Circular sanitation in relation to nutrients recycling and (urban) agriculture in the city of Amsterdam

Deliverable D4.4 Opportunities and barriers for circular sanitation within urban context

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Afvalwater is een belangrijke reststroom wat betreft nutriënten, in steden vooral van huishoudelijke bronnen. Dit rapport legt uit waarom het verbeteren van circulariteit van sanitaire voorzieningen belangrijk is, hoe het gelinkt is met circulaire (stedelijke) voedselproductie, wat circulaire sanitaire voorzieningen inhouden en welke kansen en barrières aanwezig zijn voor de realisatie ervan. De besproken aspecten zijn gerelateerd aan duurzaamheid, milieu, kwaliteit, agronomie, wetgeving, gezondheid en veiligheid, technologie, economie en bewustzijn en acceptatie. Het rapport geeft aanvullend aanbevelingen om de transitie van conventionele behandeling van afvalwater naar circulaire sanitatie en nutriënten terugwinning en hergebruik in relatie tot (stads)landbouw te stimuleren. Aanbevelingen voor Amsterdam en andere steden en belanghebbenden zijn: helderheid bieden in wetgeving, stimuleren en werken aan kwaliteitsborging, wetgevingsbarrières aanpakken, de vraag naar nutriënten en *biobased* meststoffen stimuleren, nieuwe en gerenoveerde gebouwen klaar maken voor circulaire sanitatie, winstgevendheid en duurzaamheid van circulaire sanitatie gebiedsspecifiek vaststellen en verantwoordelijkheden toekennen in de transitie naar circulaire sanitatie.

Wastewater is an important residual stream in terms of nutrients, in cities especially from household sources. This report explains why improving circularity of sanitation systems is relevant, how it is linked with circular (urban) food production, what circular sanitation systems entail and what opportunities and barriers are present for its realisation. Discussed aspects are related to sustainability, environment, quality, agronomy, legislation, health and safety, technology, economy and awareness and acceptation. The report furthermore provides recommendations to promote the transition from conventional wastewater treatment to circular sanitation and nutrient recovery and reuse in relation to (urban) agriculture. Recommendations for Amsterdam and other cities and stakeholders are: provide clarity in legislation, stimulate and work on quality assurance, tackle legislative barriers, stimulate the demand side for nutrients and biobased fertilisers, make new and renovated buildings circular sanitation proof, assess profitability and sustainability of circular sanitation area-specific, and assign responsibilities in the transition towards circular sanitation.

Keywords: circular sanitation, urban agriculture, nutrients, recovery and reuse, recycling, wastewater, decentralised wastewater systems, source separation, sewage sludge, urine, faeces, biobased fertilisers, sustainable cities, Amsterdam, sustainability, food system, phosphate, nitrogen, contaminant

The pdf file is free of charge and can be downloaded at https://doi.org/10.18174/580253 or via the website www.wur.nl/environmental-research (scroll down to Publications – Wageningen Environmental Research reports). Wageningen Environmental Research does not deliver printed versions of the Wageningen Environmental Research reports.

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Approved reviewer who stated the appraisal,

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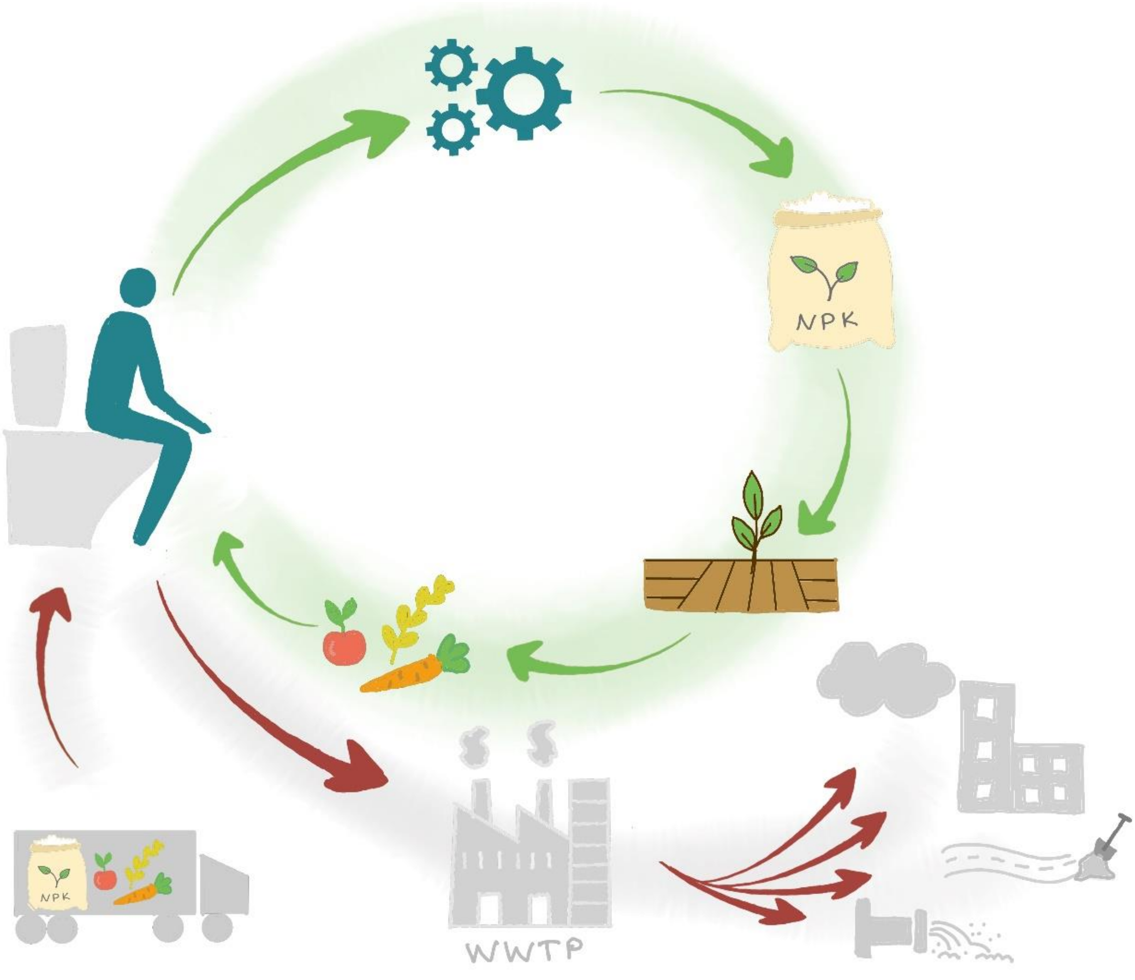
Summary

Within the Flagship project "Circularity by Design" (CbD) a (re)design process based on circularity will be applied within the Amsterdam metropolitan area with the aim to create a sustainable agri-food system.

Wastewater is an important residual/waste stream in terms of nutrients, in cities especially from communal (household) sources. At this moment, conventionally, the system from soil to food to sewage is linear, with no nutrient recovery, let alone reuse of those nutrients and (fertiliser) products in agriculture. The aim of this report is to explain why improving circularity for sanitation systems is relevant, what circular sanitation systems entail and what opportunities and barriers are present for its realisation.

The term 'circular sanitation' (CS, sometimes called 'new sanitation' as well) is used for sanitation that deals differently with wastewater than commonly used sanitation, with the aim to process wastewater effectively and sustainably. Wastewater is not seen, named or classified as waste, but as a raw material from which energy and nutrients can be recovered.

In this document, CS indicates preferably source-separated sanitation and, at minimum, a sanitation/wastewater system that is developed to enable reuse of nutrients for plant growth. Usually, this goes hand in hand with a decentralised system.



Barriers and opportunities that are encountered when implementing CS are discussed, subdivided into 1) Sustainability and environment, 2) Quality and agronomy, 3) Legislation, 4) Health and safety, 5) Technical aspects, 6) Economic aspects and 7) Social aspects.

The transition from conventional wastewater treatment to circular sanitation and nutrient recovery and reuse requires among others incentive, clarity, and changes in policies and legislation. Some recommendations and ideas are:

- A roadmap Circular Sanitation could be made available for municipalities to explain the steps that a company should take to implement circular sanitation.
- Municipalities could incentivise the implementation of circular sanitation by providing subsidies or wastewater treatment tax reductions, or on the other hand by raising taxes for building non-circular sanitation systems.
- Legislation should be adapted to make it easier to test circular sanitation products in pilots, including agronomic field test to show the agronomic values and how risks with potential contaminants can be tackled. Additionally, a list should be compiled encompassing all legislation that is relevant for circular sanitation and the recovery and reuse of nutrients and biobased fertilisers from wastewater.
- There is a need to stimulate the demand of nutrients from biobased fertilisers.
- In order to reuse nutrients from human waste, buildings that are being newly built or renovated should be prepared for circular sanitation. Generally this means pre-investments in separated or vacuum pipe systems. This makes buildings ready for the future, when we have improved knowledge on safe treatment and use of circular sanitation products and legislation that enables the use of these products.
- The options and performance of circular sanitation are area specific. The level of sustainability achieved by recycling at neighbourhood level in combination with urban agriculture should be compared with the conventional situation (with efficient regular facilities, but (almost) no nutrient recycling) and whether this outweighs all the efforts and possible extra costs.
- Assign responsibilities to the different stakeholders in the circular sanitation and/or wastewater system, including waterboards, municipalities, project developers, technology providers, demand side parties, etc. The transition towards circular sanitation is a complex societal change in which different stakeholders are involved and should take joint action.

Glossary

Circular sanitation: source-separated and/or decentralised sanitation which enables (improved) recycling of local water, energy, carbon and/or nutrients.

Urban agriculture: we use the definition as provided by Wageningen UR (*Stadslandbouw*, n.d.): "*urban agriculture can be defined as the production of food and greenery in, around and in front of the city. Agricultural food production and the urban need for care, recreation, waste processing or the management of (urban) green spaces are linked. Urban agriculture thus contributes to a more efficient use of space. Claims no longer compete for space but reinforce each other. In doing so, urban agriculture reduces the physical and psychological distance between consumer and food production."*

Urban nutrient recycling: recovery and reuse of nutrients from urban nutrient-rich flows towards a nutrient demand in the city or the region, including supply from human faeces, household wastewater, non-household wastewater, communal sewage sludge, organic waste, food waste, and demand from all types of (peri) urban agriculture/farming, sport fields, public gardens, parks, etc.

1 Introduction

1.1 Circularity by Design (CbD) project

There is a growing need for circularity in currently disconnected food chains and materials segments (e.g. from agriculture, food processing, consumption, waste, chemicals and materials) and at various aggregation levels. Circularity addresses environmental and sustainability concerns. This requires knowledge on the synergies and trade-offs between individual circular systems to design interconnected circular systems that cross segments and aggregation levels, aiming to ensure optimal use and valorisation of renewable biomass resources.

Within the Flagship project "Circularity by Design" (CbD) a (re)design process based on circularity will be applied within the Amsterdam metropolitan area with the aim to create a sustainable agri-food system. Various tools will be developed and tested within Living Labs to achieve high-end re-use of food and residual (organic) flows. The project is a collaboration between AMS Institute and 12 different scientific disciplines of Wageningen University & Research, and is joined by various local Amsterdam-based partners. Within 4 Urban Challenges, instruments are developed and tested in living labs in collaboration with different local stakeholders and at different levels. This allows us to make decisions on issues such as repurposing and processing within different scenarios. The following challenges have been identified: (1) Urban food systems, (2) Organic household waste, (3) Urban food production and (4) Circular way of living.

The aim of the CbD program is to demonstrate the feasibility of "Circularity by design" within the context of the greater Amsterdam metropolitan area. During the runtime of the project, circular (re)design principles will be applied to create designs for urban circular agri-food systems. The ultimate goals of the project are at:

1. Urban scale: (1) to enable optimal resource exchange among sectors to realise connected circularity among sectors, and (2) to create a tool for evaluating & monitoring circularity & its contribution to city goals (connecting circularity to sustainability)
2. Challenge/case scale: co-design circularity for specific challenge case (connecting science & technology to practice for circularity).

1.2 Goal of this report

This document is made by Work package 4 of the Circularity by Design project, which focuses on nutrients, soil and crops.

According to the study '*Bouwstenen voor de nieuwe strategie Amsterdam circulair 2020-2025, Ontwikkelrichtingen voor een welvarende stad binnen de planetaire grenzen'* by Gemeente Amsterdam et al. (2019), two of the objectives of the municipality of Amsterdam are:

- Creating circular food production in and for urban areas
- Accelerating the closing of local nutrient cycles from biomass and water streams

The study also mentions that organic waste and wastewater in cities are highly promising sources of compost and organic fertilisers. Recovering ammonia and phosphate from (sewage) wastewater and sludge are mentioned, but the potential solution of circular sanitation is not highlighted.

Wastewater is indeed an important residual/waste stream in terms of nutrients, in cities especially from communal (household) sources. At this moment, conventionally, the system from soil to food to sewage is linear, with no nutrient recovery, let alone reuse of those nutrients and products in agriculture. The aim of this report is to explain why improving circularity for sanitation systems is relevant, what circular sanitation systems entail and what opportunities and barriers are present for its realisation. Additionally, experiences from the CbD challenges and circular sanitation are shared, to provide insight in the opportunities and barriers they encountered.

Information about circular sanitation is relevant for a large number of stakeholders, including project developers, architects, municipalities, housing corporations, house building companies, wastewater treatment companies, waterboards, involved citizens and interested agricultural stakeholders and fertiliser companies/industry.

1.3 Circularity by Design challenges: scope of research

The Circularity by Design challenges are real-life cases where food circularity is being developed or can be incorporated. These challenges form the test ground for researchers to design their solutions or to design experiments which will help towards these solutions. The challenges should help sharpen and validate the concepts form the Framework. As a whole, they should ideally be complete enough that the developed Framework is robust and has value for future Circularity research and experiments. They are developed as Living Labs.

ARTIS Zoo Circular Food Services
Goal: Design of a circular food service concept to inspire citizens for a better awareness and stimulate them to use circular food.
Inspire and stimulate citizens to discuss the relation between food & humans and food & nature. What dreams (visions) can be lived to develop a future proof food system? The food boulevard becomes a platform to design new circular food concepts and to experience potential solutions where citizens become attracted and inspired. ARTIS' aim is to:
1. provide guidance to act according a nature inclusive food pattern
2. show how zero-waste catering could function
3. develop a physical platform to connect science, education, industry and public

Circular Organic Household Waste
Goal: Design of an organic household Waste collection and valorisation system that will be based on a grinder, to allow reuse of organic household waste and distribute the collection costs over the supply chain partners.
Development of a pragmatic organic waste collection system for (high-rise) household buildings in Amsterdam. The Living Lab becomes a platform to design new circular collection concepts and to experience potential solutions where citizens can involve, be attracted to and be inspired to.

BajesKwartier Green Tower
Goal: Design of an enclosed urban food production concept, integrated in an urban neighbourhood.
A Living Lab to facilitate investigate and design of an enclosed urban food production concept integrated in an urban neighbourhood with high ambitions on circularity, energy and health.

The Urban Tree Village
Goal: Design a circular and inclusive way of living for a community within an urban environment.
Citizen-driven co-creative design of a circular and inclusive way of living for a community within an urban environment.

Mostly for the Bajes Kwartier and Urban Tree Village challenges the reuse of nutrients from sanitation systems is relevant. There has been consultation and interaction with these two challenges about the implementation of new sanitation systems in relation to urban agriculture. More information is given in Chapter 5 and interview notes are available in 0. This report is developed as part of the living lab approach, it must be seen as feedback from the research project to these challenges, potentially leading to feedback from them towards research which can be taken into account in further development of the CbD research project.

2 Circular sanitation (CS)

2.1 What is circular sanitation?

The term 'circular sanitation' (CS, sometimes called 'new sanitation' as well) is used for sanitation that deals differently with wastewater than commonly used sanitation, with the aim to process wastewater effectively and sustainably. Wastewater is not seen, named and classified as waste but as a raw material from which energy and nutrients can be recovered. Circular sanitation is used to indicate one or a combination of these options:

1. source-separated sanitation: sanitation systems in which urine and or faeces are separated from other wastewater streams (e.g. from the shower).
2. decentralised sanitation: small-scale sanitation systems that have a wastewater treatment system separate from the centralised communal wastewater treatment.

Separating urine and faeces enables better reuse of nutrients (i.e. use as fertilisers) because the flow and nutrients are more concentrated and less contaminated. In this way risks can be reduced, for example because:

- urine can be kept separate and is not contaminated with e.g. pathogens from faeces
- sanitation streams are not mixed with other household wastewater or wastewater from industry.

It is important to note that the best approach with circular sanitation is different per situation. For example, sometimes it is better to combine streams before treatment instead of keeping them separate (Saniwijzer n.d.A).

Household waste streams, among which streams produced with CS, that are relevant for nutrient recovery and reuse can be categorised as described in Table 2-1 (see also Figure 2-1):

Table 2-1 *Description of household flows relevant for circular sanitation.*

Flows	Description
Yellow water	Urine
Brown water	faeces (and flush water)
Black water	urine and faeces (and flush water)
Grey water	used water from showers and baths, sinks, laundry, dish washers
Wastewater	black water and grey water (and ground food waste)
Food waste	organic household waste (which could be ground and added to the wastewater flow)
Solid waste	brown water and food waste

In conventional sanitation systems, black and grey water generally become mixed and form household wastewater, which is sent to a municipal sewage system (Harder et al, 2019).

Most commonly, wastewater from sanitation systems (black water) is mixed with other household wastewater, such as from showering and laundry (grey water). The result is a very diluted, watery stream, which is treated by centralised wastewater treatment plants. Conventionally, effluent containing some of the nutrients is discharged on surface waters and sludge, which contains both nutrients and organic matter, is incinerated. The resulting ash is used for roads and building materials. Due to this linear system, a large amount of nutrients is lost and cannot be used again (see paragraph 2.2).

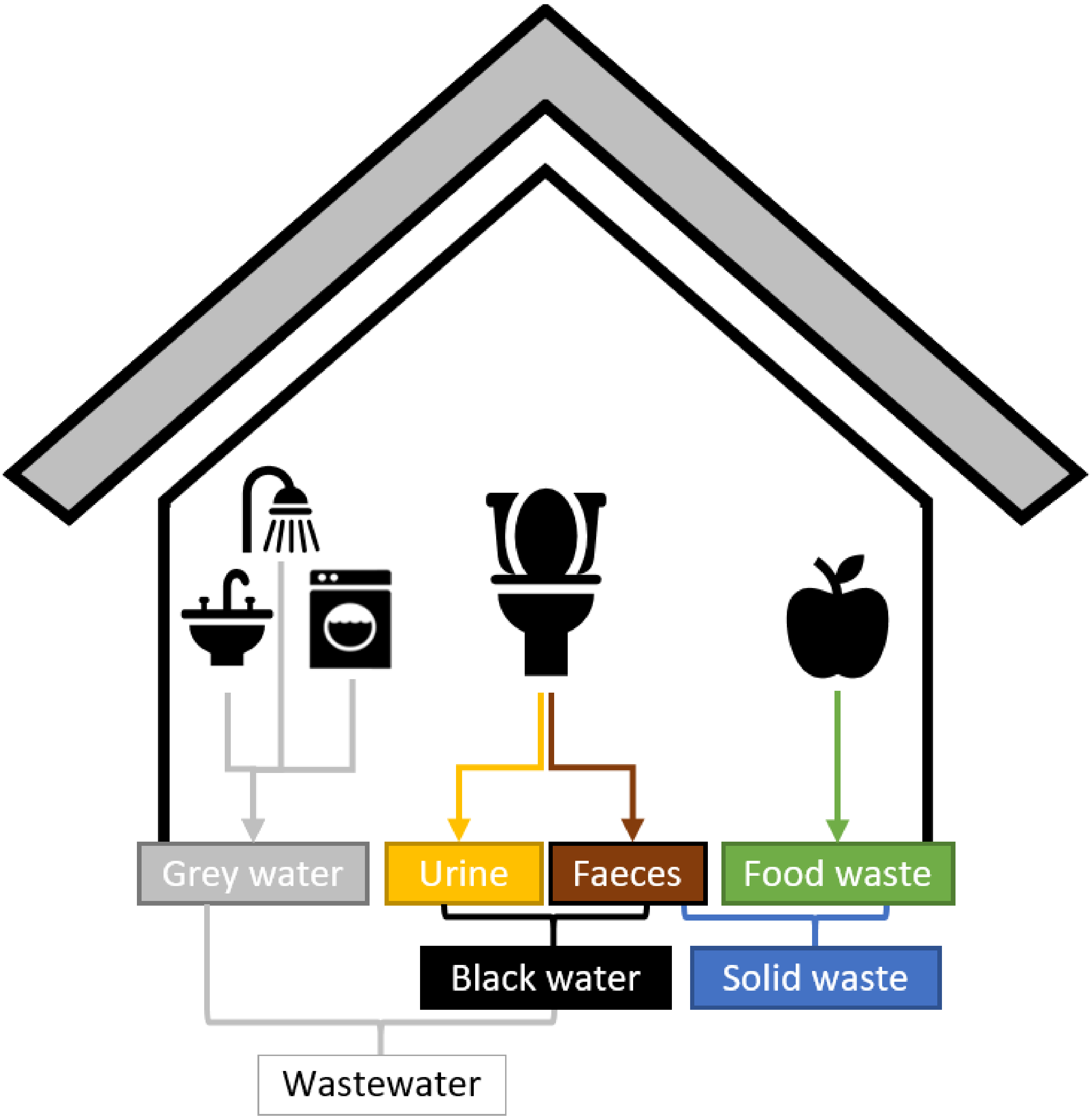


Figure 2-1 *Schematic picture of household waste streams.*
Source: L. Veenemans, this project.

2.2 Why circular sanitation?

Our food system is connected to multiple societal challenges, such as climate change, loss of biodiversity, nutrient emissions and the use of fresh water. While impacting climate change via emission of greenhouse gases, our food system is vulnerable to changing environmental conditions. The world population is increasing and diet preferences are changing, resulting in an increasing food demand (van Dijk et al., 2016). Next to increasing the production of food on the current agricultural area and using raw materials more efficiently, it is required to further close cycles if we want to be able to fulfil the increasing food demand in a sustainable manner (van Ittersum et al., 2015).

Closing the agricultural cycle requires the recovery and reuse of residual streams, and especially of the nutrients such as nitrogen and phosphorus therein. Nutrients are essential to all organisms, among others for cell growth. Recovery of nutrients is important for different reasons per nutrient. Nitrogen is extracted from the air for the production of artificial fertilisers by an energy-consuming process called the Haber-Bosch process. Recycling N could therefore save energy. Phosphorus, on the other hand, is a scarce nutrient: it is a non-renewable resource (mineral) extracted from phosphate rock that is being depleted.

In the food system, an important residual stream in terms of nutrients is wastewater, in cities especially from communal (household) sources. At this moment, conventionally, the system from soil to food to sewage is linear, with no nutrient recovery, let alone reuse of those nutrients and products in agriculture. It was found that the EU-27 lost 655 Gg phosphorus per year via human (food and non-food) consumption in 2005, which counts for 54% of all lost P in the EU-27, including agriculture, food processing and non-food production. Of these 655 Gg P, 55% was lost via wastewater. To compare, 27% of P was lost via food waste and 11% via pet excreta (Van Dijk et al., 2016). The main P leak from the system is thus via wastewater flows, of which the main pathways are via sewage sludge and, for a smaller fraction, via the effluent.

In the Netherlands, about 12 million kg phosphorus (P) is present in the communal wastewater that is created in households and treated by municipal solid wastewater plants (De Ruijter et al., 2016). Industry discharges an additional 1 million kg P to the sewage system. After treatment 10.8 million kg P is found in the sludge, which is incinerated. The phosphorus ends up in the ashes, with road building and infrastructure (concrete) as final destinations. The other residual part of about 2.4 million kg P (about 20%) is located in the effluent and is discharged to waterways, by which it is lost from the food system as well and causes eutrophication.

Circular sanitation can enable better recycling of nutrients within the food system. It can deliver nutrients and fertilising products to replace unsustainable synthetic fertiliser use from mines or energy intensive fertilising production. By enabling the reuse of nutrients locally, it can decrease the need for transport. All in all, there is a potential to minimise existing costs or bring additional financial value to the business case of companies and society.

The Netherlands is dealing with a surplus of animal manure, which decreases the need for other fertilisers. However, because the Netherlands is currently dealing with a nitrogen crisis, this might change. Because of nitrogen crisis, a policy programme, called the National Programme for Rural Areas (*Nationaal Programma Landelijk Gebied*), is developed by the government among others to protect nature areas and to fulfil requirements from European law for water quality. One of the measures mentioned is an emission reduction of 39 kiloton of ammonia (Rijksoverheid, 2022), which will require a reduction in livestock population. This will inevitably lead to a decrease in manure production. Nutrients derived from other sources may therefore become more relevant.

2.3 Common circular sanitation systems

There are two common CS systems:

1. **Vacuum toilet systems** collecting black water (plus organic solid waste via grinders) in combination with anaerobic digestion and a decentralised wastewater treatment installation recovering the nutrients and organic matter (Figure 2-2).
    - This a relatively high-tech system, suitable for urban areas where space and agricultural land is limited.
    - In the Netherlands, a similar system is implemented at pilots in neighbourhoods Noorderhoek in Sneek and Buiksloterham in Amsterdam (e.g. Schoonschip and De Ceuvel, see 2.4).
2. **Source-separated toilet systems** collecting urine and faeces separately to be used regionally on fields in combination with storage (stabilisation) and treatment for urine and high-temperature composting of faeces, both to remove/reduce contaminants (Figure 2-3).
    - This is a relatively low-tech system, suitable for peri-urban or rural areas where more space and (urban) agricultural land is available.
    - This type of systems are commonly researched and implemented in Sweden, Switzerland and in developing countries. In the Netherlands, a similar system is partly already implemented and will be further developed at the sustainable housing project Arneco in Arnhem (see 2.4).
    - Waterless urinals, this technique is used in larger (commercial) buildings. The urine is collected and often used for the production of struvite (e.g. as done by AFAS Live, see 2.4).

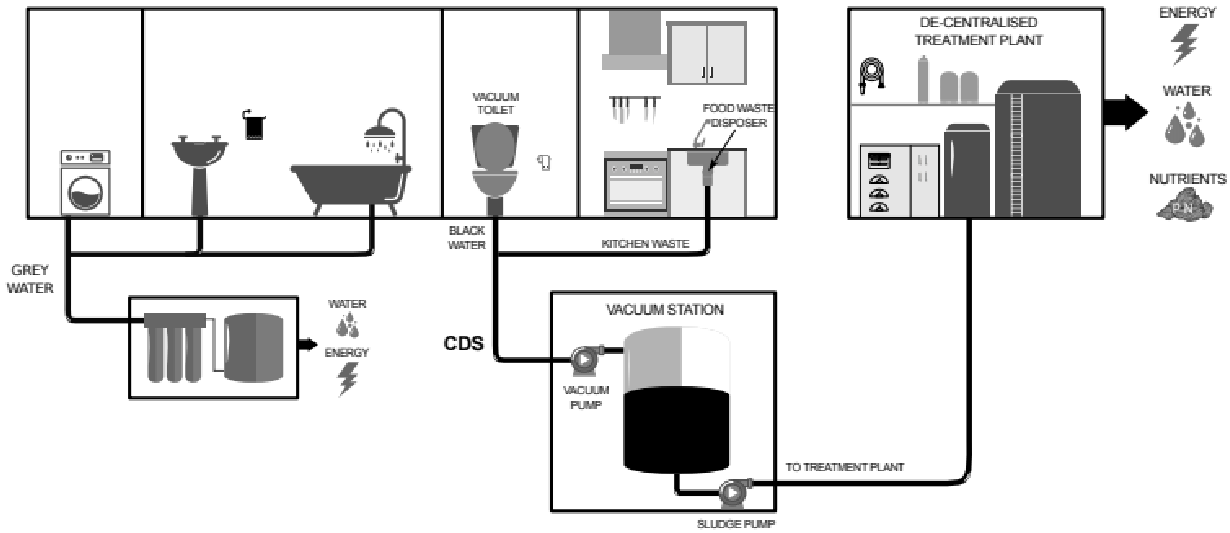


Figure 2-2 *Vacuum toilet systems collecting black water (plus organic solid waste via grinder) in combination with anaerobic digestion and a decentralised wastewater treatment installation recovering the nutrients and organic matter. One of the most common circular sanitation systems.*
Source: Thota Radhakrishnan (2019).

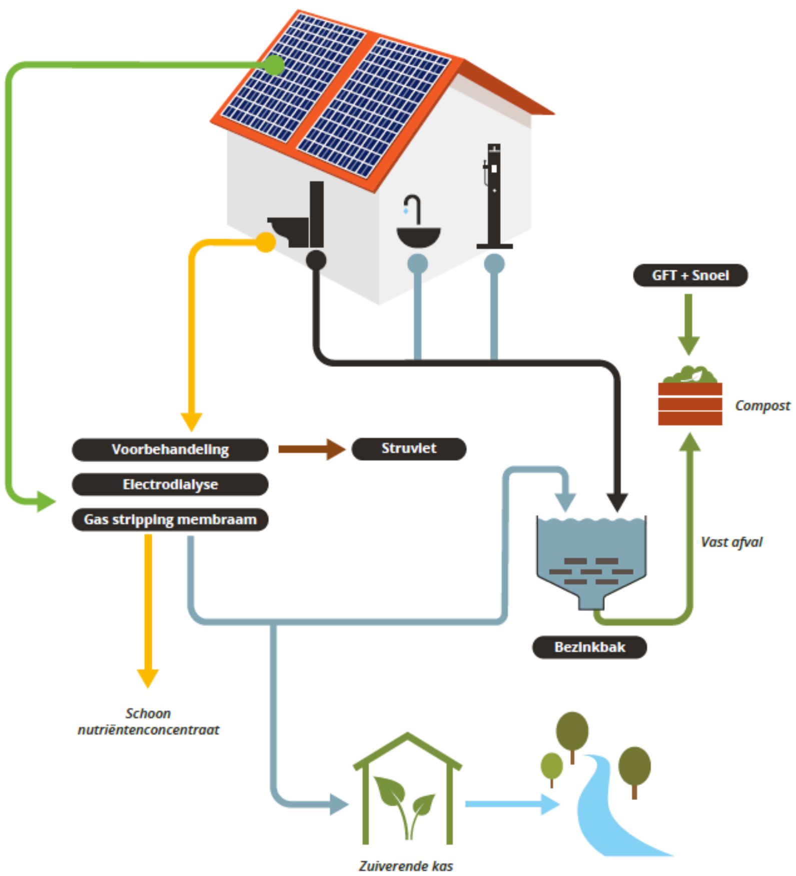


Figure 2-3 *Source separating toilet system that splits human excreta in a pure urine flow, that is used after treatment as fertiliser on land, and faeces, that is collected together with grey wastewater and further treated with a septic tank system. In the septic tank system, the solid and liquid fractions are separated. The solid fraction (biosolids) is treated with high-temperature composting and the liquid fraction is treated in with living machine ('zuiverende kas', e.g. with algae), or alternatively with a helophyte filter.*
Source: Sam Molenaar, NEWBIES project, Arneco sustainable housing project.

2.4 Infographic Circular Sanitation

With the previously mentioned CS systems, more concentrated wastewater streams can be made. These streams should be treated before the nutrients can safely be reused as fertiliser. For the different CS streams, various treatment technologies are known, which result in different fertilising products. Figure 2-4 gives an overview on the main CS streams, technologies and products and possible applications.

Potential routes for circularity in sanitation systems are shown in the infographic in Figure 2-4. Four levels in the routes are shown in the infographic:

1. **Collection systems** (top layer). These are the toilet systems. The toilet systems mainly differ in water usage (dilution of nutrients) and separation at source of waste streams. A conventional toilet (C1 in infographic) leads to a mixture of urine, faeces, flush water and grey water (water from other household systems, e.g. bathroom and kitchen), here visualised with a grey arrow. Vacuum toilets (C2) use very little water and keep the sanitation stream separate from grey water, resulting in a so-called black water stream. Separation toilets (C3) can keep urine and faeces (source) separate, creating both a yellow water and a brown water flow. Waterless urinals (C4) only collect urine and therefore lead to a concentrated nutrient solution in the form of yellow water.
2. **Treatment** systems (second layer). These are systems that treat wastewater streams e.g. to reduce mass by removing water and make sludge, to up concentrate flows, make streams safer for use by eliminating pathogens, and/or recover nutrients as fertilisers, biogas and other resources ready for (re)use. Treatment can be low-tech or high-tech and can be at different spatial scales (centralised versus decentralised).
3. **Products** (third layer). These are materials and resources resulting from treatment of sanitation streams. Many products can be used in some way to recycle nutrients or organic matter as fertilisers (P7-P11), or fibres (P5) or energy (P6). Products can be solid or liquid or gaseous. Some products could/must be further treated in the industry (X1, grey box), for nutrient rich products in the mineral fertiliser industry to make clean and safe (mineral) fertilisers, e.g. for ashes (P3). Or there can be a need to up concentrate products or mix products with other nutrient-rich streams to get a higher quality liquid and/or organic fertiliser with better nutrient composition, for example for struvite (P10) and ammonium sulphate (nutrient rich solutions, P7). See for more information about potential products and quality paragraph 3.3 and chapter 4.
4. **Applications** (bottom layer). These are the type of use and locations in which products resulting from treatment of circular sanitation streams could be used effectively (A3-A7). Most of these applications are related to (urban) agriculture for food production (A4-A6), but products from circular sanitation can also be used for fertilisation of non-food plants in households and utilities such as flowers and plants (A3), and parks, public green and sport (grass) fields (A7). Streams which have more risks in terms of contaminants like pathogens, heavy metals and organic pollutants can preferably be used for non-food plant fertilisation, whereas streams with less risks (e.g. urine, struvite and ammonium sulphate) could be more relevant in food crop production. More information about agronomy, quality, demand and applications is given in paragraph 3.3 and chapter 4.

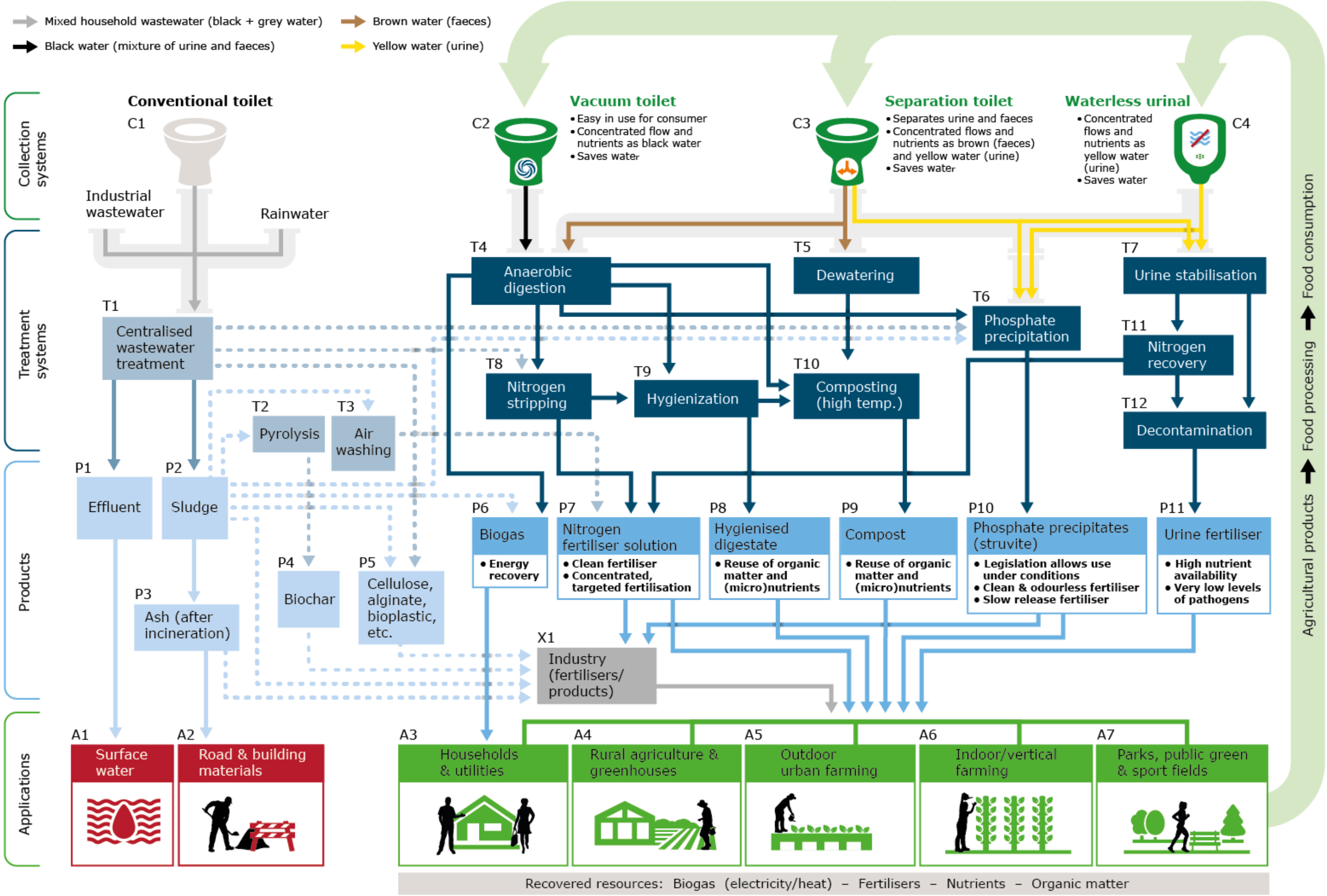


Figure 2-4 *Overview of (present, centralised) conventional wastewater treatment system (left, lighter colours) and (future, potential decentralised and source separated) new sanitation systems (right, darker colours), and most important/relevant existing and potential routes for recycling of nutrients and other resources (circularity), including collection, treatment, products and applications; codes in figure are linked to additional information in the text and Table 2-2.*

Table 2-2 *Additional explanation for some of the treatments and products shown in Figure 2-4.*

#	Description	Explanation
T2	Pyrolysis	The pyrolysis (or devolatilisation) process is the thermal treatment and decomposition of organic materials at elevated temperatures in an inert atmosphere. It involves a change of chemical composition. It is one of the processes involved in charring wood. In general, pyrolysis of organic substances produces volatile products and leaves biochar, a carbon-rich solid residue. Extreme pyrolysis, which leaves mostly carbon as the residue, is called carbonisation. Pyrolysis is considered the first step in the processes of gasification or combustion
T3	Air washing	When drying sewage sludge, ammonia is released. With air washers, this ammonia can be converted into a nitrogen fertiliser solution (ammonium sulphate).
T4	Anaerobic digestion	Anaerobic digestion is a sequence of processes by which microorganisms break down biodegradable material like sewage sludge in the absence of oxygen. The process of fermentation is used for industrial or domestic purposes to manage waste and to recover methane (biogas, renewable energy), reducing the emission of this greenhouse gas in the chain. In addition also other organic substrates can be co-digested, for example grinded organic kitchen/food waste. The residual flow digestate is nutrient rich, but still biologically not stable.
T5	Dewatering	Dewatering is the removal of water from solid material like sludge, by centrifugation, filtration, or similar solid-liquid separation processes.
T6	Phosphate precipitation	Chemical precipitation is used to remove the inorganic forms of phosphate wastewater, sludge and or urine by the addition of a coagulant and a mixing of wastewater and coagulant. The multivalent metal ions most commonly used are magnesium, calcium, aluminium and iron.
T7	Urine stabilisation	In order to use urine safely, it should be matured/stabilised for at least half a year. During storage, the pH increases due to the formation of ammonia. Storing urine for 6 months eliminates all pathogens.[1]
T8	Nitrogen stripping	Removing nitrogen from waste streams may enable more balanced fertilisation and lower N emissions during application to soil.
T9	Hygienisation	Sanitation streams consisting of brown of black water should reach sufficient temperatures during processing to eliminate pathogens.
T10	Composting	In case of sanitation flows composting must take place as a multi-step, closely monitored process with measured inputs of water, air, and carbon- and nitrogen-rich materials. The decomposition process is aided by shredding the plant matter, adding water, and ensuring proper aeration by regularly turning the mixture in a process that uses open piles or "windrows". Fungi, earthworms, and other detritivores further break up the organic material. Aerobic bacteria and fungi manage the chemical process by converting the inputs into heat, carbon dioxide, and ammonium. Generally, composting requires gathering a mix of 'green' biomass and 'brown' biomass, respectively materials that are rich in nitrogen such as sewage sludge, faeces, leaves, grass, and food scraps, and more woody materials that are rich in carbon, such as (toilet) paper, stalks and wood chips.
T11	Nitrogen recovery	See nitrogen stripping.
T12	Decontamination	Treatment with ultra violet light (UV), ozone, active carbon and/or hydrogen peroxide can remove almost all organic microcontaminants, such as medicine residues and hormones.[2]
P4	Biochar	Biochar is the lightweight black residue, made of carbon and ashes, remaining after the obtained from pyrolysis. It is a stable solid that is rich in pyrogenic carbon and can endure in soil for thousands of years. It may be a means to mitigate climate change. Biochar may increase the soil fertility of acidic soils and increase agricultural productivity.
P5	Cellulose, alginate, bioplastic, etc.	Cellulose is coming into the wastewater by the use of toilet paper and after recovery can be used potentially for the production of paper/carton, fibres, consumables and building materials. Alginates are refined from brown seaweeds, grown on wastewater, and harvested to be processed and converted into sodium alginate. Sodium alginate is used in many industries including food, animal food, fertilisers, textile printing, and pharmaceuticals. Dental impression material uses alginate as its means of gelling. Food grade alginate is an approved ingredient in processed and manufactured foods. Bioplastics are plastic materials produced from renewable biomass sources such as wastewater, sludge, digestate and recycled food waste. Some bioplastics are obtained by processing directly from natural biopolymers including polysaccharides (e.g. starch, cellulose, chitosan and alginate) and proteins, while others are chemically synthesised from sugar derivatives (e.g. lactic acid) and lipids (oils and fats), or biologically generated by fermentation of sugars or lipids. Bioplastic can replace conventional fossil-fuel based plastics.
X1	Industry	Industry indicates here mostly fertiliser producers, but includes traders and other producers (e.g. for bioplastic) as well. The industry can upgrade streams, improving their usability e.g. by making them balanced in nutrient composition to fulfil specific crop demands. Processing sanitation streams by industry can furthermore provide additional safety (better regulation of pathogens) and enable more large scale production.

[1] https://www.saniwijzer.nl/technieken/verwerking-afvalwater/opslagsystemen/urine-opslagtank
[2] https://www.saniwijzer.nl/technieken/verwerking-afvalwater/nabehandelingstechnieken

A distinction can be made between the (centralised) **conventional wastewater system** (left, lighter colours) and the (mostly more decentralised) **alternative sanitation systems** (right, darker colours). Both systems can potentially be(come) circular, although in very different ways.

The conventional wastewater system in the Netherlands includes centralised wastewater treatment plants (T1), with more than 99% of the households connected (Stichting RIONED, 2016). The combined wastewater flows via the sewage system to the wastewater treatment plant where it is separated into a sludge (P2) and effluent (P1). Since around 1995 all communal sewage sludge is incinerated into ashes (P3), over 50% by two mono-incineration plants. At this moment the (linear) centralised conventional system leads to complete loss of nutrients from wastewater. Nitrogen is lost by biological nitrification/denitrification turning ammonia and nitrate into (harmless) nitrogen gas, and elements like phosphorus and potassium by discharging effluent on surface waters (A1) and incinerating sewage sludge. The nutrients in the sludge end up in ash (P3) that is used for roads and building materials (A2). To improve circularity, these pathways should be limited and turned from a linear to a circular system.

Although not source separated, the conventional system (C1) can also deliver products that can be recycled as well, as is shown with some dotted arrow lines, e.g. from sludge (P2) to phosphate precipitation as struvite (P10). When conventional systems cannot be replaced (soon) in existing infrastructure (cities), it is important that these pathways are used to enable recycling of nutrients from centralised sewage wastewater/sludge systems (C1, T1, P2 and P3). Using sanitation systems (with source separation) that are designed with the aim to recycle nutrients remains preferential, because the flow and nutrients are more concentrated and less contaminated.

Both the more centralised conventional (C1) and more decentralised and source separated alternative sanitation systems (C2-C4) can produce other useful products apart from fertilisers as well. An additional benefit from circular sanitation can be the production of biogas (P6), in case anaerobic digestion (T4) is used. This biogas can be used for example in offices and households (A3) and replace some use of less sustainable energy sources. Other products that are now already being produced are for example cellulose, alginate and bioplastics (P5).

Most of the products depicted in the infographic are not allowed for commercial use under present existing policies and regulation. An exception is recovered phosphate (e.g. struvite) that is allowed for use in agriculture under certain conditions (e.g. related to heavy metals). Also, the new EU FPR allows the use of high purity ammonium salts derived from waste (e.g. by stripping) in agriculture. Organic fertilisers from sewage, e.g. sewage sludge or compost, can usually not be used in agricultural within the Netherlands as limits for heavy metals are generally exceeded in such products. There are, however, differences among EU member states in criteria for use of sewage sludge and products thereof in agriculture; in some EU countries sewage sludge is still an accepted and much-used fertiliser. Other products can solely be tested in pilot studies, when they have received an exemption. Although not all products can be used yet in commercial fertilisation and (food) production, it is still relevant to prepare for the future, when treatment systems may have improved and dealt with barriers such as contaminants. An important pathway is therefore to use circular sanitation systems and recover fertilisers that are useful now, whereas remaining streams, e.g. black water, can be discharged on the sewage system (T1) until future applications are enabled. This way, less water is used and the pipe system is prepared for future applications and better nutrient recovery.

Potential decontamination techniques (T12) can be required for the different routes of recovery and reuse, including treatment with for example ultra violet (UV) light, ozone, active carbon, dialysis and (thermophilic) digestion. Possible treatment techniques for removing pharmaceuticals from urine include the use of ulttra violet (UV) light, ozone and or active carbon, however these are energy-intensive. (Monetti et al., 2022).

For black water anaerobic digestion (thermophilic or with an Up-flow Anaerobic Sludge Blanket (UASB) reactor) could be used, combined with oxygen-limited autotrophic nitrification-denitrification (OLAND), an algal photobioreactor or co-composting with garden waste (Butkovskyi, 2015).

Combining treatment techniques may improve the removal efficiency of pharmaceuticals (Monetti et al., 2022). Heavy metal contaminations can best be avoided at the source, by with source separation toilets

(C2-C4) and decoupling sanitation flows from mixed wastewater flows contaminated with heavy metals, for example zinc from galvanized iron (rain pipes, gutters, street lights, guardrails, etc.) and copper and lead from old piping in houses. Pathogens potentially present in digestate from black or brown water can be removed by hygienisation techniques (T9), including heating, irradiation and drying (Hamilton et al., 2020).

2.5 Relevant circular sanitation projects

Circular sanitation has been implemented and experimented with in various projects. When implementing CS, experiences from other projects may prove helpful. The website Saniwijzer gives an overview of circular sanitation projects in Europe, mainly the Netherlands, on their website[3]. Most projects are linked to a pilot case or a living lab. These cases present and provide valuable knowledges and experiences to get circular sanitation in urban and rural context started. A few examples including some learning points are shortly discussed below.

DeSaH – Noorderhoek zwartwaterbehandeling/Waterschoon (ongoing)
In the city Sneek, the feasibility of anaerobic decentralised wastewater treatment was researched. The pilot study, with a scale of 232 homes, included investigation of UASB-bioreactors, vacuum toilets, food waste grinders and struvite reactors. The system, called WaterSchoon, cleans household wastewater mixed with food waste.[4]

Some malfunctions have occurred at the vacuum toilets and vegetable and fruit grinders, mainly caused by wrong usage by residents. Residents needed clear information on the use and value of the system. Some technical changes include installation of a ventilation system in the room of the vacuum system and replacement of magnesium oxide with magnesium chloride to reduce blockages in the struvite reactor (STOWA, 2018).

SchoonSchip (ongoing)
In Amsterdam, a pilot started in 2018 with vacuum toilets and decentralised wastewater treatment on houseboats. In time, biogas will be produced and phosphate will be recovered from black water.[5] Some difficulties were encountered with the vacuum toilet system such as noise issues, but currently the system is successful.[6] The original plan was to treat the wastewater flow from SchoonSchip together with the then to-be-built decentralised houseblocks at the neighbourhood Buiksloterham.[5] However, it was later on decided to develop the houses without decentralised sanitation (personal communication, Enna Klaversma, Waternet, 26/07/2022).

De Ceuvel (completed)
This pilot focussed on closing the loop by using compost toilets, composting installation 'tumbling composter', struvite reactor and helophyte filter. Seventeen houseboats were renovated and put on land. Urine is collected separately and used locally as fertiliser.[7]

For this pilot, decentralised drinking water was less sustainable and more costly than a centralised system, and the same level of safety could not be guaranteed. It is recommended to use such a system only when a connection to a centralised system is not feasible. Furthermore, the duration of composting should be longer than 11 months to reduce levels of bacteria to a safe level. The toilets were not regarded as comfortable, due to smells and flies. It was therefore recommended to use other sanitation solutions for future locations (KWR, 2016). The compost toilets are still in use at this location.[8]

AFAS Live (completed)
At event location AFAS Live, 54 waterless urinals are placed. From the collected urine, 52% of the phosphate is recovered as struvite, being around 420 kg struvite per year. It saves ca. 2.6 million litres of water per

3 https://www.saniwijzer.nl/projecten
4 https://www.saniwijzer.nl/projecten/desah---noorderhoek-zwartwaterbehandeling/detail=52
5 https://www.saniwijzer.nl/projecten/schoonschip/detail=72
6 https://www.vvplus.nl/artikelen/schoonschip-meer-dan-een-gesloten-energiesysteem
7 https://www.saniwijzer.nl/projecten/de-ceuvel/detail=50
8 https://deceuvel.nl/nl/about/sustainable-technology/

year and less cleaning and maintenance is required. This initiative is linked to the struvite reactor Fosfaatje of the wastewater treatment by Waternet in Amsterdam.[9] The transport of urine from AFAS Live in the southeast of Amsterdam to the wastewater treatment plant in the northwest of Amsterdam is associated with a certain footprint since urine is a bulky product (personal communication Waternet).

Arneco sustainable communal housing project (ongoing)
Arneco[10] is a sustainable and communal housing project (living lab) that is currently implementing decentralised circular sanitation in Arnhem (Figure 2-3). It houses fifteen households and the terrain of 1 ha is used for food production (vegetable garden, fruit trees, nut trees, etc), leisure, nature and biodiversity.

Source separating toilets are installed both in the private houses (Ecoflush[11] model by Wostman) and communal building (Save![12] model by Laufen). Urine is stored in containers outside. The faeces and flush water (brown water) is collected together with other household wastewater (grey water). To minimise dilution of the urine, water (and heat) saving recirculation showers (E-Shower model by Hamwells) are installed. Rainwater from the roofs is stored in tanks for irrigation and cleaning purposes. Also, two dry-composting toilets are placed on the campsite, the Ecodry[13] model by Wostman and the Villa 9010 by Separett. These type of toilets collect urine and faeces separately without the use of water.

Stabilised urine is used for fertilisation on own land. After collection of the urine via a separate piping system in a tank, the urine is stabilised and treated with a nitrifier installation. Unstable nitrogen in the form of urea is turned into more stable nitrates by oxidation stimulated by active aeration. In this way ammonia emission and smell can be reduced during both storage and application to soil. In addition, first tests with electrodialysis have shown that stabilised urine could be concentrated to form nutrient solutions that can be used elsewhere (in case of surplus).

Treatment of brown and grey water will be implemented in the near future. For the time being, the combined wastewater flow is discharged to the communal sewage system. The plan is to treat this flow with a septic tank to separate the solid fraction (mainly organic matter and nutrients) and effluent (mainly soluble nutrients). The solid fraction will be further treated together with own kitchen waste and green waste (garden, urban agriculture) with either high temperature composting or an anaerobic digester (with biogas production). The effluent of the septic tank will be further treated with a small scale Living Machine (Food Chain Reactor) ecological wastewater treatment facility. The residual effluent can be treated further with a helophyte filter (reed bed) if needed.

[9] https://www.saniwijzer.nl/projecten/afas-live/detail=13
[10] Source: K. van Dijk, homeowner at Arneco www.arneco.org
[11] https://www.wostman.se/en/ecoflush
[12] https://www.laufen.com/news-stories/save-smart-sanitation-2
[13] https://www.wostman.se/en/ecodry

3 Barriers and opportunities

3.1 Overview of aspects

In this chapter, barriers and opportunities that are encountered when implementing CS are discussed (desk study). The aspects have been categorised as follows:
- Sustainability and environment
- Quality and agronomy
- Legislation
- Health and safety
- Technical aspects
- Economic aspects
- Social aspects

3.2 Sustainability and environment

Circular sanitation systems can create opportunities for multiple environmental benefits, including:

1. **Improving nutrient recovery and reuse**:
   Sanitation wastewater that is not mixed with other waste(water) is a relatively concentrated stream. Nutrient recovery from concentrated streams requires much less energy than from diluted streams and removing contaminations can be easier.

2. **Generating sustainable energy:**
   Digesters (anaerobic treatment) can be used to generate biogas from faeces and organic household waste. Thereafter nutrients can be recovered and reused.

3. **Saving energy**:
   Communal wastewater treatment plants require a lot of energy, among others for transporting wastewater over large distances and for treatment. Also chemical compounds are used in different treatment steps for which energy and materials are used in the production phase. Decentralized systems can reduce a resident's carbon footprint by 20–23% (Arias et al., 2020, Berg et al., 2013).

4. **Saving water:**
   A circular sanitation system can save 66 litres per day per household, i.e. 24 m^3 per household per year (Berg et al., 2013). Circular sanitation systems often use less or even no water in order to keep the wastewater flows as concentrated as possible. Vacuum toilets, for example, generally use (less than) 1 litre flush water, whereas commonly used toilets require 6-8 litres (Zeeman, 2018). This is a yearly save of around 32 m^3 water per household per year (almost 30% of the total household water use per year) (Gemeente Amsterdam & Waternet, 2018). Reclaimed water can achieve 100% tap water savings when used for irrigation (Arias et al., 2020).

5. **Removing contaminants**:
   Because the wastewater is more concentrated, decentralised and especially source separated sanitation systems provide opportunities to better remove contaminants such as heavy metals, organic pollutants, medicine residues and pathogens, and by that the emission of contaminants to the environment e.g. soils and surface water. Additionally, circular sanitation systems generally do not have an effluent, avoiding the discharge of residues on surface waters.

The abovementioned opportunities are summarised per CS stream in Table 3-1.

Table 3-1 *Different waste flows from buildings and opportunities to recycle nutrients, water, energy and other resources. Adapted from Thota Radhakrishnan (2019).*

CS stream	Components	Opportunities
Brown water	Faeces (+ flush water)	- Nutrient recovery of P and other minerals (micronutrients) - Organic matter reuse - Energy production from the organic matter present
Yellow water	Urine	- Nutrient recovery, including N, P and K - Removal of micro-pollutants (e.g. medicines)
Black water	Urine + faeces (+ flush water)	- Nutrient recovery N, P, K and other (micro)nutrients - Organic matter use - Energy production from the organic matter present
Grey water	All other household water (from sinks, showers, baths, washing machines, dishwashers)	- Heat recovery for local use - Water reuse
Food waste	Food waste (from food waste disposer, in combination with grinders)	- Nutrient recovery of N, P, K and other (micro)nutrients - Organic matter reuse - Energy production from the organic matter present

Fertilisers retrieved from household wastewater not mixed with industrial wastewater generally have low heavy metal concentrations. Fertilising products that decreased in organic matter content during treatment such as digestate and compost from household wastewater, however, can contain higher heavy metal contents (Winker et al., 2009). The presence of heavy metals in soils used for food or feed may pose health risks such as the impairment of kidney function due to accumulation in food and feed and the subsequent accumulation in the human body over time (Rodrigues & Römkens, 2018). Figure 3-1 shows the heavy metal load (logarithmic scale) caused by the use of different fertilisers at a similar phosphorus application rate. Urine application resulted generally in the lowest heavy metal load, whereas for many heavy metals the loads arising from the use of cattle slurry and faeces were similar. Sewage sludge application caused the highest heavy metal loads for most metals

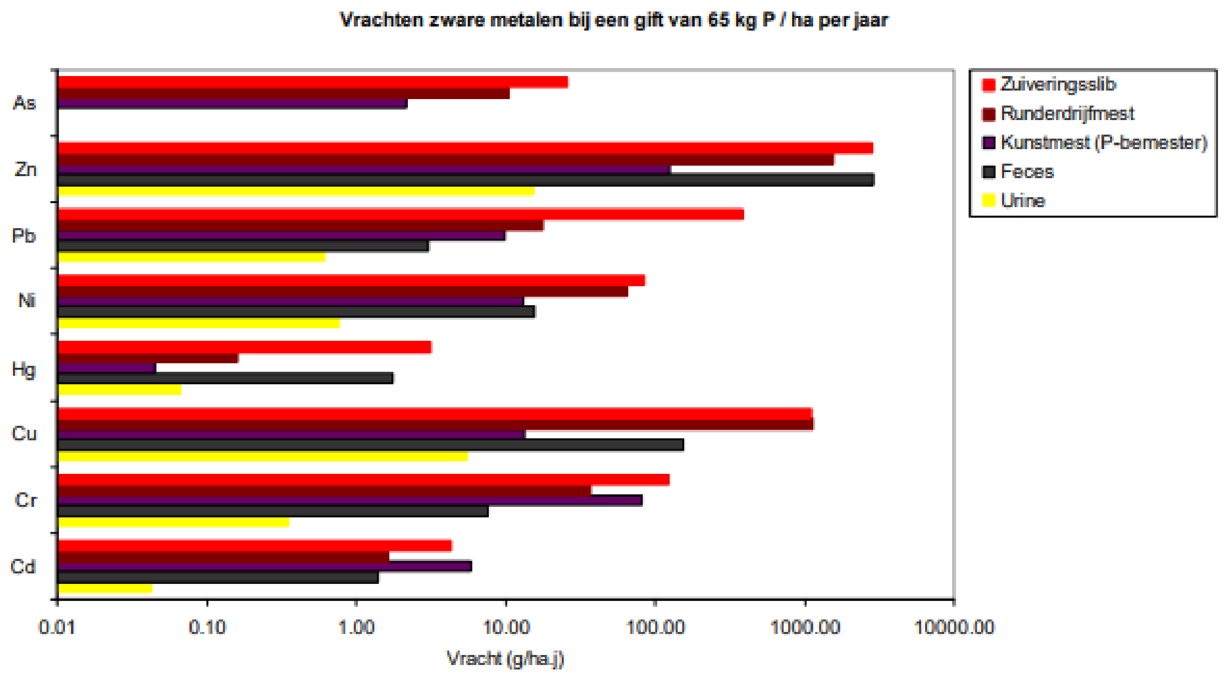


Figure 3-1 *Heavy metal loads arising from the use of sewage sludge, cattle slurry, artificial fertiliser, faeces or urine at similar P application rates.*
Source: Mels et al. (2008).

Another issue may be salt concentrations in urine. Salts can have a negative impact on soil fertility (Thoden van Velzen, 2013).

In case of struvite production, magnesium is required as component. Commonly, mined Mg is used. Using recycled Mg could improve the environmental impact of struvite production.

3.3 Quality and agronomy

In the agricultural cycle, an important residual stream in terms of nutrients is wastewater, in cities especially from communal (household) sources. Conventionally, the system from soil to food to sewage is linear, with no nutrient recovery, let alone reuse of those nutrients and products in agriculture. Circular sanitation can enable better recycling of nutrients within the food system. It can deliver nutrients and fertilising products that can replace unsustainable synthetic fertiliser use from mines or energy intensive fertilising production. In the context of the goal of circular agriculture with less livestock and thus manure nutrient surplus, there will be a net demand for nutrients like nitrogen, phosphorus and organic matter. Nutrients and fertilisers from sanitation and wastewater systems can potentially be used, if safely recovered, stored and applied and if needed, contaminants are removed and the right products is produced that farmers need.

Generally speaking the excreta of humans is relatively rich in nutrients such as nitrogen, phosphorus and potassium (Mihelcic et al., 2011), compared to excreta (manure) of animals (livestock) (Verdoes & Bokma, 2017). This can be explained by the fact that humans eat high quality nutrient rich food. Products like milk contain high concentrations of phosphorus and protein rich products contain high levels of nitrogen. Urine contains the majority of nitrogen and about half of phosphorus and potassium contained in human excreta, while faeces is rich in phosphorus and potassium and contains the far majority of carbon (Harder et al., 2019). The amount of excreted nutrients depends on dietary intake, while the digestibility of the diet determines the partitioning of nutrients between urine (digested) and faeces (undigested). The composition of household wastewater streams is given in Table 3-2.

Table 3-2 *Median values of nutrients present in wastewater streams, based on 135 studies. Adapted from Meinzinger & Oldenburg (2009); including nitrogen (N), phosphorus (P), potassium (K), sulphur (S) and organic matter (OM).*

Waste stream	Volume (l/capita/day)	Nutrient	Concentration (g/L)	Amount (g/capita/day)	Remarks
Brown water	0.14	N	14 [a]	1.5	Mainly consists of organic matter
		P	3.8 [a]	0.5	
		K	3.3 [a]	0.7	
		S	-	0.2 [a]	
		OM	-	38	
Yellow water	1.37	N	8.3	10.4	Contains most of the N in domestic wastewater and two thirds of P of black water
		P	0.8	1.0	
		K	1.9	2.5	
		S	1.6 [a]	0.7	
		OM	18 [a]	57	
Black water	1.25	N		11.9	High supply of nitrogen per person per day
		P		1.5	
		K		2.0	
		S		0.19 [a]	
		OM		51	
Grey water	110	N	0.013	1.0	Nutrient concentrations are highly variable, dependent on water use patterns.
		P	0.0046	0.5	
		K	0.0088 [a]	1.0	
		S	0.072 [a]	2.9	
		OM	0.228 [a]	65	

[a] Poor data quality.

From the sanitation streams mentioned at Table 3-1, several products can be made with different technologies. For an overview, see Figure 3-2. For more information see the demo-site, technology and product factsheets of the Run4Life project[14].

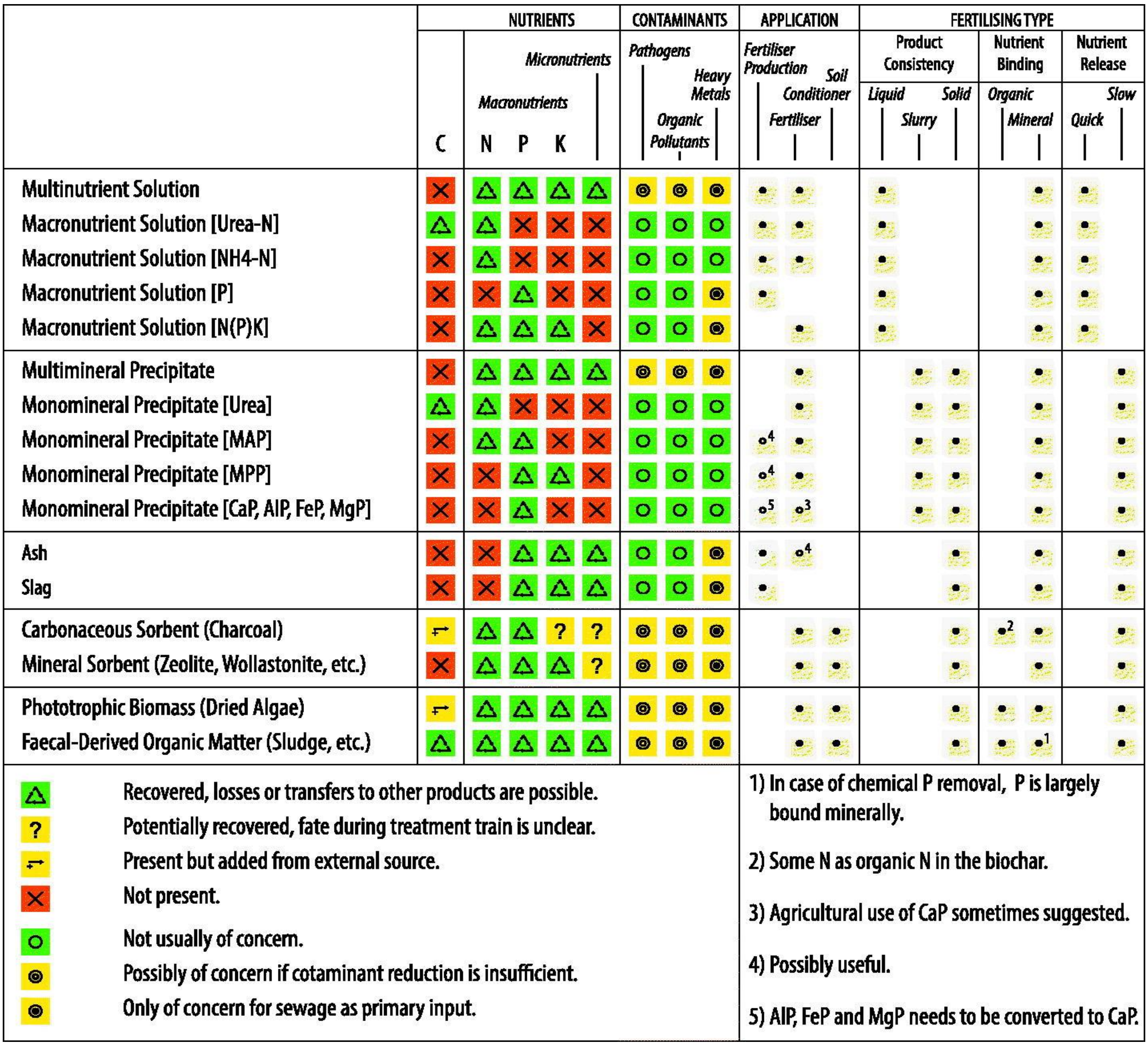


Figure 3-2 *Characteristics, application potential, fertilising type and fertiliser quality of different product subcategories. Source: Harder et al. (2019).*

Figure 3-2 additionally shows the differences in characteristics for products that can be recovered out of human urine and faeces. Different factors determine the quality of a fertiliser, depending on what a farmer needs and prefers, depending on soil type and crops grown. It shows differences among fertilising products in:

- nutrient contents, including carbon (C), macronutrients nitrogen (N), phosphorus (P), potassium (K), sulphur (S), mesonutrients (e.g. calcium, magnesium) and micronutrients (e.g. copper, zinc, manganese, etc.)
- levels of contaminants, including pathogens, organic pollutants and heavy metals (e.g. zinc and copper, which are also micronutrients)
- ways of application, including resource for the fertiliser industry to make fertilisers, as nutrient rich fertiliser and as soil conditioner
- product consistency, including liquid, slurry or solid fertiliser
- nutrient binding, including an organic or a mineral fertiliser
- nutrient release, including quick and slow release.

[14] https://run4life-project.eu/documents/factsheets

In general, taking Figure 3-2 in mind:

- products from urine (e.g. precipitates, solutions) and incineration products (e.g. ashes and slag) do not contain organic matter (carbon), whereas faecal-derived products like sludges and phototrophic biomass like algae do
- ashes, slags and some precipitates products do not contain nitrogen or only low amounts
- most nutrient solutions and precipitates do not or only little contain micronutrients, whereas ashes, slags, biochar, sludges and other biomass (e.g. algae) do contain some amounts of micronutrients
- ashes, slags, precipitates and solutions products from source separated (decentralised) sanitation / wastewater treatment usually do not have concerns regarding contaminants, however for those products from centralised wastewater treatment (sewage) heavy metals removal is generally insufficient and a potential contaminants problem, this is partly because of cupper/lead waterpipes and zinc from galvanised metal objects
- most ashes, slags, precipitates and solutions products can be used as a resource in fertilising production, for which high nutrient concentrations (lower volumes) are required
- most nutrient rich products can be used as fertiliser products, however carbonaceous sorbents (e.g. charcoal, biochar), mineral sorbents, phototrophic biomass (e.g. algae grown on wastewater) and facial derived organic matter (e.g. sludge, solid fraction) can also function as a soil improver given the organic matter content
- nutrient solutions are liquid products with nutrients in mineral form and quick release fertilisers because of higher solubility
- precipitates are solid products with nutrients in mineral form and slower release fertilisers since nutrients in the crystal structure have to resolve over time
- ashes and slags are solid products with nutrients in mineral form and slow release fertilisers since nutrients in the crystalline structure are resolving very difficult (strong acids are needed, for example as used in the mineral fertiliser industry)
- biochar, phototrophic biomass (e.g. algae) and facial derived organic matter are sludge or solid products containing nutrients both in mineral and organic form and are slower release fertilisers since nutrients are bound to organic matter and/or carbon.

Some general remarks regarding fertilisation / application:

- 4R Nutrient stewardship should be used for fertilisation of both conventional as well as recovered fertiliser products[15].
- Organic fertilisers can function as a base fertilisation at start, with nutrient release during the whole rowing season. Mineral fertilisers contain quick releasing nutrients, so best suitable as a started fertiliser in spring and a later (second) dose as top dressing.
- Nitrogen fertilisation is required for most crops, especially at the start and also later in the growing season. Nitrogen is very mobile with several potential losses, so needs good management and yearly fertilisation.
- Phosphate fertilisation in the Netherlands is limited since soils are highly loaded with phosphate, up to 2500 kg P per hectare, balanced fertilisation is the goal in which uptake of P by crops is replaced by fertilisation.
- In some fertilising products like ammonium sulphate the added sulphur can be an issue for soils, crops and ground water quality.

Wielemaker (2019) has elaborated in her PhD thesis on various scenarios for nutrient flows from circular sanitation to urban agriculture. Table 3-3 shows the average composition of urine, faeces and kitchen waste. COD is a measure of the organic matter content in wastewater (the Chemical Oxygen Demand), TN is the amount of nitrogen and TP is the amount of phosphate. These figures form the starting points of the scenarios elaborated in Table 3-4.

[15] https://nutrientstewardship.org/4rs

Table 3-3 *Average composition of urine, faeces and kitchen waste per person per day, based on EU data, including standard deviation. Source: Wielemaker (2019).*

Parameter	Unit	Urine	s.d.	Faeces	s.d.	Kitchen waste	s.d.	Total
Volume	L/p/d	1.3	0.12	0.13	0.06	0.2	-	1.63
COD	g/p/d	12.5	1.91	47.9	12.23	59	-	119.4
TN	g/p/d	10.2	1.10	1.4	0.38	1.4	0.52	13
TP	g/p/d	1.1	0.34	0.5	0.05	0.2	0.06	1.8

COD= chemical oxygen demand, TN= total nitrogen, TP= total phosphorus.

Table 3-4 *Annual basic demand and minimum demand for nutrients for urban agriculture and urban agriculture on roofs. Source: Wielemaker (2019).*

Unit		Available N*	Available P*	Organic matter[3]
Urban agriculture				
Basic demand[1] (Do)	kg/ha	109	96	7861
Minimal demand (D)	kg/ha	109	14	2685
DMI	%	0	85	66
Rooftop agriculture				
Basic demand[2] (Do)	kg/ha	113	41	1743
Minimal demand (D)	kg/ha	113	14	1743
DMI	%	0	65	0

1 Table on fertiliser advice (Van Ierssel, 2013).

2 Technische Fiche ECO-MIX 1 (DCM Nederland BV, 2014) en Organische Gedroogde Koemest (Humuforte, 2014).

3 Organic matter =32% of dry matter, Samenstelling en werking van organische meststoffen (de Haan en van Geel, 2013b).

* Nutritional values for N and P are usually expressed as the weight of N and P2O5. P is 44% of the P2O5 value. N is expressed as elementary N. Both N and P are calculated with the 'working coefficient' for compost and animal compost and 55% from chicken manure. Available P is 50% in compost and animal manure. Available N is defined as 10% in compost and 55% in chicken manure. Available P is 50% in compost with a maximum of 2.5 P2O5 / kg dry matter compost

Table 3-5 shows the nutrient requirements of urban agriculture initiatives in Rotterdam. It shows how many people are needed to supply 1000 m2 of urban agriculture or urban agriculture on roofs with 100% phosphate. This is based on the average nutrient requirement of urban agriculture initiatives in Rotterdam as shown in

Table 3-4 and the various scenarios. The two scenarios are based on two existing urban agriculture and roof-urban agriculture situations in Rotterdam, the difference in nutrient requirements is due to the different crops that are cultivated per type of urban agriculture.

Table 3-5 *Scenario's and rate of self-sufficiency. Based on Wielemaker (2019).*

Scenario's *Waste streams* *Products*	**1** **Kitchen waste & urine** **Compost & matured urine**	**2** **Kitchen waste & urine** **Compost & struvite**	**3** **Faeces + kitchen waste & urine** **Struvite, hygienised sludge & matured urine**
Amount of people needed to supply 1000 m² urban agriculture in nutrients:	22.6	2	2.6
Self-sufficiency index (%) based on 1 ha urban agriculture			
Organic matter	75	6	4
N slow	29	18	15
N fast	79	0	79
P slow	100	100	100
P fast	100	0	100
Amount of people needed to supply 1000 m² rooftop agriculture in nutrients:	19.5	4.5	4.4
Self-sufficiency index (%) based on 1 ha urban agriculture on rooftops			
Organic matter	100*	23	14
N slow	4	6	5
N fast	0	0	0
P slow	38*	100	100
P fast	0	100	0

* Scenario 1 is based on a self-sufficiency index of 100% for organic matter instead of phosphate, because this scenario would otherwise result in over-fertilisation.

Use of urine as a fertiliser has most potential for crops with a high nitrogen demand. Successful experiments have been conducted in the past with several food crops, such as grains, corn, beans, lettuce, spinach, cauliflower and tomatoes (Thoden van Velzen et al., 2013). In potato cultivation foliar fertilisation with urea-containing liquid fertilisers are interesting. Liquid fertilisers are interesting because potatoes already have to be sprayed to prevent an important disease (urine product can be sprayed at the same time) (Ter Berge, 2008).

Struvite can be used as an fertiliser, the slow release can be an advantage for several crops. It is very important for farmers that the fertiliser is clean.

Using urine can be interesting for organic agriculture because of the high (quick) availability of nutrients (Swart & Faber, 2008), and the precision with which it can be applied (Ter Berge, 2008). However, it may also be regarded as unsuitable for organic agriculture, as the fertiliser is not produced in an organic farming system, and might be seen as comparable to excreta from conventional systems: animal manures from conventional agricultural systems are not allowed to be used in organic agriculture.

Liquid urine could be a suitable fertiliser for greenhouse cultivation, after dilution and addition of missing elements it could be a suitable fertiliser for crops on water and substrate culture. The composition of urine can vary and that makes it less suitable for greenhouse horticulture, which prefers to use a constant / stable product (Ter Berge, 2008).

Aquaculture
Urine as a fertiliser can be interesting for shellfish farming, a study from 2007 showed that algae (food for shellfish) can grow well on human urine. For a breeding pond of 100 m^3 algae cultivation, the urine of 48 people a day is needed. (Van Nijen and Verment, 2008).

3.4 Legislation

Legislation points out a few parties that have responsibilities concerning wastewater:

- The municipality has a duty of care regarding the collection and transport of urban wastewater (Article 10.33 WM).
- The water board has a duty of care for the treatment of urban wastewater (Article 3.4 Water Act in conjunction with Article 1, paragraph 2 of the Water Board Act).
- New environmental law (the new *Omgevingswet*) provides more space for local and regional customisation, and cooperation between the water board and the municipality (Saniwijzer.nl).

From the variety of products that can be recovered from household wastewater, recovered phosphates (including struvite) and sewage sludge are currently the only products that under certain conditions are allowed for use as fertiliser in the Netherlands. These conditions are described in:

- the Implementation Decree of the Fertilisers Act (Uitvoeringbesluit Meststoffenwet)[16]
- the Implementing regulation of the Fertilisers Act (Uitvoeringsregeling Meststoffenwet)[17]
- the Implementing regulation use of fertilisers (Uitvoeringsregeling gebruik meststoffen)[18]
- the Decree use of fertilisers (Besluit gebruik meststoffen)[19]

Recovered phosphates, such as struvite extracted from wastewater, have been recognised as a fertiliser in the Netherlands since 2015. Article 18 of the Implementation Decree of the Fertilisers Act describes the prerequisites for the composition of recovered phosphates, including rules on pathogens, heavy metal contents and contents of organic pollutants.

In European Law, recovered phosphates are seen as a component material category for making fertilisers, under the name 'precipitated salts and derivatives' in the Fertilising Products Regulation (Regulation (EU) 2019/1009), which has entered into force on July 16th, 2022. The implementation of this law may lead to changes in Dutch law.

Sewage sludge is also a recognised fertiliser, but there are many restrictions for use in the Netherlands. In other European countries other and less stringent regulation applies. Some prerequisites in the Netherlands are:

- The soil on which sewage sludge is used must be analysed (see Implementing regulation use fertilisers)
- No more than one or two ton sewage sludge can be applied per year, depending on land use (Decree use of fertilisers)
- There are rules for the presence of pathogens, heavy metal contents and the content of dry matter or acid neutralising value (Implementation Decree of the Fertilisers Act).

WWTP sludge generally contains too many heavy metals to be allowed to be used (Saniwijzer, n.d.B).

The Environmental Management Act (*Wet milieubeheer*) labels urine, faeces and wastewater as waste, therefore, these materials are not allowed for use as fertiliser. Waste materials may only be used as fertiliser when they are taken up in Appendix A of the Implementation Regulation of the Fertilisers Act (*bijlage Aa van de Uitvoeringsregeling Meststoffenwet)*. Waste materials can be taken up in Appendix A if the material is accepted after evaluation with the associated protocol[20] (*Protocol beoordeling stoffen Meststoffenwet)*. Although they are not allowed as commercial fertiliser, it is allowed to use urine or sludge from your own septic tank in your own garden, provided that is not leads to harm to the environment.

Under certain conditions, the new environmental law offers room for experiments. It is possible to deviate from the rules, but international obligations (eg European law) must be complied with.

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[16] https://wetten.overheid.nl/BWBR0019031/2022-06-01/0
[17] https://wetten.overheid.nl/BWBR0018989/2022-07-16/0
[18] https://wetten.overheid.nl/BWBR0023115/2020-08-01/0
[19] https://wetten.overheid.nl/BWBR0009066/2022-05-05/0
[20] https://edepot.wur.nl/394876

Important to note is that waste materials mixed with another stream, such as compost, are subsequently also designated as waste.

The Dutch Nutrient Platform has published two legal factsheets about the legal status for the (re)use of struvite and ashes in the Netherlands titled '*Juridische factsheet Struviet en de wet*'[21] and '*Juridische factsheet Assen en de wet*'[22], which provide more specific information for these two materials.

3.5 Health and safety

Risks from the following contaminants are relevant for fertilising products from circular sanitation and must be eliminated or reduced to safe levels for safe usage as fertiliser, if present:

- Pathogens (bacteria, fungi, yeasts, etc.)
- Heavy metals (e.g. zinc and copper)
- Organic contaminants (e.g. medicine and antibiotics residues)

These contaminants are more or less of an issue depending on the production process and the fertilising product that is recovered. For example, ammonium salts are generally produced by stripping nitrogen and sorption in an acid. Thus, the fertilising product is produced separate from the wastewater stream, avoiding contamination. On the other hand, phosphate precipitates such as struvite are generally formed in a reactor while in contact with the wastewater stream. In some cases, phosphate precipitates are not hygienically safe (Bisschops et al., 2019), and then require a hygienisation step.

Figure 3-1 shows that for similar P loads, the heavy metal loads of black water and cattle slurry are quite similar and the heavy metal load caused by urine application is lower. In terms of heavy metals, these streams are thus not more contaminated than the commonly used fertiliser manure.

Organic contaminants are inevitably present in most wastewater streams. Because it is an undiluted source, black water contains relatively high concentrations of pharmaceutical residues. Some of these compounds can be effectively degraded in treatment systems (Bisschops et al., 2019).

Wastewater at communal wastewater treatment plants is much diluted with all type of waste(water). This makes removal of micropollutants like hormones and pharmaceuticals very difficult (similarly to the recovery of nutrients). When sanitation waste streams remain concentrated, instead of being mixed with relatively clean wastewater (e.g., shower water, rainwater), removal of these organic contaminants is much easier, specific and effective.

For urine, a bit more information is available:

- Around 70% of the medicine residues and hormones that humans excrete end up in urine. (Thoden van Velzen et al., 2013).
- The heavy metal, hormone and antibiotic content of human urine is lower than that of cattle- and pig slurry and manure (Winker at al., 2009 with Hammer & Clemens 2007).
- Urine has a much lower heavy metal content than most animal manure and other fertilisers (Thoden van Velzen et al., 2013).
- The amount of enterogenic microorganisms in urine is so low that applying urine to the soil can be accepted (Swart & Faber, 2008). Storage does not or hardly break down medicines in urine (Thoden van Velzen et al., 2013) Urea hydrolysis and long-term storage of source-separated urine for reuse as fertiliser is insufficient for the removal of anthropogenic micropollutants (Monetti et al., 2022).
- Although some knowledge gaps need to be addressed, using urine does, according to experts, not rise agricultural concerns. The health risks of using urine for crop production for human consumption are low (Thoden van Velzen et al., 2013).
- LeAF is experimenting with the use of urine and struvite in foreign projects, as there are different requirements for testing. From the experiments, the use of urine and struvite seems safe.

[21] https://www.nutrientplatform.org/en/documents/juridisch-factsheet-hoe-zit-het-met-struviet-en-de-wet
[22] https://www.nutrientplatform.org/documenten/juridische-factsheet-assen-en-de-wet

- In their experiment Viskari et al., 2018 compared barley fertilised with urine and with a comparable mineral fertiliser. They did not find pathogen indicators or heavy metal concentrations in the urine. Hormones and pathogen values in the soil were below detection limits, nor could they be found in the barley at the end of the growing season, except for progesterone, which had a concentration of 3 µg/kg dry matter in the barley (the detection limit is 1 µg/kg dry matter).

3.6 Technical aspects

Some potential challenges for circular sanitation systems are (personal communication, Tiemen Nanninga, LeAf, 9/12/2020 and 16/02/2021):
- Different and/or separated pipe systems required compared to conventional toilet, e.g. pipe thickness, continuous flow and slope and minimalization of strong angles.
- Noise from some special toilets, especially in vacuum toilets and high-rise building the constructor needs to take the acoustics into account.
- Regular and more specific maintenance required, or by houseowners or external parties.
- More difficult to manage, several small installations at building or neighbourhood level.
- Space required for storage of residual streams and products.
- Odour issues at the toilet, at storage and during application can be a potential issue and needs to be tackled, it is imported to have a water lock in the toilet, hermetically sealed storage, and good management during application e.g. injection into the soil during fertilisation.
- Technical aspects must be incorporated in the design of the building in an early stage, specific knowledge and experiences required by different parties in the building chain.

For example, in case of stored urine, it is imported to have hermetically sealed storage, because urine has a strong odour due to the presence of ammonia. When applying urine to the soil, odour can be significantly limited by the right type of application, such as injection (Thoden et al., 2013).

Collection and storage of urine: long-distance transport is difficult due to salt deposits in the pipe system. To prevent blockage, stagnation of urine must be prevented as much as possible (Bisschop and Mels, 2008). Therefore, free-fall pipes with a slope of at least 1% and a pipe diameter of 75mm are recommended (Stockholm Vatten, 2001).

Attention should be given to the choice of cleaning products to avoid the presence of components that hamper biological treatment during e.g. digestion or composting (Thoden van Velzen et al., 2013).

Nutrients can be recycled at different scale. Both the recovery of nutrients (supply) and reuse of nutrients (demand) can be on different scales.

The **recovery** of nutrients can be done at the level of:
- an apartment
- house
- flat building
- block
- neighbourhood
- village
- city
- farm / rural areas

The most optimum form of collecting nutrient rich flows is on domestic scale, with a central storage for the collected flow (urine, faeces). This is not possible on the short term, therefore private collection or collection on public places like concert halls and arenas has potential (Vijn & Weijma, 2020). Sanitation systems with separation at source are most effective usually at flat, block or neighbourhood level.

3.7 Economic aspects

Important costs that could play a role and should be taken into account in the business case are the costs of:
- Toilets and installation (including maintenance)
- Piping systems (including maintenance)
- Treatment installation (including maintenance and depreciation)
- Use of energy, water, other materials
- Storage
- Transport (can also be the seller of the products)
- Application equipment and labour (can also be the seller of the products)

The investments and running costs must be covered by (1) a reduction or exemption from communal wastewater treatment tax, (2) reduction of costs by replacing used and purchased (fertiliser) products by own recovered products, or (3) revenues from selling (fertiliser) products e.g. to fertiliser industry, public green maintenance companies/organisation (municipality) and citizens/consumers (via garden markets/centres).

Economic costs and values are location and region specific. By comparing two decentralised and two centralised systems, Arias et al. (2020) showed that:
- Capital costs of decentralised systems are about 98% higher, but this is compensated by the operational costs. These are reduced by 66–77%, mainly because of lower energy consumption. The payback time is estimated to be 8–9 years, which is lower than that of centralised systems. In this study, the payback time was 4-5 years for the decentralised systems and 8-13 years for the centralised systems.
- Decentralised wastewater treatment systems are especially recommended for new developments because of the problems associated with changing and replacing existing networks.

The pilot system in Noorderhoek in Sneek is approximately 6 times more expensive than the conventional sewage system. This project found that the minimum system scale to achieve a feasible business case and good treatment efficiency was 1200 home equivalents (Gemeente Amsterdam and Waternet, 2018). This system has additional costs of 35 euros per resident per year compared to centralised references (STOWA, 2018, Table 3.5). At a capacity of around 3,000 residents, the system is competitive with reference systems with 30,000 or 100,000 residents (STOWA, 2018).

Below an economic case is presented for circular sanitation with source separated toilets and the production of struvite for 2,250 people, based on expert knowledge and judgement (personal communication Tiemen Nanninga, LeAF, 9/12/2020 and 16/02/2021).

- Sewerage in the countryside (pressure sewer), or modifications to sewerage by expanding residential area, is often more expensive than local treatment (Saniwijzer, n.d.C)
- Average costs of pressure sewerage in rural areas: 700 euros per connection (Saniwijzer, n.d.C, based on research from STOWA and RIONED)
- Collection on a larger scale gives lower costs, the processing of urine only pays off at a flow rate of 0.5-1 m^3 per ha, which equates to the urine of 5,000 to 10,000 people
- Collection, processing and application of urine as fertiliser close to the location where urine is collected can reduce costs enormously, transport of urine is expensive (Gemeente Amsterdam & Waternet, 2018).

An extra pipe for urine next to an existing pipe connected to a struvite reactor is often used. The storage of urine and application after 6 months is experienced with abroad. In this example we assume a struvite reactor.

On a small scale, the pipe can have a standard diameter. The connection of a urinal is 50 mm, in apartments the urine stream is small enough for the currently used diameter. However, 125 mm is definitely a safe choice, this diameter makes inspection and cleaning (possibly precipitation in pipes).

- Piping, free fall: € 60 per meter, including material and labour (substantiated estimate, normally on a building basis);
- Struvite reactor for black water: 300 litres at € 55,000 excl. unforeseen costs and surcharges;
- Benefits of struvite as fertiliser: € 500 (value € 50-100/ ton);
- Struvite reactor for urine only: 2.5 m^3 per day, 50 litres at € 20,000- € 30,000 (estimate);
- Effluent struvite reactor requires post-purification before discharge, or discharge into the sewage system to WWTP.

The pipes of the vacuum toilet can also be connected to the pipes of washbasins, etc. The question is how many toilets are involved, and whether vacuum makes sense. An alternative is toilet water in a conventional free-waste sewer and to WWTP.

Advantages of a waterless urinal
- Save on water and maintenance (due to limescale);
- Struvite can be recovered from effluent.

Cost grinder system
A grinder system for swill can be fermented locally or it can be sold at, for example, Meerlanden or Orgaworld for higher-quality processing (preferably LAP3).
Technologically, this is possible with a quantity of 2,250 people, the digester can then keep itself running. In terms of costs, there is an additional cost compared to conventional collection and processing. A digester costs € 200,000 for 21 m^3 per day of toilet water (black water) with swill from the grinder;
- Swill only digester: 2,000 people supply ~ 1.5 m^3 per day. This requires a digester of 11 m^3. This costs € 40,000 (excluding storage costs, contractor, etc., contractor costs + 71.4%);
- The swill remains in the digester for ~ 7.5 days;
- The effluent still has to get an 'end-of-waste status' before it can be used in the garden: hygienisation step (70 degrees heating) necessary -> check whether it may be used.

Piping for grinder (vacuum):
- Costs are € 120 per meter, installation and piping material. Need attention during installation: mirror axes required;
- Take acoustics into account, especially in high-rise buildings (other building material required, additional costs);
- Vacuum grinders: € 1,400 each, from 100-500 grinders discount -> € 1,000 each;
- Vacuum pump at the end: € 60,000 incl. Installation for system that only collects swill;
- Vacuum pump with also black water: € 150,000 incl. Installation, excl. surcharges.

In general, it costs more energy to transport wastewater to the WWTP, than to treat the wastewater. Transportation of separated wastewater can lead to an energy reduction of 25-50 percent. The treatment of different types of wastewater requires for all about the same amount of energy (De Brauw et al., 2012).

3.8 Social aspects

Important aspects are:
- Social acceptance
- Involvement and support of user
- Appropriate use of systems
- General awareness in the transition towards circular sanitation

The approach of circular sanitation systems, especially decentralised and source separated wastewater treatment, is more visible in households and possibly as well in the neighbourhood, depending on the treatment system. This requires and can create more awareness and involvement of the residents in their sanitation use and the way how, what and how much they discharge.

a)  b)  c) 

Figure 3-3 *(a) No mix toilet. Source: Sustainable Sanitation Alliance on Wikimedia Commons. (b) waterless urinal. Source: USEPA Environmental-Protection-Agency on Wikimedia Commons, (c) vacuum toilet. Source: Wrightbus on Wikimedia Commons.*

Research by the Swiss institute EAWAG showed that most participants were positive about the use of urine as fertiliser, 80% found that the NoMix urine separation toilet was at least as good as conventional models and 72% would buy urine fertilised food, provided that there are no health risks (Larsen & Lienert, 2078).

From studies on consumer acceptance in Germany and the Netherlands, it could be concluded that the acceptance is higher for use on grains (90%) and energy crops (82-88%) than for vegetables (40-75%) (Thoden van Velzen et al, 2013; Mels, 2008).

4 Application

After recovery of nutrients from sanitation, the nutrient-rich products/flows should be **reused** in society. The fertilisers can be used in food production or non-food plant production (e.g. public green and sport fields), either directly or indirectly via the fertiliser industry. When used for non-food plant production, nutrients are not part of the agricultural cycle (used for plant growth, eaten, excreted, recovered). This pathway can however still replace the use of other fertilisers which consume raw materials and/or energy during production.

Nutrients or products produced from wastewater (in urban areas) can potentially be used in and around cities, for example in the Amsterdam Metropolitan Area:

- Urban agriculture
  - Outdoor urban farming
  - Indoor /vertical urban farming
  - Allotments
- Peri urban agriculture around the city
- Rural agriculture
- Greenhouse horticulture
- School gardens
- Household gardens
- Parks and public green
- Sport fields
- As resource in the fertiliser industry

For various sanitation products, Table 4-1 shows the most important potential issues that are encountered, including issues regarding agronomy, distance/traffic, environment, health, legislation, odour, practicality, social acceptance and timing sensitivity. For an explanation of the production routes of the products, see the infographic in section 2.4.

Taking the challenges per recovered products in Table 4-1 into account, Table 4-2 presents the overall qualitative application potential of the recovered products for each potential use.

Colours per field indicate a strong issue (red), medium issue (orange) and (almost) no issue (green). This classification and the determination is based on expert judgement by the authors.

Overall, the fertilisers that are evaluated with ‘green’ and ‘orange’ most often for the various issues as presented in Table 4-1, are phosphate precipitates and nutrient solutions.

Fertilising products from sanitation (except for phosphate precipitates) are generally not suitable for sport fields, because they are generally used on a daily basis which is difficult in combination with smell issues.

For allotments it is assumed that an organisation is in charge and educates its users.

Ashes are mainly suitable to be used indirectly as resource for the fertiliser industry to produce mineral fertilisers that can be used by agriculture, greenery and consumers. Application on non-food plants can be considered, but only if contaminants are at a safe level. In ashes nutrients are not plant available. Risks for contaminants such as heavy metals and incineration compounds should be mitigated before nutrients can be reused. Organic contaminants are removed during incineration and do not pose a problem. Direct contact with humans and animals should be minimised. Ashes cannot be applied directly because of dust and should be pelletised before application on land.

Stabilised urine is most suitable in peri urban agriculture and under conditions within the city in outdoor urban agriculture, allotments, school gardens, but also in parks and public green, and rural agriculture if distances are low. Urine is liquid and thus bulky, the transport distance should therefore be minimised. Concentrating urine is energy intensive and subject to loss of nitrogen. Urine is not very useful as a resource in the mineral fertiliser industry since nutrient concentrations in urine are low and transport costs are high. If to be used in household gardens, users should be educated about right application. Potential odour issues are lower outdoors and can be minimised if application is followed by irrigation or done by injection. For additional safety, urine should not be in direct contact with food crops that are harvested very shortly after fertilisation. Preferably, urine is applied by professionals and contact with children is avoided. Urine contains high salt concentrations, which is not preferred in fertilisation, but can be mitigated by dilution including irrigation after application, or desalinisation techniques. In closed water loop systems like greenhouses and vertical farming systems, salts can build up, which makes urine less suitable as fertiliser in these systems. It should be made certain that pathogens are eliminated, for example by a sufficiently long storage duration. Field application is relatively easy at start of the growing season, additional fertilisation later on (with crops in a further growing stage) is more difficult.

Nutrient solutions generally have a high use potential in urban, peri urban and rural agriculture and parks and school gardens. Generally there are good experiences in the transport, storage, application and the effects on soils and crops with nutrient solutions produced by the fertiliser industry. Higher concentrations and smaller volumes improve conditions for transport. One of the potential products, ammonium sulphate, is a well-known fertiliser for nitrogen and sulphur. The high level of sulphate should be taken into account in application limits. Injection is recommended to minimise smell and ammonia emissions. Some nutrient solutions are not suitable for closed water loop systems (e.g. in greenhouses or hydroponics in vertical agriculture) due to high salt levels. Nutrient solutions are too bulky for large scale fertiliser production, but can be traded and/or mixed with other liquid fertilisers, e.g. to reach crop-specific ratios of nutrients. Generally, nutrient solutions not processed by industry are too bulky for household use.

Phosphate precipitates are suitable for almost all types of fertiliser uses, including urban, peri-urban and rural agriculture, public green, school gardens, household gardens, sport fields, and when dissolved also in water-based growing systems in greenhouses. Phosphate precipitates from wastewater flows are slow-release, concentrated and solid fertilisers and are easy to transport. They can be used in precision fertilisation if processed/dissolved to form a quick release fertiliser and are easy to apply. Smell issues are minimal. Fertilisation with recovered phosphates, including struvite, is legally allowed, under specific conditions (agreeing to prerequisites such as heavy metal and organic pollutant limits). Phosphate precipitates can form a contamination risk for closed water loop systems if the product contains too high contents of organic matter, as this can lead to pipe blockages and can be a substrate for germs. It can be used as resource in fertiliser production and industrial processing is relevant as an intermediate step for relatively unclean precipitates and if the production of a quick release fertiliser is preferred.

Digested sludge (digestate) is generally not suitable for indoor and in the city farming, but could be an option for peri-urban and rural agriculture, and maybe for public green. Digestate is usually not biologically stable (depending on the retention time), containing reactive carbon, which can cause oxygen depletion in the soil. Direct contact with humans and animals should be avoided due to risks of pathogens. Odour issues are difficult to control. Digested sludge is not suitable for closed water loop systems, because they need liquid, organic matter-free fertilisers. Digested sludge could be used in professional urban agriculture around the city, when applied at the start of the season by professionals with right application methods. There are potential uses in green spaces that are not visited directly by public. This is a less socially-accepted fertiliser. For safety digestate should not be in direct contact with crops that are harvested very shortly after fertilisation. It is not suitable as a resource for the fertiliser industry because it is bulky with relatively low nutrient concentrations, but it can be mixed with other fertilisers.

Composted sludge (compost) is generally more suitable for (peri) urban and rural agriculture, public green, household gardens, and soil based greenhouse production, and not for sport fields or as resource for mineral fertiliser production. Compost in general (i.e. not based on sanitation streams) is a well-known, accepted, odourless organic soil improver with organic matter and diverse nutrients. However, composted sludge is less accepted by the public. High temperature composting and good mixing is required for stabilisation and pathogen elimination (bacteria, fungi, seeds, etc.). Depending on the source of the sludge contaminations such as heavy metals (mainly in centralised wastewater) or organic pollutants (depending on the human use) can form a challenge and must be removed. Composted sludge is not suitable for closed water loop systems because these require liquid organic matter-free fertilisers. There are health risks in case of direct contact with people. It is not suitable as a resource for the fertiliser industry because it is bulky with relatively low nutrient concentrations, but it can be mixed with other fertilisers.

Biochar application is more suitable in peri urban and rural agriculture, somewhat suitable in urban agriculture, public green, household gardens, and not suitable for application on sport fields or closed water loop systems. Biochar consist out of stable carbon with some slow-releasing nutrients. Depending on the source of the sludge contaminations such as heavy metals (mainly in centralised wastewater) or organic pollutants can form a challenge and must be removed. Not much is known yet about biochar made from human waste, but a review of meta-analyses on biochar, produced from various inputs, showed that the use of biochar has a positive impact among others for carbon storage and water use efficiency (Schmidt et al., 2021). Biochar does not pose odour risks. Biochar could potentially also be a resource for growing media commonly used. It is not suitable as a resource to produce mineral fertilisers, but can be traded and/or mixed with other solid organic fertilisers or as growing media. Additionally it is a potential way of carbon sequestration to prevent climate change, but only if carbon stays in the soil for very long time scales.

Phototrophic biomass (e.g. algae) has generally highest use potential in peri urban and rural agriculture, maybe some potential in urban agriculture, public green, household gardens, and is not suitable for application on sport fields. Phototrophic biomass can be used as feed material for livestock (outdoor) or insect farming (indoor). As dried pelletised product, it could be used as organic fertiliser, where odours can be challenge. As composted product of the fresh biomass, it could be used as soil improver. Potential contaminants should be removed to reach acceptable levels. Biomass from algae could be a biorefinery resource for the production of growing media/substrates. The system of biomass production from algae, followed by composting or simple biorefinery, could be used for educational purposes.

Table 4-1 *Qualitative overview of issues relevant for fertilising products from sanitation (from excreta or wastewater), colours per field indicate a strong issue (red), medium issue (orange) and (almost) no issue (green); In this table all products are derived from sanitation systems: ashes result from incineration of sewage sludge, stabilised urine is produced from source-separated urine; ashes, digestate, compost and biochar are produced from wastewater sludge, source-separated faeces or black water; nutrient solutions, phosphate precipitates and phototrophic biomass are produced from urine and wastewater.*

Issue	Ashes	Stabilised urine	Nutrient solutions (e.g. ammonium sulphate)	Phosphate precipitates (e.g. struvite)	Digestate	Compost	Biochar	Phototrophic biomass (e.g. algae)
Agronomy	Nutrients not plant available, only in the form of minerals	High salt levels, but irrigation can mitigate risks	Risk of over-fertilisation, for example for sulphur in case of ammonium sulphate	Slow release fertiliser, useful for certain crops/base fertilisation. Only contains nitrogen, phosphorus and magnesium (no micronutrients)	Not stable product, nutrients plant available like in manure	Balanced organic soil improver with organic matter and diverse nutrients, increasing soil water holding capacity	A very slow releasing fertiliser, source of carbon contributing to carbon storage and water holding capacity	Fresh biomass should be composted to stabilise
Distance / traffic	Concentrated, dry product	Liquid bulky product, relatively low nutrient concentrations	Liquid bulky product, nutrient concentrations depend on technology	Less transport volume since crystals are solid and have high nutrient contents	Relatively bulky, difficult to pump	Stable solid product with high nutrient concentrations	Stable solid product with high nutrient concentrations	Bulky when not composted or dried
Environment	Heavy metal and incineration compound contaminations	Medicine residues should be removed, ammonia emission should be mitigated	Risk for ammonia emissions, which can be reduced when applied by injection	Low emissions since slow release (good), however struvite production requires magnesium input from mines	Risk of ammonia emissions, which could be mitigated by injection or further processing	Compost should be incorporated into soil for minimal emissions	More concentrated heavy metal contaminations	Risk of ammonia and methane emissions, which could be mitigated by controlled indoor composting
Health	Presence of heavy metals and incineration compounds which should be removed	After storage for stabilisation no risks	Relatively clean fertilisers regarding contaminants	Relatively clean when pure crystals with low amounts of organic matter	Can contain pathogens which should be removed If produced from sewage sludge: presence of heavy metals	Presence of heavy metals, can contain organic pollutants which should be removed	Presence of heavy metals	Presence of pathogens and toxins, needs to be hygienised
Legislation	Commercially not allowed to use on agricultural land	Commercially not allowed to use on agricultural land	Not allowed at this moment, but e.g. ammonium sulphate	Use allowed at this moment under conditions	Commercially not allowed to use on agricultural land. If produced from	Commercially not allowed to use on agricultural land. If produced from	Commercially not allowed to use on agricultural land. If produced from	Commercially not allowed to use on agricultural land

Issue	**Ashes**	**Stabilised urine**	**Nutrient solutions (e.g. ammonium sulphate)**	**Phosphate precipitates (e.g. struvite)**	**Digestate**	**Compost**	**Biochar**	**Phototrophic biomass (e.g. algae)**
			from other sources is an accepted fertiliser		sewage sludge, use is allowed under strict conditions	sewage sludge, use is allowed under strict conditions	sewage sludge, use is allowed under strict conditions	
Odour	Almost no odour	Risks can be mitigated by stabilisation, good timing and irrigation afterwards.	Risks can be mitigated by proper application incl. timing and injection	No or very minimal odour issues	Risks can be large and mitigated by good application incl. timing and injection	No or very minimal odour issues	No or very minimal odour issues	Risks for dried product when applied
Practicality	Too dusty for application, should be pelletised	Application should be injection or followed by irrigation, bulky product requires anti soil compaction tractors/trailers	Application should be injection or followed by irrigation, bulky product requires anti soil compaction tractors/trailers	Can be applied as crystals near seeds and during seeding, alternatively could be dissolved into a liquid fertiliser for injection	Application should be injection or followed by irrigation, bulky product requires anti soil compaction tractors/trailers	Bulky product requires anti soil compaction tractors/trailers	Can be dusty for application, should be pelletised	Fresh product is bulky, dried product is dusty and should be pelletised
Social acceptance	Perceived as industrial, safe but also non-organic	Perceived by some as unsafe because of human excreta	Seen as reliable and clean fertiliser, especially with additional processing steps	Seen as reliable and clean fertiliser, especially when very pure and light coloured crystals	Perceived by some as unsafe because of human excreta and biological active product	Perceived by some as unsafe because of human excreta and biological active product	Perceived as clean soil improver due to heat process, with carbon sequestration benefits	Seen as clean soil improver, if algae odour is mitigated
Timing sensitivity	Year round production, can be stored easily	Year round production, only applied in growing season, long-term storage required	Year round production, only applied in growing season, long-term storage required	Year round production, can be stored easily	Year round production, only applied in growing season, long-term storage required or additional processing into dried pellets	Year round production, only applied in growing season, long-term storage required	Year round production, can be stored easily	In Dutch climate, only production during warmer months, year round production possible indoor

Table 4-2 *Qualitative overview of application potential of the different nutrient rich products from sanitation (from excreta or wastewater) for different uses in (urban)agriculture, urban green spaces, households and fertiliser industry; colours per field indicate a high/good potential (green), medium potential (orange) and low potential (red). In this table all products are derived from sanitation systems: ashes result from incineration of sewage sludge, stabilised urine is produced from source-separated urine; ashes, digestate, compost and biochar are produced from wastewater sludge, source-separated faeces or black water; nutrient solutions, phosphate precipitates and phototrophic biomass are produced from urine and wastewater.*

Applications	**Ashes**	**Stabilised urine**	**Nutrient solutions (e.g. ammonium sulphate)**	**Phosphate precipitates (e.g. struvite)**	**Digestate**	**Compost**	**Biochar**	**Photo-trophic biomass (e.g. algae)**
Outdoor urban farming	[red]	[green]	[green]	[green]	[red]	[green]	[green]	[orange]
Indoor urban farming	[red]	[red]	[orange]	[green]	[red]	[green]	[green]	[orange]
Vertical urban farming	[red]	[red]	[orange]	[orange]	[red]	[red]	[red]	[red]
Allotments	[red]	[green]	[orange]	[green]	[red]	[green]	[green]	[orange]
School gardens	[red]	[orange]	[green]	[green]	[red]	[green]	[green]	[orange]
Peri urban agriculture	[red]	[green]	[green]	[green]	[orange]	[green]	[green]	[green]
Rural agriculture	[red]	[orange]	[green]	[green]	[green]	[green]	[green]	[green]
Greenhouse horticulture	[red]	[red]	[orange]	[orange]	[red]	[orange]	[red]	[red]
Household gardens	[red]	[orange]	[orange]	[green]	[red]	[green]	[green]	[orange]
Parks and public green	[orange]	[green]	[green]	[green]	[orange]	[green]	[green]	[orange]
Sport fields	[red]	[red]	[orange]	[green]	[red]	[red]	[orange]	[red]
Fertiliser industry (intermediate)	[green]	[red]	[orange]	[green]	[orange]	[orange]	[orange]	[orange]

5 Experiences from practise within CbD

5.1 Interactions and sessions with CbD challenges

As described in paragraph 1.3, four different challenges are taken as examples within this project. Of these challenges, reuse of nutrients from circular sanitation is most relevant for the Bajes Kwartier and Urban Tree Village because of (1) their scale (neighbourhood / building level), (2) use of stripped or new built buildings, and (3) room for application of nutrients in the building, around the building and in the direct region.

FABRICations, the organisation working on the design of the Green Tower of the Bajes Kwartier, was enthusiastic and saw possibilities for use of fertilisers from circular sanitation in the garden of the Green Tower, which would produce food for the restaurant. At the start of 2021 this work package provided input which was used in a meeting on the design of the building. No further input was asked for and we have not received an update.

During the interview, the Urban Tree Village was at the start of its development. The project leader was very enthusiastic. However it seemed it was too early in the process; the group still had to be formed and a location for the living community building had to be found. In the mean-time meetings and brainstorms were held for the Urban Food Garden, the pilot version of the food producing greenhouse that should be part of the community building. Also for that initiative there was large interest to close the nutrient loop, also by implementing circular sanitation and recover nutrient to reuse as fertiliser. The concept of nutrient recycling was discussed during a stakeholder meeting about the concept and business case. Both the Urban Tree Village and Urban Food Tower are also focused on outreach, workshops and education, which would also be a good chance for promotion of circular sanitation concept to professionals, policy makers, neighbours and the general public.

For circular sanitation often different pipe systems with different slopes are required than is conventional. Because the design of the Green Tower, part of the Bajes Kwartier challenge, was already far in progress, it was more difficult to incorporate the pipe systems in the building/renovation plan. Circular sanitation for the whole neighbourhood was also discussed, but because of financial reasons and different commercial project developers it was difficult to get it implemented. There was also still uncertainty what type of buildings would be part of the new neighbourhood, with very different options like (or a mix of) (student) housing, offices, educational building, restaurants, etc. This is crucial information to shape a decentralised circular sanitation system at building- and neighbourhood level, taking into account type, locations and dimensions of toilet systems, piping systems, treatment installation, but also on the output side: the type and quantity of products that can be produced and appropriate application.

For both challenges one of the interests and drivers for nutrient recycling from sanitation was to recover nutrients and reuse them as fertiliser for urban agriculture (food production) in the building or direct surrounding. This is an innovative progressive goal which requires high quality of the final end products to be used for fertilisation. In addition to treatment routes and technologies, there was also a need to think about the routes of reuse including the management, distribution and application of the products. A very interesting concept, but also rather new and difficult to develop and avoid risks in implementation, investments and operation costs and practical issues. For both challenges there is high density of residents or public in de building, providing a hotspot of nutrients. Outside the urban area’s there is plenty of potential demand of nutrients, including dairy production grassland around the river Amstel, arable farming and fruit/nut production in Flevoland, etc.

In both challenges, another important bottleneck discussed was the issue of forming a good business case in order to have also a financial solid case. Additional investments and running costs must be covered by (1) a reduction or exemption from communal wastewater treatment tax, (2) reduction of costs by replacing used and purchased (fertiliser) products by own recovered products, and/or (3) revenues from selling (fertiliser) products e.g. to fertiliser industry, public green maintenance companies/organisation (municipality) and citizens/consumers (via garden markets/centres).

Summaries of some interviews held with stakeholders from Bajes Kwartier and Urban Tree Village are reported in 0.

5.2 Co-organised Nutrient Platform stakeholder workshop Circular Sanitation

A stakeholder event "*Nieuwe sanitatie en stadslandbouw*" about circular sanitation and urban farming was organised together with the Dutch Nutrient Platform, to stimulate discussion among the different stakeholders linked to circular sanitation, including researchers, policy makers (municipal, provincial and national), waterboards, sanitation experts, projects, etc. See the reports of plenary and parallel sessions and presentations in Annex 2.

Learning points presented at and obtained from the workshop based on the Urban Tree Village and Urban Food Tower were:

- You only build or renovate a building or neighbourhood once in a long time, so that is a window of opportunity, in which maximum sustainable use and good preparation are required.

- In the chicken-and-egg dilemma surrounding supply and demand for recycled nutrients, the demand side is the most important in the transition. The demand must be clear in order to be able to sell products. If there is no concrete demand, it must be made more clear, stimulated and/or created.

- It is easier to first look at the demand on the non-food side, so that safety plays less of a role: office greenery / ornamental cultivation / bulb cultivation / parks / sports fields, etc. If the concept has been tested with non-food plants, then it can be further developed also for food production.

- Decentralised processing of wastewater with biological processes is possible with the concept of a "living machine", for example as performed at the monks' monastery De Koningshoeve, Brabant.

- Existing parties such as water boards should also become involved in circular sanitation; there often seems to be interest (Waternet in Amsterdam is already involved at e.g. Buiksloterham).

- Waste: contaminants must be removed and solved, struvite route is possible.

- Compost toilets were not popular with the project on the Ceuvel in Amsterdam. (pathogens, user satisfaction, costs). Application of composting toilets (as compared to other circular sanitation toilets) is therefore not recommended in future developments (see also KWR (2016)).
- Does Amsterdam have experience in going through new types of permits processes, including for circular sanitation?

- There certainly seem to be some informal small-scale initiatives to close nutrient cycles, including circular sanitation and (urban) agriculture. There is a lot of interest in just getting started. Safety is partly taken into account, but it is not necessarily legally mapped/embedded.

- There is a need for clarity in policies for the safe reuse of human flows and nutrients among various stakeholders. Circular sanitation (with urban agriculture) can only take off once that clarity is achieved and provided by governments.

5.3 Learning points from the CbD challenges

Based on the interactions with the CbD challenges some learning points can be made that could function as a guide to other initiative, pilots, the city of Amsterdam and other cities in the Netherlands and abroad with interest for circular sanitation.

We did not manage to implement circular sanitation within the challenges. Partly that could be because the building projects were or in a too early stage or a too late stage. Although the interest was there, a good timing is crucial to put interest into realisation. This is strongly linked to the fact that circular sanitation is still very new and not mainstream and consequently there is a lot of uncertainty in this innovation.

Another barriers was that we as experts/researchers were not part of project development teams. At this moment, knowledge and experiences are still scarce within important stakeholders in the building/renovation chains like architects, project developers, social housing associations, policy makers, civil servants, building companies and even on average within waterboards (wastewater treatment organisations). It is crucial for the development of circular sanitation that specific expertise is brought in the project team from the start.

Challenges owners had high interested in a clear practical guide/handbook for the implementation of circular sanitation, with selected overview of the options, and clear overviews of benefits and disadvantages, including:

- Financial costs and benefits of the concepts, including capital investment and operational costs at start and over time versus increased profits and reduced costs compared to business as usual.
- Overall sustainability of the installation (over life time) and the environmental impact of the products.
- Social acceptance linked to the marketability of the building, as houses, offices etc.
- Realistic indication and if possible concrete market channels for the products, for example as fertilisers and the link with fertiliser industry, urban/rural agriculture, public green and consumer garden markets.
- List of potential risks along full implementation and how to mitigate them properly.
- Showcases of existing example of circular sanitation, including monitoring results/data.
- Technical aspects and conditions about the toilet, piping, treatment, storage and transport systems, including robustness, reliability, dimensions, energy and piping requirements.
- Present legal aspects and future prospects regarding policy changes in the context of circularity, nutrient recovery and reuse as biobased fertilisers.
- Scalability to other locations, including the profitability and readiness for different scales.

6 Recommendations & suggestions

6.1 Recommendation for Amsterdam and other cities and stakeholders

Treating our wastewater with circularity in mind creates opportunities for nutrient recovery and reuse, thanks to which less production of artificial fertilisers is required. Nutrient loops can be closed more locally, thereby saving in transport costs and creating more awareness. Additionally, circular wastewater treatment enables specific removal of contaminants, such as hormones and pharmaceuticals, because sanitation streams are kept separate and are not diluted as much.

The transition from conventional wastewater treatment to circular sanitation and nutrient recovery and reuse requires among others incentive, clarity, and changes in policies and legislation.

Provide clarity
This report shows that one of the main barriers for implementing circular sanitation is uncertainty. Preferably, municipalities would have a roadmap Circular Sanitation available to explain the steps that a company should take to implement circular sanitation. Offering a simple overview may remove uncertainty, for example on the issues related to legislation. It should become more clear what is accepted for pilot studies and how to apply for specific exemptions. Developing a Green deal / chain agreement regarding circular sanitation at the municipality and the national level together with all stakeholders could give an impulse to circular sanitation. If the initiative is not coming from the private sector (market), governments should take the initiative.

Stimulate and work on quality assurance
Municipalities could incentivise the implementation of circular sanitation by providing subsidies or wastewater treatment tax reductions, or on the other hand by raising taxes for building non-circular sanitation systems. Furthermore, setting up a certification or quality assurance system for biobased fertilisers from circular sanitation could provide guidelines for producers and also some security for consumers.

Tackle legislative barriers
An important barrier is formed by legislation. As of now, only few fertilising products recovered from sanitation systems are allowed for commercial use. It should become easier to test circular sanitation products in pilots, including agronomic field test to show the agronomic values and how risks with potential contaminants can be tackled. Additionally, a list should be compiled encompassing all legislation that is relevant for circular sanitation and the recovery and reuse of nutrients and biobased fertilisers from wastewater. The list could be similar to list that the Rijksdienst voor Ondernemend Nederland has for manure.[23] Some relevant legislation to cover:

a. Spatial planning / destination plans
b. Building decree
c. Fertilising Products Regulation (EU) and Fertiliser Act (NL)
d. End-of-waste criteria and animal by-products regulation
e. Storage
f. Transport
g. Specific regulation at municipality level
h. Specific regulation at province level (link to environmental services = “omgevingsdiensten”)
i. Specific regulation at watershed level by waterboards

[23] https://www.rvo.nl/onderwerpen/mest

Stimulate the demand side for nutrients and biobased fertilisers
There is a need to stimulate the demand of nutrients from biobased fertilisers. There is a role for different stakeholders, but there is also a need for initiative by governments together with agricultural organisations like LTO to bring in the perspective of farmers. Especially, if large quantities of nutrients/fertilisers would be recovered, more potential demands/applications in urban farming is needed in at a larger geographical scale around the location of recovery. In that case also transport issues can occur. Scaling up at city level is important to get significant amount of products to make logistics possible and business cases viable. The Netherlands currently have a manure surplus. If this surplus disappears, e.g. because of the development towards circular agriculture and restrictions on livestock amounts, a potential demand for nutrients arises outside the urban area.

Make new and renovated building circular sanitation proof
In order to reuse nutrients from human waste, buildings that are being newly built or renovated should be prepared for circular sanitation. As of this moment there is a strong need for additional houses because of the house shortage, and a need to renovate existing houses to reach better insulation performances. This momentum can be used to implement circular sanitation or at least make houses circular sanitation ‘ready’, for example by installing separate piping systems or define spaces in buildings and neighbourhood for decentralised wastewater treatment. This makes buildings ready for the future, when we have improved knowledge on safe treatment and use of circular sanitation products and legislation that enables the use of these products.

Assess profitability and sustainability of circular sanitation area specific
The options and performance of circular sanitation are area specific. The level of sustainability achieved by recycling at neighbourhood level in combination with urban agriculture should be compared with the conventional situation (with efficient regular facilities) and whether this outweighs all the efforts and possible extra costs. Municipalities and waterboards should assess and take into account in their policy decisions the savings that could be made if no sewer connection is required and waste water treatment plants would not have to process more wastewater and possibly increase capacity, if decentralised systems are put in place.

Assign responsibilities in the transition towards circular sanitation
Traditionally, food suppliers, water suppliers, water purification, etc. are established parties that also represent a high level of knowledge and can provide quality and cost guarantees. The question is how this applies to smaller units such as a residential area or community. Who bears the responsibility for this, who would bear the responsibility if it was arranged at community level? Assign therefore responsibilities to the different stakeholders in the circular sanitation and/or wastewater system, including waterboards, municipalities, project developers, technology providers, demand side parties, etc. The transition towards circular sanitation is a complex societal change in which different stakeholders are involved and should take joint action.

6.2 Suggestions for further research

Based on the interactions with the challenges and the circular sanitation work within the CbD project, the following suggestions for key research questions further research are proposed. Answering these questions will stimulate the transition towards sustainable circular sanitation with recovery and reuse of nutrients and biobased fertilisers from sanitation and wastewater.

1. How can the transitional agenda be developed together with stakeholders to move society from conventional sanitation toward circular sanitation?

2. What is the role and responsibility of each stakeholder in the transition towards circular sanitation?

3. What is the role of circular sanitation in circular agriculture when taking into account future developments such as livestock number and manure availability decrease, reduction of artificial fertiliser use and the transition towards biobased material (replacing fossil fuels)?

4. How can present agronomic recommendations for current conventional fertilisers and experiences for application methods be used for recovered products from circular sanitation and in relation to urban agriculture?

5. What are the societal (financial) costs and benefits of implementing circular sanitation systems instead of commonly used sanitation in new built and renovation buildings and neighbourhoods?

6. How can governments stimulate implementation of circular sanitation (e.g. financially, legally, market, etc.)?

7. What legislation is or should be developed for living labs/experimental area's/pilots regarding circular sanitation?

8. Which legislation is in place, should be updated and in what way for the transition towards circular sanitation in terms of collection, treatment, products, application etc.?

9. What is the overall sustainability and environmental impact of recycling (recovery plus reuse) of nutrients via circular sanitation for the whole system using a life cycle perspective, taking into account water, energy, resources, biodiversity and climate change?

10. How to assess and improve the quality and contaminants level and minimise important risks of circular sanitation recovered (fertiliser) products (e.g. by developing a product quality assurance system by all stakeholders)?

Source: Laufen Bathrooms.

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Annex 1 Interview notes Challenges

Bijlmer Bajes, 06/11/20 (in Dutch)

Aanwezigen:
Kimo, Hellen, Ciska, Lotte, Aranka, Alexander, Micha Wijngaarde
Micha Wijngaarde: helpt bij de ontwikkeling van de groene toren van de Bijlmer Bajes. Daarnaast bezig met 'Boulevard of circular dreams': paviljoens naast een kanaal, met veel winkeltjes. Mogelijk kan daar ook off-grid worden gewerkt zodat er minder leidingwerk nodig is (mogelijk toepassing Ecoflush).

Overzicht Bajes Kwartier (bouw in 2021, kan misschien al geen rekening meer worden gehouden met ontwerp):
- Woningen
- Kantoren
- Hotel
- Scholen

Het wordt dus eigenlijk een wijkje, waarbij ook één toren van de Bijlmer Bajes is gebleven.

Overzicht de Groene Toren (bouw/renovatie over 2 jaar. Voor leidingen kan nog rekening gehouden worden met ontwerp):
- Groene ambities moeten zichtbaar worden
- Educatief programma
- Verticale tuinen, met ook voedselproductie
- Restaurant
- Klimmen (kletterzeig)
- Brouwerij
- 1000 m^2 tuin
- Planten zullen groeien in het gebouw, maar niet nog in kassen (open).

Twee mogelijke insteken:
- Nutriënten in de toren circuleren
- Nutriënten van de wijk toepassen in de toren. Hierbij zit veel potentie in gebruik van het Ecoflush toilet in kantoren (vanwege het onderhoud). Het gemakkelijkst zal zijn om nutriënten te gebruiken voor niet-voedseldelen van de tuinen. Bij toepassing voedselgewassen: meer onderzoek nodig; kan via AMS.

Optie:
Nu urinescheiding toepassen en alleen urine gebruiken. Het gebruik van de vaste fractie kan mogelijk over 5 of 10 jaar dan nog worden onderzocht/toegepast. Uit deze urine kan struviet worden gewonnen om elders te gebruiken (transport per schip over de Amstel?). De rest van de urine kan dan nog lokaal gebruikt worden (potentieel probleem: geuroverlast). (Waarschijnlijk is het een overschot voor hoeveel in de toren gebruikt kan worden).

Potentiële winst:
Afkoppeling van het riool; mogelijk af te spreken dat er geen rioolheffing wordt toegepast.

Leidingen nodig:
- Urine
- Vaste fractie
- Grijs water
- Regenwater. Dit water kan gebruikt worden voor fertigatie/irrigatie van plantsoenen. Drinkwater ervan maken lijkt niet rendabel.

De vaste fractie + grijs water kan bijv. verwerkt worden met vergisting.

Urban Tree Village, 23/02/2021 (in Dutch)

Aanwezigen:
Naleye Sultan Buddista, Kimo van Dijk, Ciska Nienhuis, Lotte Veenemans
Naleye: creatief entrepreneur/adviseur en kunstenaar
Het gesprek ging over Urban Tree Village en voornamelijk over het Marineterrein.

Urban Tree Village
Eerst community opbouwen, daarna de locatie bepalen naar behoefte van de community. Kas van 20 bij 20m (net als bij Urban Food Tower). Waarschijnlijk 200 appartementen. De kas zal waarschijnlijk voornamelijk een kruidentuin zijn, niet grote voedselproductie. Het gebouw wordt zoveel mogelijk gemaakt van hout.

Marineterrein
Het Marineterrein wordt een locatie voor experimenten, waarvan ze kunnen leren voor de Urban Tree Village. Omdat het Marineterrein een Living Lab is, mag hier veel geëxperimenteerd worden (versoepelde regels). De kas, van 20m bij 20m, is genaamd de Urban Food Garden, onderdeel van de Urban Food Tower van het Marineterrein. De Urban Food Tower bestaat uit 5 verdiepingen plus begane grond, waarvan de begane grond en de bovenste verdieping ingedeeld/gebruikt worden door mensen van UTV voor een publiekstoegankelijke begane grond een dakkas met oranjerie (restaurant). Daar kunnen cursussen worden gehouden. De andere 4 verdiepingen worden gebruikt door GrowX voor vertical gardens & onderzoek en innovatie. Het gebouw wordt geen vaste bouw, maar volledig modulair: houtskeletbouw.

Urine toepassing ziet Naleye voornamelijk binnen het Marineterrein: zo is de cirkel klein en is het gebruik makkelijker te verantwoorden naar buiten en naar financierende partijen. Op het terrein kunnen ze er zelf mee experimenteren. Bij succes kan het geïntegreerd worden in de UTV.

De verwachting is dat het bezoekersaantal in de honderden per dag zal lopen. Daarnaast zijn er 120 mariniers. Dit zal teveel urine opleveren voor alleen gebruik op het Marineterrein. De verwachting is dat er zo'n 20-25 toiletten en/of urinoirs zullen zijn in de Urban Food Tower. Eerste hele grove schatting kosten leidingwerk: 22 k€ (excl. toiletpotten). Mogelijk lagere kosten, omdat de leidingen niet in beton komen. Voorstel Kimo: regel een rioolstelsel waarbij je de mogelijkheid hebt om de urine te collecteren of de urine toch naar het riool te sturen, afhankelijk van wat benodigd is. De minimale bijdrage die je kunt leveren voor de transitie is een apart leidingstelsel voor urine inbouwen.

Urine bevat zo'n 90% van de totale stikstof (TN) en twee-derde van de totale fosfor (TP) van de menselijke sanitatie-stromen (urine+feces).

Urine moet gestabiliseerd worden voor 6 maanden, het liefst met UV-licht, bijv. in een IBC vat. Er zijn meerdere bassins nodig, voor oude en nieuwe urine, zodat de opslag van 6 maanden behaald kan worden in batches. Alternatief is struviet winnen uit de urine, waardoor transport, opslag en verkoop aan consumenten mogelijk zou kunnen zijn. Urine zou het best geïnjecteerd kunnen worden om stankoverlast te voorkomen, maar hoe dit kan worden toegepast op kleine schaal weten we nog niet. Struviet is bijna geurloos.

Regenwater kan gebruikt worden voor het doorspoelen, Naleye dacht dat regenwater zou worden opgeslagen, maar heeft nog niet nagedacht over/geen beeld van waar de tanks komen. Regenwater bevat minder ionen zoals magnesium (minder struvietvorming in de leidingen) en geen kalk (geen kalkvorming in de leidingen), en is daarom ook beter dan drinkwater.

Struviet mag verkocht worden aan tuincentra, maar omdat het een eenzijdige voedingsstof is, is het niet heel aantrekkelijk. Voor sportvelden en golfbanen is struviet wel een goed product, en op daktuinen met Sedum bijvoorbeeld ook. Voor fosfaatbehoeftige akkerbouwgewassen of groenteteelt, is struviet geen aantrekkelijk product, omdat er met struviet niet kan worden voldaan aan de jaarlijkse stikstof behoefte van een gewas. De magnesiumbehoefte van een gewas wordt vaak wel gedekt met struviet. Weggeven vindt

Naleye in eerste instantie prima, omdat het een experiment is. Mogelijk kan struviet een positieve waarde krijgen, andere winst kan gehaald worden bij het afvalwater systeem volledig decentraal te maken en daarmee geen of verminderde afvalwaterheffingskosten te betalen.

De kas zal voornamelijk kruiden en groenten voortbrengen die dagelijks gebruikt worden, zoals sla, wortels en tomaten. Ze willen werken met houten bakken die makkelijk verplaatsbaar zijn (1m hoog). Ze willen cursussen geven over het opzetten en onderhouden van moestuinen. Verder zijn er plannen voor allerlei andere workshops, zoals paddenstoelenkweek, etc.

Annex 2 Report co-organised Nutrient Platform stakeholder workshop CS (in Dutch)

Aanwezigheidslijst:

Renske Verhulst	Nutrient Platform
Emmeken van den Dungen	Nutrient Platform
Ad de Man	Waterschap WBL
Anko Vos	Nedmag
Annita Westenbroek	DBC
Bart van der Veer	IV-Water
Berend Reitsma	Tauw
Ciska Nienhuis	WUR
Fedde Jorritsma	Localwise
Fides Lapidaire	Stichting Rondgang
Frank de Ruijter	WUR
Frank Peters	Waterschap Vallei &Veluwe
Henk de Bruin	Omgevingsdienst ZHZ
Herman Walthaus	Ministerie van I &W
Hylke Simonides	Avebe
Jan Roefs	NCM
Jan Weijma	LeAF/WUR
Jan Willem van der Schans	ZZP/Korte Ketens
Jouke Boorsma	Aquaminerals
Kees Roest	KWR
Kimo van Dijk	WUR
Lennart Zwart	Provincie Groningen
Lex Lelijveld	Waternet
Lotte Veenemans	WUR
Marco van Hedel	Gemeente Nieuwegein
Marthe de Graaff	Evides
Miriam van Eekert	WUR
Naleye Buddista	Urban Food Tower
Paul Telkamp	Tauw
Peter Scheer	Nijhuis Industries
Roland de Bruijne	Knoell
Rosanne Wielemaker	Witteveen+Bos
Tiemen Nanninga	LeAF
Wim de Jong	Twence
Wouter de Buck	Rewin
Yanna Hoek	Broodje Poep

Programma:

13.00	Update secretariaat
13.15	Presentatie Jan Weijma over nieuwe sanitatie
	Presentatie Jan Willem van der Schans over korte ketens
13.45	Drie voorbeelden uit de praktijk
	1. Nieuwegein - ambities duurzame sanitatie
	2. Kerkrade- Superlocal
	3. Amsterdam - Urban Food Village/tower
14.15	Pauze
14.30	Break-out sessies rondom de drie voorbeelden
15:00	Samenkomst en terugkoppeling
15:15	Break-out sessie voor ideeën Nutrient Platform 10 jaar via Miro
15.30	Afsluiting en verplaatsen naar Wonder

Presentatie Jan Weijma (LeAF) – Nieuwe sanitatie

Voor inhoud, zie losse presentatie.
De vragen die opkomen tijdens de presentatie gaan over of de meststoffen gebruikt kunnen worden in openbaar groen. Dit zou kunnen maar daar wordt weinig bemest. Lex Lelijveld haalt het voorbeeld van Oosterwold aan, waar men zelf eten wil kweken en het teveel afzetten bij voedselbanken. De nieuwe sanitatie roept vragen op over schaalvergroting en hoe dit vanuit een stadslandbouw perspectief bij elkaar past.

Presentatie Jan Willem van der Schans – Korte ketens en stadslandbouw

Voor inhoud, zie losse presentatie.
In de definitie van stadslandbouw zit het gebruik van stedelijk afval en daarmee dus niet het exporteren van dit afval. Een van de voorbeelden die wordt aangehaald is Rotterzwam. Zij worden betaald voor het ophalen van afval, zonder deze inkomsten wordt er niet genoeg inkomen gehaald uit de verkoop van paddenstoelen. Voor de paddenstoelen wordt 20% van het organische materiaal omgezet en de rest is nog steeds substraat. Helaas mag koffiedrab niet worden uitgereden in het veld omdat het afval is. Nu lopen er proeven in het veld en de pot om te kijken naar bodem-verbeterende capaciteiten. In vertical farming wordt veel aandacht gegeven aan waterrecycling maar minder aan nutriënten recycling. In Ede zijn ze bezig het met World Food Centre om te kijken naar hoe voedselproductie geïntegreerd kan worden in de lokale omgeving. Een ander interessant vraagstuk is of er binnen een coöperatie uitwisseling van stoffen mag plaatsvinden, als een alternatieve juridische optie.
Dit onderwerp roept discussie om, over hoe regelgeving belemmerend werkt en aan de andere kant juist ter bescherming is tegen risico's qua gezondheid en milieu.

Drie voorbeelden uit de praktijk

Presentaties van de presentatoren, zie losse bestanden

1. SuperLocale nutriënten in Kerkrade - Paul Telkamp, Tauw
Website: https://www.superlocal.eu
De drie circulaire proefwoningen zijn een experiment om te achterhalen of we woningen kunnen realiseren van ten minste 90% uit het projectgebied afkomstige hergebruikte materialen. Nieuwe materialen die worden toegepast zijn bio-based (plantaardig). De woningen moeten voldoen aan de huidige woonstandaarden.

- Deelproject: Drie circulaire proefwoningen
- Geplande opleverdatum: Najaar 2019
- Ambitie: Bewoonbare woningen die voor ten minste 90% gemaakt zijn van de elementen, materialen en bouwstoffen uit een te slopen hoogbouwflat.

Ook het water in het SUPERLOCAL-gebied wordt hergebruikt. De komende jaren doen we ervaring op met een gesloten waterkringloop. Regenwater wordt opgevangen en gezuiverd tot drinkwater. Gebruikt water wordt lokaal gezuiverd en in de woningen komen waterbesparende maatregelen. En tot slot wordt er ook nog nuttig gebruik gemaakt van het afvalwater.

- Deelproject: Gesloten waterkringloop
- Geplande opleverdatum: Medio 2020
- Ambitie: Een gesloten waterkringloop waarin regenwater in het gebied wordt opgevangen, gezuiverd en gebruikt door 130 huishoudens.

In de gesloten waterkringloop krijgt regenwater een tweede en zelfs een derde leven. Het regenwater wordt opgevangen en gezuiverd tot drinkwater. Afvalwater uit de douche en wasbak (grijs water) wordt gezuiverd door planten. Het grijze water wordt dan waswater, dat gebruikt kan worden in een (centrale) wasserette en autowasstraat. Het gebruik van vacuümtoiletten en voedselrestenvermalers in de woningen zorgt voor een zeer geconcentreerde stroom zwart water. Via vergisting ontstaan uit dat zwart water biogas, dat wordt omgezet in elektriciteit of warmte, en hoogwaardige meststof.

De gemeente Kerkrade en Waterschapsbedrijf Limburg zorgen er samen voor dat deze wijk niet langer op het riool is aangesloten. Ook voor het afvalwater zijn lokale ‘circulaire’ oplossingen gevonden. Het water afkomstig van de douche, wasmachine, wastafel en keukenkraan wordt afgevoerd naar een rietfilter (helofytenfilter) die midden in de wijk ligt. Hier maken de rietplanten, wortels en de bodem het vuile water schoner. Hierna kan het verder gezuiverd worden tot bijvoorbeeld waswater. De ontlasting uit de vacuümtoiletten en het groenafval uit de voedselrestenvermalers worden verzameld met een vacuüm systeem. Deze dikkere biomassa wordt verhit in de vergistingsinstallatie. Hier ontstaat biogas en het overblijfsel is een voedzame massa. Deze kan hergebruikt worden in de landbouw. Uiteindelijk gaat geen enkele druppel water meer in het riool.

2. De circulaire stad Nieuwegein – Marco van Hedel, Gemeente Nieuwegein

Nieuwegein kijkt naar de optie van een fyto systeem onder het busstation. Vanuit Vitens is de ambitie om 5% drinkwater te besparen en te kijken naar of schoon water hergebruikt kan worden voor irrigatie. De vraag is wie waarvoor gaat betalen. Ondergronds bergen ligt mogelijk bij de provincie. Maar hier komt een vraagstuk bloot over hoe er verschuiving nodig is of zal gaan gebeuren vanuit een governance perspectief. Voor nieuwe systemen zijn altijd investeringen nodig terwijl de oude systemen al liggen en die worden niet meegeteld als investering. Er zal vergisting per bouwblok gaan plaatsvinden, waarbij ruimte wordt gereserveerd in de kelders. De N gaat verwijderd worden met de Olandreactor en P wordt neergeslagen als struviet door toevoeging van magnesiumchloride. De OLAND-reactor (zoals toegepast door DeSaH in Sneek) bestaat uit een Rotating Biological Contactor (RBC, ook wel biorotor genoemd). In de reactor wordt circa de helft van het ammonium (NH_4^+) omgezet naar nitriet (NO_2^-). Daarna zetten Anammox-bacteriën het ammonium en de nitriet om in stikstofgas.

Een aantal punten die nog toegevoegd zouden kunnen worden aan de discussie:

- Bij Nieuwegein wordt een Olandreactor voorgesteld. Hierbij wordt N omgezet naar N_2 gas, waardoor het kwijt is. N terugwinnen is vanuit duurzaamheid beter (mits het niet meer energie kost dan het Haber Bosch proces voor de productie van N fertiliser).

- Een aparte urineleiding werd niet besproken. Aparte urine inzameling zou het mogelijk makkelijker kunnen maken om struviet te produceren en N terug te winnen, gezien het zo’n geconcentreerde en relatief schone stroom is. De cases Kerkrade en Nieuwegein hebben beide vacuümtoiletten ipv no-mix toiletten in gedachten.

3. Urban Food in Amsterdam – Naleye Buddista, initiatiefnemer

De vraag wordt gesteld waarom het toevoegen van voedselresten aan de slibcompostering duurzaam is, omdat het mogelijk meer verontreinigingen toevoegt. Terwijl het misschien beter is om de voedselresten los te composteren. Hier wordt instemmend op gereageerd maar helaas is de inzamelefficientie in NL nog niet goed genoeg in grote steden en daarom wordt er naar alternatieven gekeken. Dit is ook een van de redenene waarom de vermaler bij SUPERLOCAL in beeld is gekomen. In conventionele situatie zouden de voedselresten met het restafval worden afgevoerd en worden verbrand.

Break-out sessies

SuperLOCAL in Kerkrade – Paul Telkamp (Tauw)
Het project gaat om herstructurering van 130 woningen, waarbij hemelwater gebruikt gaat worden als drinkwater. Er worden vacuüm toiletten geïnstalleerd om hergebruik van nutriënten te stimuleren. Dit wordt gecombineerd met een vergister. Ook hoort er een monitoringsprogramma bij, waarbij wordt gekeken naar de technische werking, de robuustheid en betrouwbaarheid. De meetcampagne duurt 3 jaar.

De intentie is om de herwonnen producten uit de vergister te gebruiken voor een andere, waarschijnlijk niet-voedsel gerelateerde) toepassing. Mogelijk is extra onderzoek door middel van potproeven hiervoor nodig. Het grijze water wordt behandeld met een helofytenflter en geloodst op het oppervlaktewater. Er wordt ook gekeken naar hoe het water hergebruikt kan worden, zo wordt een deel al bij de wasserette hergebruikt.

De schaal van Kerkrade is klein, pas vanaf 500-1000 woningen wordt het echt rendabel.

De huidige stroom is erg waterig en te laag in concentratie van meststoffen, daarnaast is de wens vaak om alleen N, P, K meststoffen te maken. In Zweden wordt zwart water en keukenafval apart ingezameld waarna er N-P-K pakkets van worden gemaakt.

Voor toepassing moet naast concentratie ook werkbaarheid worden bekeken. Mogelijk is het product te vergelijken met verdunde drijfmest en kan dit via dezelfde apparatuur gebruikt worden.

De verwachting is dat de meststoffen in vergelijking met mest te kostbaar zijn en dat dit principe in het buitenland meer potentie heeft.

Urban Tree Village and Urban Food Tower – Naleye Buddista (initiatiefnemer) en Kimo van Dijk (Wageningen University & Research)
Een aantal punten uit de break-out sessie van de toekomstige case in Amsterdam:

- Gebouw zet je maar 1 keer neer, er is dus maximale duurzame invulling en goede voorbereiding nodig.
- Routines doorbreken is lastig. Maar als iemand een nieuw huis koopt, dan kan een volledig pakket van nieuwe sanitatie goed ingepast worden.
- In het kip-ei dilemma rondom vraag en aanbod naar gerecyclede nutriënten is in de transitie de vraagzijde het allerbelangrijkst. De vraag moet helder zijn om te kunnen afzetten. Is er geen concrete vraag, dan moet die helder worden of gecreëerd worden.
- Misschien makkelijker om eerste bij de vraag te kijken aan de niet-voedsel kant, zodat blokkades minder een rol spelen: kantoorgroen / sierteelt / bollenteelt / parken / sportvelden etc. Als het concept dan getest is ook naar voedselproductie.
- Decentraal verwerken van afvalwater kan met een living machine, voorbeeld bij monnikenklooster De koningshoeve, Brabant.
- Ook bestaande partijen zoals waterschappen (Waternet) dienen betrokken te raken bij nieuwe sanitatie, er lijkt veelal interesse.
- Afvalstoffen: contaminanten moeten opgelost worden, struvietroute is mogelijk.
- Composttoiletten waren niet in trek bij het project op de Ceuvel in Amsterdam. Het moet wel aantrekkelijk gemaakt worden.
- Er is ervaring bij Nieuwegein voor het doorlopen van nieuw type trajecten voor vergunningen, ook voor Nieuwe Sanitatie?

- Er lijken zeker wat informele kleinschalige initiatieven te zijn van nutriëntenkringlopen sluiten, inclusief nieuwe sanitatie en (stads)landbouw. Er is veel interesse om gewoon aan de slag te gaan. Wel veilig, maar niet perse juridisch afgekaart/ingebed.

- Bij verschillende stakeholders is er behoefte aan duidelijkheid in beleid voor veilig hergebruik van menselijke stromen en nutriënten. Pas als die duidelijkheid er komt kan nieuwe sanitatie (met stadslandbouw) een vlucht nemen.

Stad Nieuwegein – Marco van de Hedel (Gemeente Nieuwegein)
In de break-out sessie ontstond een interessante discussie rond de governance.

Traditioneel zitten voedsel, waterleveranciers, waterzuivering e.d. bij gevestigde partijen die ook een hoog kennisniveau vertegenwoordigen en kwaliteits- en kostengaranties kunnen geven. De vraag is hoe dit ligt bij kleinere eenheden zoals een woonwijk of community. Wie draagt hierin de verantwoordelijkheid, wat wie zou de verantwoordelijkheid dragen als het op gemeenschapsniveau wordt geregeld? Kan dit echt losgeknipt worden van het huidige systeem? Het gaat om milieu en gezondheid. Een tussen variant zou kunnen dat de gevestigde partijen het beheer op zich nemen, maar de vraag is in hoeverre zij dat willen. Hier ligt nog een uitdaging.

Het tweede punt ging over het duurzaamheidsniveau wat men bereikt door op wijkniveau te recyclen in combinatie met stadslandbouw, in vergelijking met de ''nul-situatie'' (met efficiënte reguliere voorzieningen) en of dit opweegt tegen alle inspanningen en mogelijk extra kosten (het toets Duurzaamheidskader. Zo zou er bespaard kunnen worden als er geen rioolaansluiting nodig is en de RWZI niet vergroot zou hoeven te worden. En dan komt men op een systeemvraag: moeten we het huidige systeem wel of niet vasthouden?

Andere relevante vragen die dan gaan spelen zijn: hoeveel is biodiversiteit waard, moeten alle stakeholders erop vooruitgaan, wat is essentieel en wat is een nice to add? Aangezien bij dit soort projecten vaak de voordelen liggen bij andere stakeholders dan de partijen die actie zouden kunnen ondernemen.

Hoewel het geproduceerde water schoon genoeg zou moeten zijn voor gebruik in het gebouw, mag het niet als drinkwater worden gebruikt omdat in Nederland alleen drinkwaterbedrijven drinkwater mogen produceren. Toch is hergebruik van het grijze water zeer gewenst, voor spoeling en voor bijvoorbeeld irrigatie van daken en tuinen. Vitens heeft de ambitie om 5% water te besparen per jaar en dat kan door dit soort initiatieven.

Links die zijn gedeeld:
- PPS project Kringloopsluiting Cleantech Playground Amsterdamhttps://www.tkiwatertechnologie.nl/projecten/kringloopsluiting-cleantech-playground-amsterdam
- Lokaal gebruik van producten uit afvalwater in Berlijn: https://www.bwb.de/de/berliner-pflanze.php
- De crowdfunding actie en de trailer van Broodje Poep voor hun documentaire Let's talk about shit! https://www.broodjepoep.com/let-s-talk-about-shit

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