3	3	3
	Nutrient recovery	6, 9, 11, 12	% N-recovery from total household wastewater	3	5	5	5
			% P-recovery from total household wastewater	5	5	5	5
	Energy demand	9	% of annual apartment energy demand for urine concentration	5	2	5	5
Technical	Space efficiency	11	Space required in residential area (m2/household)	5	5	4	5
Economic	Cost and affordability	6	Annual cost per household (SEK/year)	-	2	1	4
Health	Working environment	3, 8	Additional risks for workers (Semi quantitative)	-	4	3	3

The performance matrix demonstrated that all urine concentration technologies investigated were graded as very good in several criteria, which in turn suggests that it could potentially contribute to the SDGs connected to respective criteria. On the other hand, when applied at this scale it had no significant effect on the eutrophication. The energy consumption of the alkaline dehydration system was higher than the other systems. However, optimizing the alkaline dehydration system could potentially have changed the grading. Increasing energy demand at the WWTP, due to increasing wastewater load and stricter emission requirements, could also have provided incentives for an application of urine concentration technologies. The costs had great uncertainties and could change significantly. The cost was graded based on today's VA tariff and it was assumed that the population in Sege Park would pay for the implementation. At the same time, perhaps such an implementation could receive a state subsidy or be shared among the entire population, as it could potentially contribute to a reduced load on the sewage treatment plants and fertilizer that could be used locally.

This thesis does not provide the full picture of the sustainability and further research is required in order to determine if urine concentration could be an option for future wastewater treatment. The social acceptance, which is an important criterion for sustainable sanitation, was not included in this study and should therefore be investigated further. In addition, the performances were not weighted. Weighing the results could have changed the outcome of the MCA performance matrix if the criteria were graded based on their importance according to local stakeholders. Trade-offs between the different criteria may potentially be identified, where for example the cost could have been legitimated due to the elevated nitrogen recovery. An expansion of Sjölunda WWTP is planned (VA SYD & EnviDan 2019) and it may be of interest for further investigation to compare the costs for the expansion with the costs for implementation of urine concentration.

4.8 Wider implementation

Eutrophying emissions

Expanded installation of urine concentration in Malmö could potentially lead to reduced nitrogen concentration in the effluent from the WWTP (Figure 9). A good performance in the MCA could, according to the calculations in this study, be reached if 30% of the wastewater produced in Malmö was treated with urine concentration systems. The reduced content of nitrogen in the influent could however have affected the capacity of the WWTP. According to Wilsenach & Van Loosdrecht (2003), urine diversion would generate reduced nitrogen emissions in a WWTP where the nitrogen was removed in a biological process. In their study the nitrogen concentration in the WWTP effluent were reduced significantly up to 50% of urine diversion, but after that the change was not as clear.

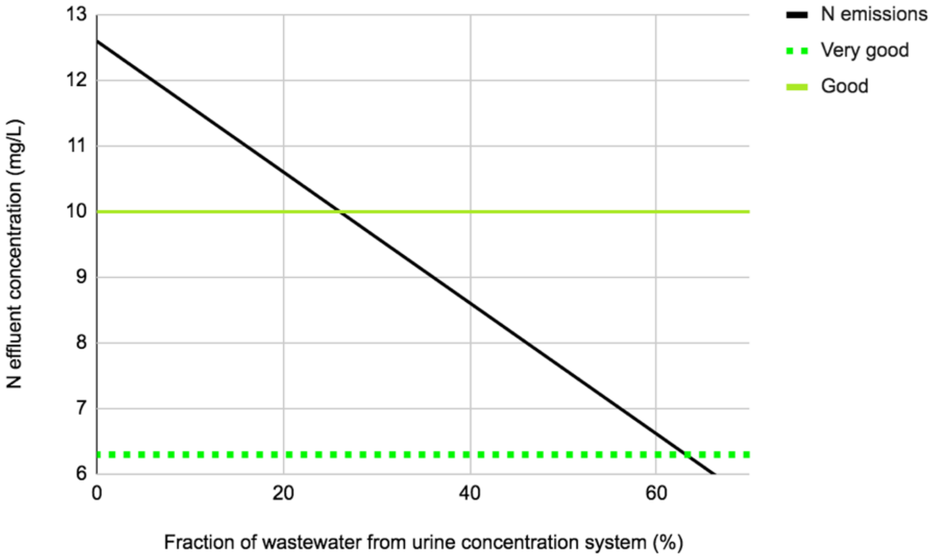

Figure 9: N effluent concentration from the WWTP when different fractions of the wastewater comes from urine concentration systems. The result for the nitrogen emissions for the different urine concentration technologies is presented with one line because the difference between the technologies is not visible on this scale. The lines Good and Very good define limit values for the performance levels in the MCA.

The majority of the phosphorus was already removed in the WWTP and therefore there was no radical change in the phosphorus removal efficiency when a greater proportion of

Malmö installed urine diverting toilets. The result showed that for a 0.1 mg P/L reduction, around 70% of the wastewater produced in Malmö would have to be diverted (Figure 10). However, in order to reach a good performance in the MCA for the phosphorus concentration in the effluent, slightly more than 20% of the wastewater in Malmö was required to come from systems connected to urine concentration.

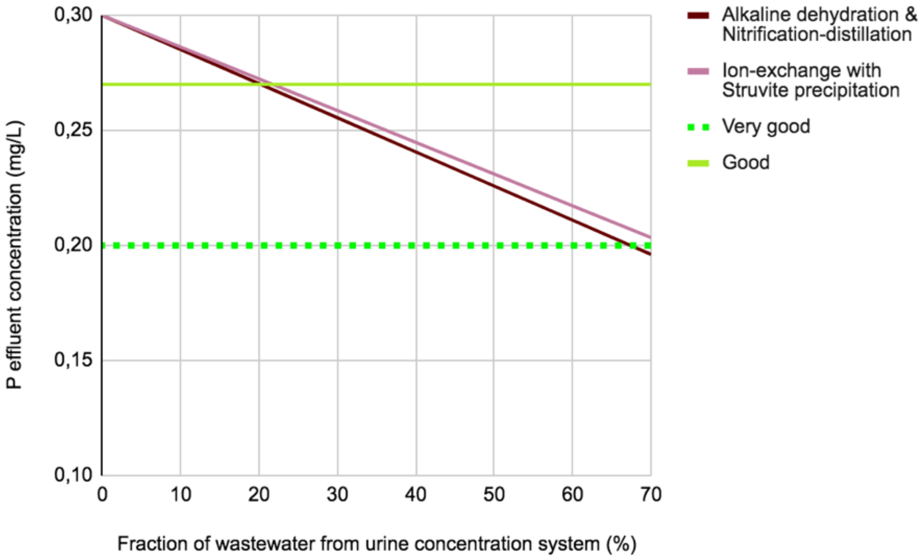

Figure 10: P effluent concentration from the WWTP when different fractions of the wastewater comes from urine concentration systems. The lines Good and Very good define limit values for the performance levels in the MCA.

The calculations were based on the wastewater produced in Malmö and therefore the application of urine concentration was not restricted to households. Urine concentration may also be applied for example in office buildings or department stores. However, the morning urine generally contains the highest concentration of nutrients (Etter & Udert 2015) and is often excreted at home. This is important to keep in mind when installing urine concentration sanitation systems. In addition, these are simplified calculations that were based on the assumption that the removal in the WWTP did not change with decreasing inflow concentrations. It is therefore recommended that the potential removal of eutrophying emissions is investigated in more detail future studies.

Fertilizer demand

Depending on the nutrient recovery rate of the urine concentration technology, different proportions of the urine excreted in Malmö would be required in order to cover the city's fertilizer demand. In order to cover the fertilizer demand of nitrogen for the agricultural land in Malmö, a little more than 40% of the urine would be required to be treated with urine concentration technologies at a 99% nitrogen recovery rate (Figure 11). At a recovery rate of 70% would instead over 50% of the urine be required to be treated with urine concentration. However, in the calculations it was assumed that all the nitrogen in the urine would be recovered and be plant available. In a study by Stintzing et al. (2001), fertilizer trials were performed where urine and commercial fertilizer were applied so that the amount of nitrogen was the same. The study showed that urine gave a yield of 70-100% compared to when a commercial fertilizer was used, which indicates that all of the nitrogen might not be plant available. Therefore, it could be of interest to compare plant trials for the different fertilizer products from the urine concentration technologies.

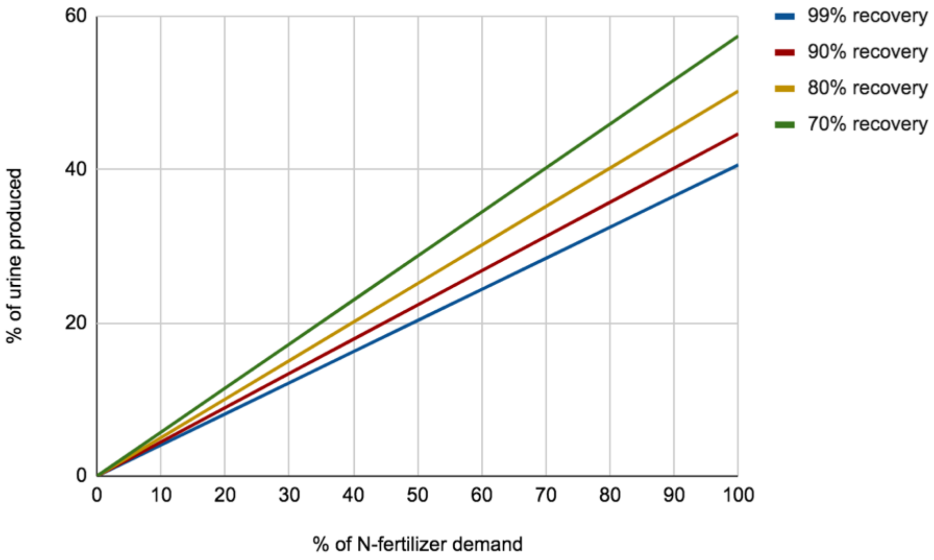

Figure 11: The percentage of urine produced in Malmö required to be treated with urine concentration technologies at four different N-recovery rates, in order to cover different percentages of the N-fertilizer demand in Malmö.

To cover the phosphorus fertilizer demand in Malmö, about 30% of the urine produced in the city had to be treated with urine concentration at a 100% recovery rate (Figure 12). At 70% recovery rate, about 40% of the urine was required instead.

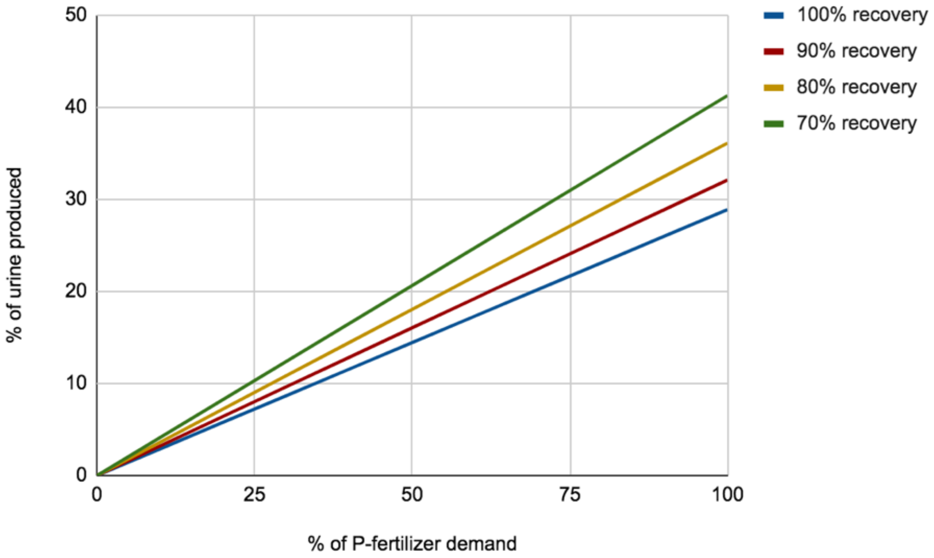

Figure 12: The percentage of urine produced in Malmö required to be treated with urine concentration technologies at four different P-recovery rates, in order to cover different percentages of the P-fertilizer demand in Malmö.

Despite the fact that it is uncertain exactly how much urine is needed to cover the N and P-fertilizer demand in Malmö, the results still show that a large part the demand may have been covered without all urine in Malmö being treated with urine concentration technology. However, Malmö is not self-sufficient, but imports a large part of the food. According to Harder et al. (2021) nutrient accumulates around the centres and may thereby cover a large part of the fertilizer demand in for instance larger cities. Meanwhile, other areas may be deployed of nutrients.

The quality of the WWTP sludge may be affected in the event of an expansion of urine concentration because less phosphorus ends up in the sludge. This would affect the Cd/P ratio in the sludge. According to Svenskt Vatten (2020b) there is an aim of a maximum Cd/P ratio of 17 mg cadmium per kg phosphorus. This is because cadmium may be toxic to organisms already at moderate increases (Svenskt Vatten 2019). As of 2019, only 38% of the Revaq-certified WWTP had a ratio under 20 mg Cd per kg P (Svenskt Vatten 2020b). If the sludge becomes unusable, it affects not only the phosphorus recycling, but also the carbon addition to the soil, which is beneficial for the soil structure.

Space

If urine concentration was applied in the homes of half of the population in Malmö the amount of parking windows required would have been 2780 for the alkaline dehydration system, 4640 for the nitrification-distillation system and 1550 for the ion-exchange system. Normally in Malmö, 0.7-1.0 parking windows per apartment is required (Malmö Stad 2010). Assuming an average of 0.85 parking windows per apartment and 3 persons per household the space requirement for the alkaline dehydration technology represented 6% of residential parking for apartments for half of the population in Malmö. For the nitrification-distillation and ion-exchange system 9 and 3%, respectively, of the residential parking for apartments for half of the population in Malmö was required. All systems still fall within the range 0.7-1.0 parking windows per apartment and given that newer areas aim at having 0.5 parking windows per apartment (Malmö Stad 2015), this could potentially be places that can be dispensed with in favor of semi-centralized treatment centers for urine concentration.

5 Conclusions

In this study the sustainability of three different urine concentration technologies was evaluated in a MCA. The technologies investigated were alkaline dehydration, nitrification-distillation and struvite precipitation followed by ion-exchange. The alkaline dehydration system was found to have a high energy consumption and both the alkaline dehydration and nitrification-distillation technology were found to have high annual costs. The ion-exchange system generates a waste stream and almost solely recovers the selected nutrients, leaving other important nutrients in the effluent. Common to all the urine concentration systems was that they performed significantly better in terms of nitrogen recovery than the conventional system and thereby contribute to SDG 6, 9, 11 and 12.

When implemented at the scale investigated in this study, the urine concentration did not have an effect on the eutrophying emissions from the WWTP. The eutrophying emissions could however be reduced in the case of a wider implementation. The wider implementation also showed that a large part of the N and P-fertilizer demand may be met, without the need for all urine produced in Malmö to be treated with a urine concentration system.

The urine concentration technologies investigated are still developing and have areas of improvement. Further studies of the urine concentration technologies and their sustainability are therefore required in order to determine whether urine concentration can be an alternative as a complement to the existing wastewater treatment. It was however demonstrated that the urine concentration technologies perform well in many of the sustainability criteria examined, especially in the nitrogen recovery criteria. This study can therefore be an incentive for further studies where the sustainability of an implementation of urine concentration in Sweden is addressed.

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Senecal, J. (2021) Personal communication with researcher at SLU. March-May 2021

A Assumptions for Environment category

Table 15: Assumptions and design parameters Environment category

Assumptions and design parameters		
Homes Sege Park	700	(Malmö Stad Stadsbyggnadskontoret 2017)
Persons per household	3	Assumed
Time spent at home	2/3	(von Münch & Winker 2011)
Household wastewater	See Table 1	See Table 1
Conc. N in urine	7270 mg/L	(Vinnerås et al. 2006)
Conc. P in urine	663 mg/L	(Vinnerås et al. 2006)
Density urine and greywater	1 kg/L	Assumed
Density toilet paper	1.4 kg/L	Assumed
Density faeces	1.075 kg/L	av. 1.06-1.09 (Penn et al. 2018)
Wastewater to WWTP	40478500 m3/y	(VA SYD 2019)
Fraction Sege Park of total wastewater	0.25%	Calculated from values in Table 1 and (VA SYD 2019)
N conc. of incoming wastewater WWTP	42 mg/L	(VA SYD 2019)
P conc. of incoming wastewater WWTP	5 mg/L	(VA SYD 2019)
N removal WWTP	72%	(VA SYD 2019)
P removal WWTP	94%	(VA SYD 2019)
N losses during pipe transport and storage	Negligible	Assumed due to limebox and closed tanks
N recovery WWTP	15%	Assumption based on (Jönsson 2019)
P recovery WWTP	94%	Assumed to be the same as the removal
Potential N recovery		
Alkaline dehydration	98%	Simha et al. (2020b)
Nitrification-Distillation	99%	(Etter et al. 2015)
Ion-exchange	99%	(Tarpeh et al. 2018b)
Potential P recovery		
Alkaline dehydration	100%	(Senecal 2020)
Nitrification-Distillation	100%	(Etter et al. 2015)
Struvite precipitation	93%	(Etter et al. 2015)
Energy demand		
Alkaline dehydration	1 kWh/L_{urine}	(Senecal, personal communication)
Nitrification-Distillation	0.15 kWh/L_{urine}	(Etter & Udert 2015)
Ion-exchange	1 Wh/L_{urine}	Estimated from category *others* in Kavvada et al. (2017)
Struvite precipitation	20 Wh/L_{urine}	(Antonini 2013)
Commercial fertilizer production	95 Wh/L_{urine}	Calculated from 45 MJ/kgN, 29 MJ/kgP (Maurer et al. 2003) see Eq. 4
N removal with carbon source at WWTP	27 Wh/L_{urine}	Mean 10 MJ/kgN Maurer et al. (2003) & 34 Wh/L_{urine} (Kavvada et al. 2017) see Eq. 5
Apartment	3600kWh/y	(Vattenfall 2020)

The energy demand to produce an equal amount commercial fertilizer to the one recovered from the urine calculated from values from a study performed by Maurer et al. (2003) where the energy to produce commercial fertilizer were 45 MJ/kgN and 29 MJ/kgP. The recovery rate for the systems with the lowest maximum N and P-recovery was used as well as the nitrogen and phosphorus content per liter urine according to Vinnerås et al. (2006).

$$E_{com.fert} = \frac{45MJ/kgN}{3.6MJ/kWh} \cdot \frac{4kgN/y \cdot 0.98}{550L_{urine}/y} + \frac{29MJ/kgP}{3.6MJ/kWh} \cdot \frac{0.4kgP/y \cdot 0.93}{550L_{urine}/y} = 0.095kWh/L_{rec.urine} \tag{4}$$

The energy demand for N-removal at a WWTP was calculated as a mean value based on studies by Maurer et al. (2003) and Kavvada et al. (2017) as well as the nitrogen content per liter urine according to Vinnerås et al. (2006).

$$E_{Nremoval} = \frac{\frac{10MJ/kgN \cdot 4kgN/y}{3.6MJ/kWh \cdot 550L_{urine}} + 0.034kWh/L_{urine}}{2} = 0.027kWh/L_{urine} \tag{5}$$

B Assumptions for Economic category

Table 16: Assumptions and design parameters Economic category

General assumptions and design parameters		
Time spent at home	2/3	(von Münch & Winker 2011)
Urine produced in Sege Park	2110 L/d	Assumed
Conc. N in urine	7270 mg/L	(Vinnerås et al. 2006)
Salary employee	37000 SEK/mth	32000-42000 SEK (Unionen 2021)
Workers required	2	Assumed
Service	Once a week	Assumed
Electricity	0.6 SEK/kWh	(SCB 2020c) (cost for electricity grid not included)
N fertilizer	9.2	(The Swedish Board of Agriculture 2021)
P fertilizer	18.98	(The Swedish Board of Agriculture 2021)
1 €	10.15 SEK	(DI 2021) (15/3-21)
1 $	8.51 SEK	(DI 2021) (15/3-21)
Standard toilet	6000 SEK	(Avloppscenter 2021) (17/3-21)
Urine diverting toilet	10400 SEK	(Avloppscenter 2021) (17/3-21)
Pipes	0 SEK	Assumed neglible
Lifetime (years)		Based on Svenskt Vatten (2015)
Toilet	25	
Pipes	50	
Process control & electricity	20	
Pump and machines	15	
Ion-exchange vessel, Plastic vessels and boxes	10	
Discount rate		
Lifetime 1-30 y	3.5%	(Söderqvist 2006)
Lifetime 31-75 y	3.0%	(Söderqvist 2006)

Table 17: Basis cost estimation alkaline dehydration

Alkaline dehydration			
Treatment capacity (L_{urine}/d)		30	Set-up from pilot by Simha et al. (2020c)
Treatment units		70	Based on capacity
Material	*Cost*	*Quantity*	*Reference*
Ca(OH)2	0.68 SEK/kg	0.02 kg/L_{urine}	Cost: (Muster et al. 2013) Quantity: (Senecal, personal communication)
MgO limebox	2.55 SEK/kg	0.042 kg/limebox,week	Cost: (Bray & Ghalayin 2020) Quantity: (Kanti Deb, personal communication)
Electricity	0.6 SEK/kWh	1 kWh/L_{urine}	See Table 15 and 16
Service	231 SEK/h	40 h/p,week	Based on assumption of av. 30 min/week per unit and av. 5 min for transportation between stations
Toilet w. limebox	9600 SEK	700	Additional cost to conventional toilet. Toilet w. limebox assumed cost x1.5 Urine div. toilet
Plastic box	100 SEK	210	Set-up from pilot by Simha et al. (2020c) Costs based on products used.
Fan	800 SEK	420	Set-up from pilot. Costs based on products used. Assumed fan cost x2
Dehumidifier	10000 SEK	70	Set-up from pilot. Costs based on products used
Floor heating mat	2200 SEK	70	Set-up from pilot. Costs based on products used

Table 18: Annual costs for alkaline dehydration

Alkaline dehydration					
O&M costs		*Capital costs*		*Fertilizer sales*	
Item	**Annual cost (SEK/y)**	**Item**	**Annual cost (SEK/y)**	**Item**	**Annual cost (SEK/y)**
MgO	3903	Toilets	407730	N	-50490
$Ca(OH)_2$	10484	Plastic boxes	2537	P	-9699
Electricity	462000	Dehumidifier	61055		
Service	959831	Floor heating	13432		
		Fans	29306		
Total	1436218	**Total**	514060	**Total**	-60189

Table 19: Basis cost estimation nitrification-distillation

Nitrification-distillation			
Nitrification rate (mg/Lreactor,day)		450	Based on nitrification rate: 100-800 according to Etter & Udert (2015) Partial nitrification
Volume nitrification column (L)		120	(Etter & Udert 2015)
Amount of nitrification columns per unit		2	(Etter & Udert 2015)
Treatment capacity (L_{urine}/d,unit)		30	Assumed based on nitrification rate and used N-concentration (Vinnerås et al. 2006)
Treatment units		70	Based on capacity
Material	*Cost*	*Quantity*	*Reference*
Electricity	0.6 SEK/kWh	0.15 kWh/L_{urine}	See Table 15 and 16
Service	231 SEK/h	40 h/p,week	Assumed av. 30 min/week,unit and av. 5 min for transportation between stations. 2 workers
Toilet	4400 SEK	700	Additional cost to conventional toilet.
Storage tank set	8455 SEK	70	Cost: (Etter & Udert 2015)
Dosing pumps	33829 SEK	70	(Etter & Udert 2015)
Air compressor	42295SEK	70	(Etter & Udert 2015)
Nitrification columns	25375 SEK	70	(Etter & Udert 2015)
Distiller	406000 SEK	70	(Etter & Udert 2015)
Sensors	50750 SEK	70	(Etter & Udert 2015)
Process control	84580	70	(Etter & Udert 2015)

Table 20: Annual costs nitrification-distillation

Nitrification-distillation

O&M costs		*Capital costs*		*Fertilizer sales*	
Item	**Annual cost (SEK/y)**	**Item**	**Annual cost (SEK/y)**	**Item**	**Annual cost (SEK/y)**
Electricity	69300	Toilets	186876	N	-51005
Service	959831	Storage tanks	71518	P	-9699
		Dosing pumps	206570		
		Air compressor	258212		
		Nitrification columns	154927		
		Distiller	2478836		
		Sensors	251099		
		Process controll	418498		
Total	1029131	**Total**	4026536	**Total**	-60704

Table 21: Basis cost estimation ion-exchange with struvie precipitation

Ion-exchange			
Treatment capacity (L_{urine}/d,unit)		100	Assumed and designed after
Treatment units		22	Based on capacity
Volume reactor per liter urine		0.17 L	Assuming the same ratio as Kavvada et al. (2017)
Material	*Cost*	*Quantity*	*Reference*
Dowex Mac 3 (100 uses)	0.019 SEK/L_{urine}	-	(Tarpeh 2018a)
Sulfuric acid	0.036 SEK/L_{urine}	-	(Tarpeh 2018a)
MgO	2.55 SEK/kg	1.4 kgMgO/kgP	Cost: (Bray & Ghalayin 2020) 1.1:1 (Mg/P-ratio) (Etter et al. 2015)
Electricity	0.6 SEK/kWh	0.021 kWh/L_{urine}	See Table 15 and 16
Service	231 SEK/h	16 h/p,week	Assumed av. 30 min/week,unit and av. 15 min for transportation between stations. 2 workers
Toilet	4400 SEK	700	Additional cost to conventional toilet.
Storage tank 1000 L	4400	66	V calculated from Eq. 1 (2/3 time spent at home & 30 d storage) Cost:(Aj Produkter 2020)
Intermediate storage tank 300 L	3000	22	Assumed volume required Cost:(Aj Produkter 2020)
Dosing pumps	33829 SEK	22	Assumed approx. same amount of pumps as nitr-dist per unit
Struvite vessel	1787 SEK/m^2	1.1 m^2	(Ishii & Boyer 2015) Assumed 50 L/vessel
Stirrer	13800 SEK	22	For 50 L Cost assumed based on (fisher scientific 2021)
Ion-exchange vessel	16637 SEK/m^2	2.5 m^2	(Landry & Boyer 2016)

Table 22: Annual costs ion-exchange with struvite precipitation

Ion-exchange

O&M costs		*Capital costs*		*Fertilizer sales*	
Item	**Annual cost (SEK/y)**	**Item**	**Annual cost (SEK/y)**	**Item**	**Annual cost (SEK/y)**
Dowex Mac 3	14416	Toilets	186876	N	-51020
Sulfuric acid	27521	Storage tanks	40906	P	-9020
MgO	1866	Struvite vessel with stirrer	25388		
Electricity	9702	Ion-exchange vessel	4924		
Service	378788	Dosing pumps	61689		
Total	432293	**Total**	319783	**Total**	-60040

C Basis risk assessment

WWTP

Inhalation of aerosols

Aerosoles, small particles of wastewater in the air, contain microorganisms that can cause gastrointestinal infections. This is one of the most common health effects among the staff at a WWTP (IVL 2018) . The risk of exposure is highest around moments where the wastewater may be sprayed in the air e.g. around pumps or when cleaning basins or mixers. To prohibit the risk of ingestion of aerosols through inhalation or ingestion, adequate ventilation, avoiding manual cleaning, working equipment is advised and proper hand hygiene (IVL 2018) . Infections caused from contaminated water often cause gastrointestinal infections with symptoms including acute diarrhea, abdominal pain, headache, nausea and vomiting (Folkhälsomyndigheten 2016), which according to (WHO 2016) results in moderate severity S=4. The likelihood was decided to be likely L=4. → **R=16**

Inhalation of toxic gases

While treating the wastewater (especially at anaerobic degradation) it can generate a production of hydrogen sulfide. If the hydrogen sulfide was to be inhaled, it may numb the sense of smell resulting in difficulty to notice if surrounded by high concentrations (IVL2019). The concentration of hydrogen sulfide in the air at a WWTP has been evaluated and was 0-3 ppm, causing malodour. However, concentrations at a maximum of 100 ppm have also been detected. Concentrations of 50 - 100 ppm can cause eye irritations of different severity (IVL2019). Provided working equipment and adequate ventilation, the severity was thereby classed as S=2 and the likelihood as likely L=4 → **R=8**.

Noise

There are several machines causing noise at a WWTP (IVL 2012f). Being exposed to noise during a long period can cause permanent hearing damage and could lead to higher blood pressure. From this, the severity was graded as major S=8. Ear protection should be provided if the mean value is 80 dB(A) for a working day and worn if the mean value exceeds 85 dB(A) (IVL 2012b). At WWTPs there are several processes that cause a higher noise level. From this the likelihood was judged as possible, L=3. → **R=24**.

Heavy lifts and poor working positions

Working in tanks and other confined spaces entails awkward working positions that may cause congestion or acute discomfort (IVL 2012f). The same hazards may be the result of monotone working tasks as well as heavy lifts that are performed non-ergonomic. There are several moments where heavy lifts are performed (e.g. lab staff lifts test cans with wastewater of 10- 25 kg) and the work is monotone according to IVL (2012f). From this information S=8 and L=4. → **R=32**

Exposure to chemicals

Different chemicals are used at a WWTP including process and laboratory chemicals (IVL 2012f). Precipitation chemicals may cause irritation or corrosion to skin, eyes and the respiratory system (IVL 2012e). Polymer may cause dry skin and airways (IVL 2012e). From this information the severity was judged as major in the case of an eye damage, S=8. Assuming that information about the risks and how the chemicals should be handled are provided and that working equipment also is provided (and worn), the likelihood was classed as possible L=3. → **R=24**

Risk of falling

There have been several documented cases of falling accidents at WWTPs (IVL 2012d). The injuries documented ranged from sprains to broken ribs, resulting in a severity of S=8. However, some of the cases were a result of not using proper work equipment (e.g. using a metal trash can as a ladder). Based on the number of reported cases, the likelihood was determined as possible, L=3. **R=24**

Risk of explosion

At anaerobic degradation of organic material in the wastewater (e.g. at biogas production) methane is produced. Accumulation of methane may lead to an explosion. The explosion can be caused by a spark from an electrical machine (IVL 2015). However, the risk of explosion is evaluated at different zones and precautions are taken. The precautions include education for staff working in zones with explosion risks, providing protective equipment and, when possible, effective ventilation before and during the work is done (IVL 2012a). In the case of an explosion, the consequences are catastrophic S=16 but the likelihood is judged as very unlikely L=1 because of the measures taken. → **R=16**

Falling in to basin

There is a risk of falling into a basin while working beside it which in the worst case may lead to drowning (IVL 2012c), S=16. The risk of falling increases with lack of guardrail or if the coverage has been removed (IVL 2012c). But provided guardrail and coverage, and that this kind of work is not performed alone, the risk of drowning is classed as very unlikely L=1. → **R=16**

Alkaline dehydration

Ammonia vapour

Inhalation of ammonia vapors may cause potential health risks since it is irritant to lungs and eyes. At low concentration in inhalation could irritate the airways and cause coughing. Ammonia concentrations at 20-25 ppm cause irritation to the airways and the irritation increases with the concentration (Arbetshälsoinstitutet 2014). Concentrations measured in livestock barns in a study by Dewey et al. (2000) was ≥25 ppm in 8% of the cases. The vapors from the alkaline dehydration technology could possibly contain low concentrations of ammonia (McConville et al. 2020). However, the concentration from the operation vapors is very low and is therefore not an issue (Senecal, personal communication). This is because ammonia volatilisation is not wished for since the aim is to capture all of the nitrogen. Given this information the severity was classed S=2. The likelihood was classed as possible L=3 since the vapours come from operating the system, but given good ventilation the likelihood may be reduced. → **R=6**

Alkaline substrate and changing the substrate

Pathogens As mentioned before, infections caused from contaminated water may cause acute diarrhea, abdominal pain, headache, nausea and vomiting (Folkhälsomyndigheten 2016). Viruses and bacteria have a fast inactivation in the dry alkaline media (Senecal et al. 2018). Severe ascaris infection may cause severe abdominal pain, cough and respiratory issues, but most ascaris cases come from abroad (1177 Vårdguiden 2020) and thus not likely from a Swedish perspective. Assuming that gloves and other protective clothing are used and that the task is performed by educated staff. Therefore, S=4 and L=1 → **R=4**

Alkaline substrate Irritations may be caused to skin by the alkaline substrate. The substrate could also cause damage to the eyes (National Center for Biotechnology Information 2021), S=8. If working equipment and eye protection is used properly the likelihood is quite low, but in the case of improper use there is a possibility of exposure, L=3. → **R=24**

Cleaning of pipes

The pipes should be rinsed with an alkaline solution every week for an office of 25 people according to McConville et al. (2020). However, according to Senecal (2020) the growth of a biological film could potentially be prevented by e.g. using a very hydrophobic material or a coating that prevents the build-up of a biological film. This might reduce the frequency of the maintenance. There is a risk of exposure to pathogens while cleaning the pipes and they may cause gastrointestinal infections with e.g. diarrhea as a symptom (Folkhälsomyndigheten 2016) resulting in a moderate severity. However, the risk of transmission of pathogens from urine is low if no cross-contamination of faeces occurs (Schönning 2001). Although, the risk of cross contamination is higher when urine is collected from several households. The resulting severity and likelihood were classed as S=4, due to the symptoms previously described (acute diarrhea etc.), and, assuming that working equipment is used, L=3 due to that transmission may possibly occur under regular circumstances. → **R=12**

Nitrification-distillation

Ammonia volatilisation at urine urine storage

Inhalation of ammonia causes, as mentioned before, severe irritation or even corrosion to the respiratory system and eyes at high concentrations. When large volumes of urine are stored it might result in accumulation of ammonia in the headspace of the tank. Therefore, suiting working equipment, including a mask with the ability to filtrate ammonia and eye protection (Etter & Udert 2015). From this information the severity was decided to be higher than for the operation vapors for the alkaline dehydration S=8 and the likelihood was decided as unlikely L=2 provided masks are worn when opening storage tanks. → **R=16**

Accumulation of nitrite and the production of nitrous acid

The accumulation of nitrite might result in the production of nitrogen oxides (Etter & Udert 2015) which is a health hazard because the oxides may cause irritation in the airways and mucous membranes (Naturvårdsverket 2020). The accumulation occurs when instability in the process occurs. For a stable process it is very important with an even supply of urine (overloading may lead to accumulation of nitrite) and a constant pH. Nitrous acid is a strong acid and highly corrosive (Swedish Poisons Information Centre 2018). It may cause severe damage to eyes and serious damage when ingested or at contact with eyes and skin. Provided process control and an even supply of urine S=8, L=2 → **R=16**

Explosion caused by ammonium nitrate

There is a risk of explosion if the distiller runs dry due to the thermal instability of the ammonium nitrate (Etter & Udert 2015). The critical temperatures are 170 degrees when in solution and 96 degrees if the evaporation is complete. Meanwhile, the highest boiling temperature of the solution is 130 degrees and the distiller operates at temperatures around 80-85 degrees. The recommendations are to not remove more water after the first precipitation occurs and to always ensure that there is enough liquid throughout the distillation process according to Etter & Udert (2015). However the likelihood is assumed to be low due to the fact that the operating temperature is considerably lower than the critical temperature (Etter & Udert 2015). From this information, the severity was decided to be catastrophic S=16 if an explosion would occur because it may cause serious body injuries, but the likelihood was set as very unlikely L=1 because of the difference between the operating and critical temperature. → **R=16**

Pathogens concentrated urine

Fulfills pasteurization requirements and are free from pathogens according to Etter et al. (2015). L=1, S=1 → **R=1**

Cleaning of pipes

See *Alkaline dehydration.* However for this system, the cleaning of the pipes should be performed yearly (Etter & Udert 2015) resulting in a somewhat lower likelihood. S=4, L=2 → **R=8**

Ion-exchange

Ammonia volatilisation at urine urine storage

See *Nitrification-distillation* → **R=16**

Struvite

Pathogens Only a partial removal of pathogen when drying struvite in the ambient air according to Etter & Udert (2015). But, urine does not contain a high concentration of pathogens if not cross-contaminated (Schönning 2001). Given a storage time of 30 days recommended by Swedish EPA (2013) the pathogen reduction is enough to use as a fertilizer. The severity was classed as moderate S=4 and the likelihood as unlikely L=1, given that adequate working equipment is worn. → **R=4**

Chemical The struvite has not been classed as a dangerous chemical however, protective equipment should be worn and in case of skin or eye contact rinsing with water is recommended (Sigma-Aldrich 2021). If inhaled, remove to fresh air. From this information the severity S=2 and likelihood L=3 were decided. → **R=6**

Regeneration of the resin with sulfuric acid and collection of fertilizer from ion-exchange

Chemicals Sulfuric acid is highly corrosive to skin and eyes, and may cause blindness (CarlRoth 2019). Therefore the severity was classed as S=8 and the likelihood, given that working equipment including protective glasses and gloves, was judged as possible L=3 → **R=24**

Pathogens The pathogen removal when using the ion-exchange for nitrogen removal has not yet been addressed according to Tarpeh et al. (2018a). However, according to Swedish EPA (2013) the pathogen reduction is generally enough to use as a fertilizer after 30 days of storage of urine. Therefore, S=4 and L=1 → **R=4**

Cleaning of pipes

See *Nitrification-distillation.* The likelihood and severity was assumed to be L=2 and S=4, respectively. → **R=8**