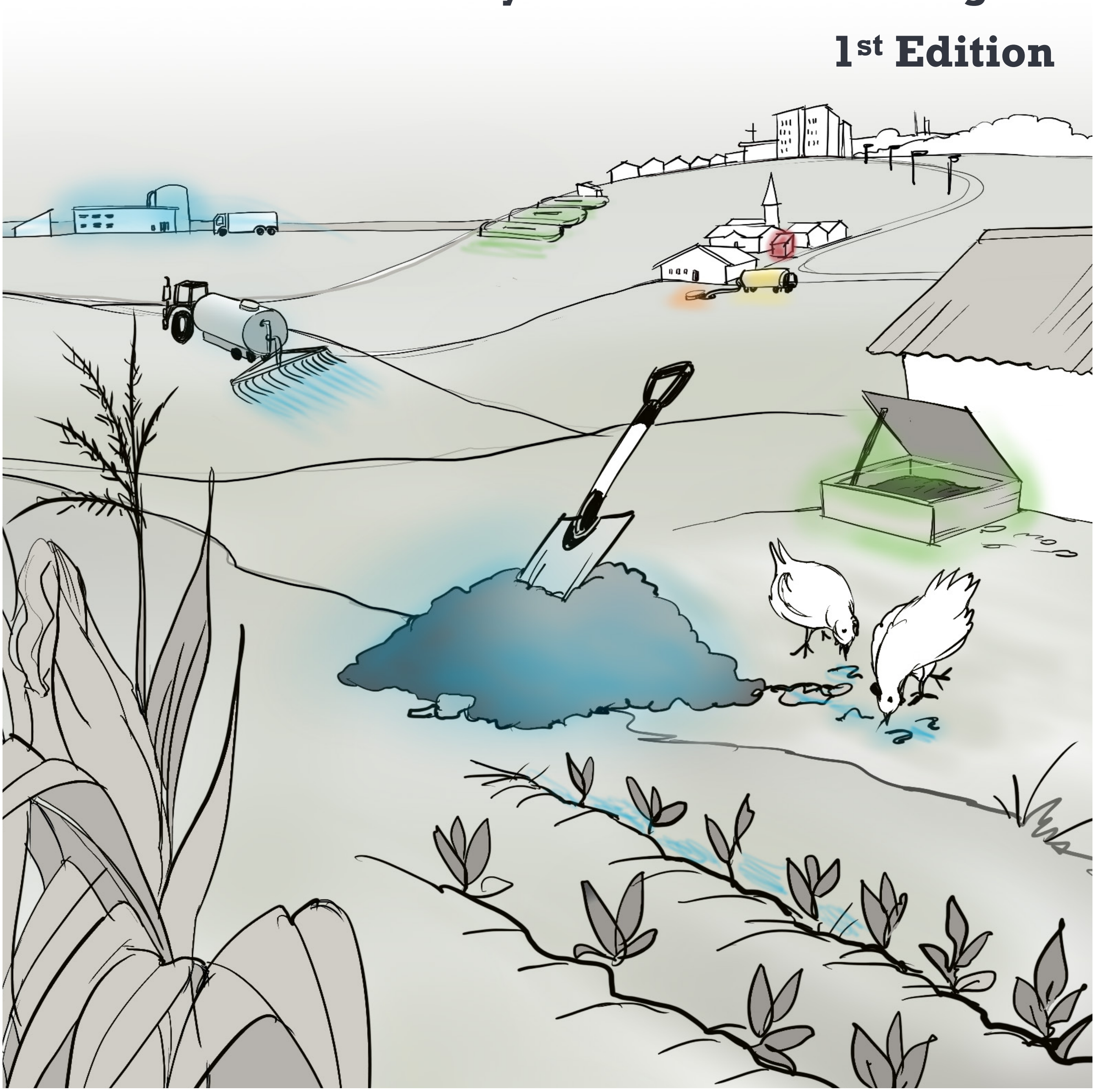
# Guide to Sanitation Resource Recovery Products & Technologies

## A supplement to the Compendium of Sanitation Systems and Technologies

1st Edition



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# Guide to Sanitation Resource Recovery Products & Technologies

## A supplement to the Compendium of Sanitation Systems and Technologies

**Jennifer McConville, Charles Niwagaba, Annika Nordin, Marcus Ahlström, Vivian Namboozo and Mark Kiffe**

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# Introduction

## Background

The world is currently undergoing a paradigm shift towards a circular society in which resources are recovered and reused rather than discarded. The global population has surpassed seven billion people, and rapid urbanisation in many areas is putting a significant strain on our ability to provide basic services to all. The Sustainable Development Goals highlight the fact that millions still lack access to food, healthcare, water and sanitation. At the same time, it is increasingly evident that we are consuming the Earth's resources and releasing waste into the environment in an unsustainable manner. The resulting effects on climate change, biodiversity loss and changing nutrient cycles threaten to over-step critical planetary boundaries. Crossing these boundaries has the potential to cause irreversible environmental change and to threaten the ability of humanity to develop and thrive. Sanitation systems manage carbon, nutrient and water flows, which are key resource flows that affect the planetary boundaries and thus should be recovered and recirculated instead of being released into the environment. Increasing resource recovery within our sanitation systems can play a critical role in shifting to a more sustainable society.

There are significant resources within excreta and wastewater fractions that can be recovered and turned into useful products. For example, the average person excretes 4.5 kg of nitrogen, 0.5 kg of phosphorus and 1.2 kg of potassium every year. These elements and other micronutrients found in excreta are critical for the fertilising and restoration of agricultural soils. The energy value of faeces is on average 4 115 kcal/kg of dry solids. This energy can be utilised as a renewable energy source. On top of this, there are large volumes of wastewater that can be captured, cleaned and reused. However, human excreta and wastewater contain pathogens and other undesired substances, risks that need to be managed in a reuse system. The growing demand for recycling needs to be complemented with a growing knowledge of how to do it safely.

The aim of this document is to provide an overview of the possibilities for resource recovery from sanitation and provide guidance on treatment processes to achieve safe products for reuse. The focus of this document is on resource recovery from the organic wastes managed in sanitation systems and, to a lesser extent, on the recovery of water and energy generation. Resource recovery sanitation systems are defined as systems that safely recycle excreta and organic waste while minimising the use of non-renewable resources such as water and chemicals. Safe recycling means that waste flows are managed so that physical, microbial and chemical risks are minimised. Thus, the recycled product should not pose any significant health threat or environmental impact when correctly used.

The specific objectives of this document are:

1. To expose the user to a broad range of recovered sanitation products and innovative treatment technologies.
2. To help the user to design functional solutions for resource recovery by illustrating the linkages between sanitation inputs, treatment technology and the recoverable products.
3. To provide an overview of basic information regarding design aspects, operational requirements and health, safety and social considerations related to resource recovery technologies and products.
4. Describe and fairly present technology-specific advantages and disadvantages.

## Target Audience

The Guide to Sanitation Resource Recovery Products and Technologies is primarily a reference book. It is intended to be used by engineers, planners, end-users, researchers, technology developers, sanitation entrepreneurs, non-governmental organisation (NGO) staff and students who are interested in creating circular systems for resource use. It aims to support and enable decision making for increased resource recovery by providing information on key decision criteria for a range of recovered products and treatment technologies, thus highlighting the diversity of options available for resource recovery.

This publication should be seen as a starting point to access relevant information for the design of suitable resource recovery systems for sanitation solutions. It is not meant as a stand-alone document to provide a final decision or as an implementation guide for specific technologies. Users are also directed to additional information through further references in this document. It should be noted that this document is based on the current state of the technology and knowledge within a sector that is rapidly expanding. Readers are encouraged to look for the latest publications related to reuse products and technologies of interest.

## Linkage to the Eawag Compendium of Sanitation Systems and Technologies

This document is designed as a supplement to the Eawag ***Compendium of Sanitation Systems and Technologies***[1], which from here on out will be referred to as the Eawag Compendium. The Eawag Compendium highlights different technologies along the sanitation service chain in five functional groups: the User Interface (toilet), On-Site Storage and Treatment, Conveyance, (Semi-) Centralized Treatment and Use and/or Disposal. It offers a collection of technology information sheets for different options along the entire service chain, as well as system templates for how the various technologies can be put together to form a complete system. While the Eawag Compendium does include information sheets for technologies that are designed for the reuse of sanitation products (e.g., application of compost), it provides little information on the characteristics of reusable products or on how resource recovery in technologies actually might be best implemented.

Therefore, the Guide to Sanitation Resource Recovery Products and Technologies focuses on reuse products that can be made from excreta and wastewater fractions and on the technologies that can produce these products. This document provides additional technology information sheets for technologies in the functional groups for Reuse and Treatment that are not in the original Eawag Compendium. It includes both well-established technologies and recent innovations. In contrast to the Eawag Compendium, which refers to the end of the service chain as functional group D **Use and/or Disposal**, we refer to this step as R **Reuse**. In order to avoid confusion with the reference numbers in the Eawag Compendium, this document starts numbering of the T **Treatment Technologies** from T.20. The information sheets in this document are structured in a similar way to those in the Eawag Compendium so that the Reuse and Treatment Technologies included in this document can easily be used in the system templates and planning tools that are referenced in the Eawag Compendium. We use the same color-coding system as the Eawag Compendium for the functional groups.

## Structure and Use of the Guide

This document consists of three major sections. The first two focus on functional groups in the sanitation system, Part 1-Reuse Products and Part 2-Treatment Technologies for resource recovery. The final section, Part 3, presents a number of important cross-cutting issues that can be relevant for any resource recovery sanitation system. An overview of the Reuse and Treatment technologies included is presented at the beginning of each section. The overview also clusters the technologies into different

1. Tilley, E., Ulrich, L., Lüthi, C., Reymond, Ph., Schertenleib, R. & Zurbrügg, C. (2014). Compendium of Sanitation Systems and Technologies. 2nd Revised Edition. Swiss Federal Institute of Aquatic Science and Technology (Eawag). Dübendorf, Switzerland.

groups depending on the type of reuse product, e.g., fertiliser or biomass, or on the type of treatment process, e.g., chemical or biological. The information sheets that follow are 2-page summaries that provide an overview of the basic characteristics, design aspects, operational requirements and health, safety and social considerations. Each information sheet also provides an overview of the advantages and disadvantages of the technologies. Lists of references for each technology are listed in the end of the document.

# Terminology

Human excreta and wastewater are often referred to as wastes. However, in order to enable the concept of a circular economy in sanitation, we prefer to call them resource flows. These resource flows normally consist of human excreta mixed with used water and other organic matter, as well as anal cleansing material that ends up in mixed wastewater or faecal sludge (Figure 1). The Eawag Compendium refers to all flow fractions as products. In order to avoid confusion with the safely recovered Reuse Products that are created through proper management in the sanitation service, this document refers to incoming resource flows as inputs, to partially treated resources as intermediary flows and to final outputs from the sanitation system as Reuse Products or other outputs.

This document focuses on the sanitation outputs that can be safely reused. These reuse products are general fertilisers, soil conditioners, biomass, water or energy. In this document, we define a fertiliser as any material of natural or synthetic origin that is applied to soil to supply one or more of the essential nutrients needed for plants to grow. Thus, fertilisers directly affect plant growth by improving the supply of nutrients in the soil. Soil conditioners, on the other hand, improve the soil's physical condition (e.g., soil structure, water infiltration), thus indirectly affecting plant growth. Further details of these differences can be found in the cross-cutting section on fertilising with reuse products (X.3).

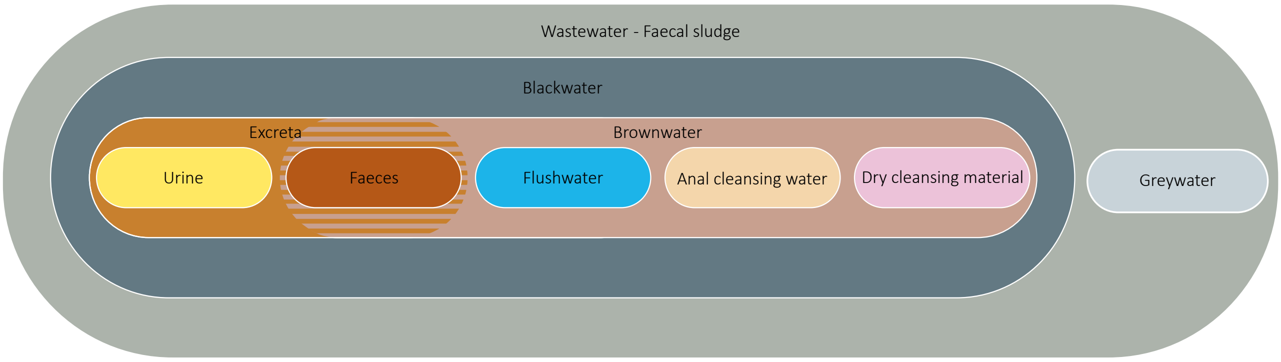



***Figure 1:** Possible inputs into the sanitation service chain. Note that several treatment processes can also incorporate other organic wastes (e.g., food waste, animal manure, organic fractions from industrial processes).*

### *Input resource flows*

**Urine** is the liquid produced by the body to rid itself of urea and other wastes. In this context, urine refers to pure urine that is not mixed with faeces or water. Depending on diet, human urine collected from one person during one year (approximately 300 to 550 L) contains on average approximately 3 to 4 kg of nitrogen (N), 0.3 kg of phosphorus (P) and 0.7 kg of potassium (K)[2]. Few pathogens are excreted in urine; however, urine is likely to be contaminated with faeces in urine-diverting sanitation systems.

**Faeces** refers to (semi-solid) excrement that is not mixed with urine or water. Depending on diet, each person produces approximately 50 L per year of faeces. Fresh faeces contain 70 to 80% water. Of the total nutrients excreted, the faeces from one person excreted over one year contains on average about 0.6 kg of N, 0.2 kg of P and 0.3 kg of K[2] . Faeces can potentially contain a large number of pathogens.

**Excreta** consist of urine and faeces that are not mixed with any flushwater. Excreta are small

2. Rose, C., Parker, A., Jefferson, B., & Cartmell, E. (2015). The Characterization of Feces and Urine: A Review of the Literature to Inform Advanced Treatment Technology. Crit. Rev. Environ. Sci. Technol. 45, 1827–1879. DOI: 10.1080/10643389.2014.1000761

in volume but concentrated in both nutrients and pathogens. Depending on the quality of the faeces, it has a soft or runny consistency. Excreta are a sum of urine and faeces, and therefore, their quantity is a summation of the above, generally translating to roughly 350 to 600 L per person per year.

**Dry cleansing materials** are solid materials used to cleanse oneself after defaecating and/or urinating (e.g., paper, leaves, corncobs, rags or stones). Sanitation systems are often designed to manage inputs of toilet paper and thin organic material like leaves; however, denser/harder materials should be collected and disposed of as solid waste.

**Menstrual hygiene products** include blood from menstruation and hygiene products like sanitary napkins and tampons. On average, a woman loses 40 ml of blood during her period, amounting to 0.5 L per menstruating women per year. Some of this may be absorbed by menstrual hygiene products, but it may also be deposited in the toilet. Menstrual blood contains both blood and vaginal fluids that may be treated safely with the excreta. While menstrual blood is not likely to contain intestinal pathogens, it may contain blood-borne infectious pathogens like human immunodeficiency virus (HIV) and hepatitis B and C viruses. Although extremely important and often deposited in toilets, menstrual hygiene products are not included in this document. In general (although not always), they should be treated along with the solid waste generated in the household.

**Anal cleansing water** is water used to cleanse oneself after defaecating and/or urinating. It is generated by those who use water, rather than dry material, for anal cleansing. The volume of water used per cleaning typically ranges from 0.5 L to 3 L.

**Flushwater** is the water discharged into the User Interface to transport human excreta and anal cleansing material and/or clean the user interface. Freshwater, stormwater, recycled greywater or any combination of the three can be used as a flushwater source. The volume of flushwater used depends on the toilet but generally ranges from 2 to 15 L per flush.

**Brownwater** is the mixture of faeces and flushwater and does not contain urine. It is generated by urine-diverting flush toilets, and therefore, the volume depends on the volume of the flushwater used. The pathogen and nutrient load of faeces is not reduced, only diluted, by the flushwater. Brownwater may also include anal cleansing water (if water is used for cleansing) and/or dry cleansing materials.

**Blackwater** is the mixture of urine, faeces and flushwater along with anal cleansing water (if water is used for cleansing) and/or dry cleansing materials. Blackwater contains the pathogens of faeces and the nutrients of urine and faeces that are diluted in the flushwater.

**Greywater** is the total volume of water generated from washing food, clothes and dishware, as well as water from bathing and showering, but it does not include material from toilets. It may contain traces of excreta (e.g., from washing diapers) and therefore also pathogens. Pathogens may also originate from food. Greywater accounts for approximately 65% of the wastewater produced in households with flush toilets. Volumes of greywater entering the sanitation system from households with on-site sanitation can vary depending on whether or not the greywater disposal is connected to the toilet.

**Wastewater** is typically defined as the mixture of excreta and all used water, e.g., excreta, flushwater, cleansing materials and greywater, collected through a sewer network. It contains the pathogens of faeces and the nutrients of urine, diluted with large volumes of water from the greywater. Wastewater from multiple sources, including domestic and industrial buildings, is generally collected together. In some cases, wastewater is mixed with stormwater during transport to the treatment plant.

**Faecal sludge** is broadly defined as what accumulates in on-site sanitation technologies and is not transported through a sewer. It is composed of excreta and anything else that goes into an on-site containment, e.g., flushwater, cleansing materials, menstrual hygiene products and greywater. It can also contain solid waste. In an urban context, faecal sludge is generated from a variety of residential, industrial and public spaces, including households, schools, restaurants, office building and factories. For a more detailed characterisation of faecal sludge, refer to Strande et al. (2014)[3] and Velkushanova et al. (2020)[4] .

**Organics** refer to biodegradable plant material (organic waste) that can be added to some technologies (e.g., composting chambers) in order for them to function properly. Organic degradable material can include, but is not limited to, leaves, grass, ash and market waste. Although other inputs in this document contain organic matter, the term "organics" refers to undigested plant material.

**Stormwater** is the general term for the water that is collected from rainfall run-off from roofs, roads and other impermeable surfaces. It is the portion of rainfall that does not infiltrate into the soil. The quality of the stormwater depends on the surface that the run-off is collected from, but it generally contains insignificant amounts of nutrients and low levels of pathogens. The quality is influenced by the level of unimproved sanitation systems or practice of open defaecation in the area.

***Intermediary resource flows***

**Sludge** is a semi-solid slurry that is produced in a variety of technologies along the sanitation service chain (Figure 2). Due to large variations in how the sludge is produced, its chemical composition can be highly variable. Depending where it is captured in the service chain, it can include raw or digested excreta in combination with sand, grit and other materials that may have entered the sanitation system.

**Reject water** is used as a blanket term to describe the water streams that are generated as by-products from both mechanical dewatering of sludge and the use of membrane filters. As such, reject water composition varies but it can generally be said to be a highly concentrated stream that is rich in nitrogen and phosphorus, although not yet safe for reuse.

3. Strande, L., Ronteltap, M., & Brdjanovic, D. (2014). Faecal Sludge Management. Systems Approach for Implementation and Operation. IWA Publishing, London, UK.

4. Velkushanova, K., Strande, L., Ronteltap, M., Koottatep, T., Brdjanovic. D., & Buckley, C. (eds.) (2020). Methods for Faecal Sludge Analysis, IWA publication..

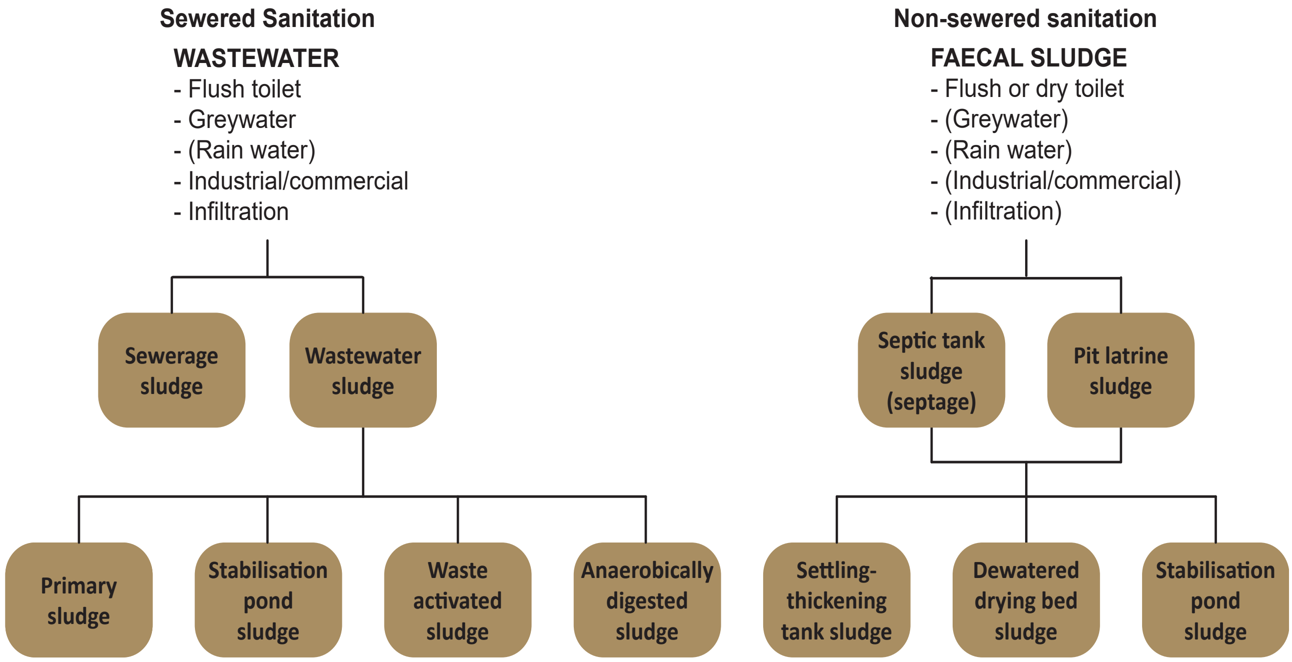



***Figure 2:*** *Examples of terminology used for different types of sludge relating from sanitation systems. (Adapted from Englund and Strande, 2019)*[5].

5. Englund M. & Strande L. (eds.) (2019). Faecal Sludge Management: Highlights and Exercises. ISBN 978-3-906484-70-9, Eawag: Swiss Federal Institute of Aquatic Science and Technology

# Reading the Information Sheets

## Reuse Product Information Sheets

The Reuse Product information sheets give a general overview of the reuse products that, according to the current state of the art, can be recovered from sanitation systems. All information in the Reuse product sheets is limited to use of the product after production and post-processing activities, e.g., after the treatment step. However, this distinction is not clear-cut on occasions when the reuse product can be recycled back into treatment processes, e.g., worms within vermicomposting or biochar in filters. It is also important to note that reuse products can sometimes be used in multiple ways, e.g., algae as a biofuel or an animal feed. The information sheets may present multiple options for reuse; however, the focus of the text is often on the most widely applied usage.

These sheets are limited to the current state of knowledge regarding the technology that is used to produce the reuse products, although with advancements from ongoing research and up-scaling, many of these products will become significantly more cost-efficient to produce, particularly for the technologies with low and medium technical maturity levels.

Note that it is possible to recover water and generate electricity and heat from several of the treatment technologies that are shown in this document. However, since the use of these products is deemed to be of common knowledge, specific information sheets for the general reuse of water and generation of energy have not been included. Nevertheless, they are reported as possible reuse products in the treatmtechnology sheets when it is possible to recover or generate these resources.

***How to read the heading table of a Reuse Product information sheet***

| R.11 | Compost | | |
|---|---|---|---|
| | **Intended use:**<br>Soil conditioner, Solid fertiliser<br><br>**Technical maturity:**<br>High | **Application level:**<br>** Household<br>* City<br>* Regional<br>Global | **Treatment technologies:**<br>T.20 Vermicomposting and Vermifiltration, T.21 Black Soldier Fly Composting, (T.16 Co-composting, S.8 Composting Chamber) |

### Intended use

This segment suggests different applications where the use of the product, based on its composition and physical characteristics, is appropriate.

### Technical maturity

Technical maturity is an indication of how well-established use of the product is. Technical maturity is ranked as low, medium or high. Low technical maturity indicates that the reuse concept has been applied in pilot projects. Medium technical maturity indicates that the reuse practice is emerging and has been demonstrated in one or more different contexts. High technical maturity indicates that the reuse practice is established and operational in one or more contexts.

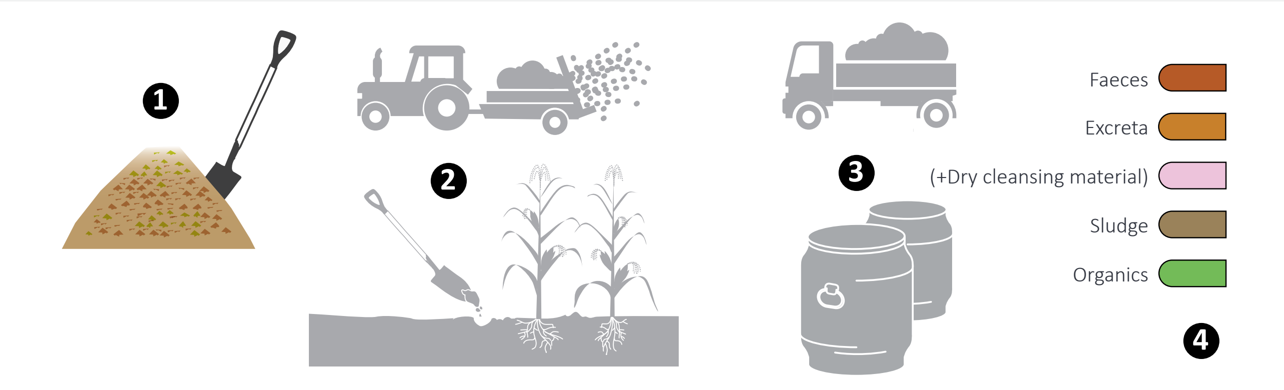
## Application level

This segment defines the spatial scale where the Reuse Product can be utilised. The decision on the number of asterisk symbols was guided by current state of technology, constraints relating to requirements and complexity and with reasonable judgement on its projected use (no asterisk = not suitable, * = less suitable, ** = suitable). Household implies that the product can be used on-site by individual households and/or businesses. City implies that the product is used in decentralised areas within the urban context where it is produced, e.g., in urban farming. Regional implies that the product can be transported and used within the region surrounding the production site, often in larger-scale farming or industrial uses. Global implies that the product can be transported internationally and applied in contexts geographically distant from the point of production.

## Treatment Technologies

This segment presents the different Treatment Technologies that can be applied to produce the reuse product. The treatment technologies shown without parentheses are the technologies that are included and described in this document. The technologies in parentheses are technologies that are described in the Eawag Compendium of Sawnitation Systems and Technologies and are not included in this document. In some case, technologies for user interfaces and collection and storage are referred to in this section when the Reuse Products can be collected directly from these technologies.

### *How to read the figure on a Reuse Product information sheet*




The figures reads from left to right, starting with **(1)** a symbol showing type of product (e.g., liquid, solid, biomass, energy), **(2)** how it is applied/used, **(3)** how it may be contained when reaching the user and **(4)** possible inputs used to produce the product, e.g., information regarding its origin and composition. The inputs shown without parentheses are the typical inputs to that product. For some Reuse Products, these inputs represent possible alternatives, of which not all are necessary. Inputs in parentheses with a plus (+) are additional (optional) inputs that may or may not be used or occur depending on the design or use context. Optional inputs marked this way are generally included in addition to the standard inputs without parentheses.

### *How to read the text of a Reuse Product information sheet:*

## Characteristics

This section presents aspects such as energy content, composition, nutrient content and state of matter (solid, liquid or gas) of the product. However, this section may be integrated within the description for certain reuse products.

## Health and safety considerations

The health and safety concerns illustrated in this section include hazards that may be encountered during product application and use. Where available, hazard mitigation measures are also presented.

### Social considerations

This section is informed from studies relating to the social acceptability of the product and any relevant legal/region-specific limitations. Where available, interventions to increase acceptability are also presented.

### Distribution to market

This section reports on the current mechanism of reuse product distribution and suggests possible product specific market strategies. Where applicable, it also includes reference to existing relevant businesses commercialising the reuse product. Further reading regarding potential business models, regulations and policy implications are included in the section on cross-cutting issues at the end of the document.

## Treatment Technology Information Sheets

The technology information sheets provide an overview on selected technologies for the production of Reuse Products and the most appropriate/widely accepted design of the technology. The sheets provide a basis for a quick introduction and are useful in rapid decision making and technology comparison. They are not sufficient to design the detailed implementation of the technology and its integration into an entire sanitation system. These sheets are limited with the current state of the technology, although with advancements from ongoing research and up-scaling these technologies and reuse products will be significantly more efficient. References are provided for further reading.

***How to read the heading table of a treatment Technology information sheet:***

**T.20 Vermicomposting and Vermifiltration**

| Inputs: | Reuse: | Application level: | Management level: |
|---|---|---|---|
| Excreta, Blackwater, Sludge, Organics | R.18 Worms, R.11 Compost, (R.19 Irrigation water) | * Household<br>** Neighbourhood<br>** City | * Household<br>* Shared<br>** Public |
| | | **Technical maturity:** High | **Complexity:** Medium |

### Inputs

This segment lists suitable flow fractions that can be used as inputs to the treatment technology. The inputs shown without parentheses are the inputs that will typically go into a technology. For some technologies, these inputs represent possible alternatives, of which not all are necessary. Inputs in parentheses with a plus (+) are additional (optional) inputs that may or may not be used or occur depending on the design or use context. Optional inputs marked this way are generally included in addition to the standard inputs without parentheses.

### Reuse

This segment lists the Reuse Product that can be recovered from applying the technology to treat the suggested inputs. The Reuse Products are numbered to simplify orientation/browsing in the document. Products in parentheses can be recovered, but are not the primary focus of the resource recovery technology.

**Application level**

The applicability level encompasses the appropriateness of the technology for different scales of usage. It is based on consideration of space requirements per capita served and on the characteristics of the waste streams that can be treated. Application level of the technology is guided by its intrinsic criteria (e.g., current state of technology, technical complexity, hydraulic retention times and operations), regardless of cost implications (no asterisk = not suitable, * = less suitable, ** = suitable). Household implies that the technology is appropriate to use for one or several households, i.e., serving <10 person equivalents (pe). Neighbourhood means that the technology is appropriate to use for anywhere between several and several hundred households, i.e. 10 to 1 000 pe. City implies that the technology is appropriate at a citywide level, either as one unit for the whole city or as many units for different parts of the city, i.e. >1 000 pe.

**Management level**

This segment describes the appropriateness of the technology to be effectively and efficiently managed with minimal difficulty. It is closely informed by the technical complexity of operations, design and expected responsibilities. The level indicated by the number of asterisks may dictate the need to offset these responsibilities to higher management levels or to private entities (no asterisk = not suitable, * = less suitable, ** = suitable). Household implies that the household (e.g., the family) is responsible for all operations and maintenance (O&M). Shared means that a group of users (e.g., a school, a community-based organisation or market vendors) handles the O&M by ensuring that a person or a committee is responsible for them on behalf of all users. Shared facilities are defined by the fact that the community of users decides who is allowed to use the facility and what their responsibilities are. Public implies institutional or government-run facilities, and all O&M are conducted by the agency operating the facility. Usually, only users who can pay for the service are permitted to use public facilities

**Technical maturity**

Technical maturity is an indication of how well established the technology it. A common reference would be the technology readiness level (TRL). Technical maturity is ranked as low, medium or high. Low technical maturity indicates that the technology has been applied in pilot projects, i.e., TRL 5. Note that technologies with a TRL lower than pilot scale were not included in this document. Medium technical maturity indicates that the technology is emerging and has been demonstrated in one or more different contexts, i.e., TRL 6 to 8. High technical maturity indicates that the technology is established and operational in one or more contexts, i.e., TRL 9.

**Complexity**

This segment describes the technical complexity of designing, operating and maintaining adequate function of the technology in terms of low, medium or high complexity. This relates the amount of technically complicated O&M tasks and the level of specialisation/training that is demanded from the operator. Technologies with low complexity demand basic manual labour to function as intended, which can generally be fulfilled by, e.g., a homeowner. Medium complexity requires skills from a craftsman or technician. High-complexity technologies demand specialised knowledge about chemical and/or biological processes, e.g., generally require engineering skills.

**Technical illustration of the technology**

The illustration shows principle features that are usually present in the technology. Note that configurations in real life may vary depending on, e.g., scale of application, location, inputs being treated and technology advancement.

***How to read the text of a Technology information sheet:***

**Design considerations**

This section presents a qualitative overview of the most widely used designs with particular focus on the important design parameters.

**Applicability**

The applicability section encompasses the appropriateness of the technology, putting into consideration (wherever appropriate) geographical suitability and the character of the waste streams that can be treated.

**Health and safety**

The considerations in this section include concerns during ordinary operations of the technology. This section also includes hazards that may arise directly from the reuse products immediately during processing and handling. In some cases, remedies to certain common risk events are also cited.

**Operations and maintenance**

This section describes the key operational activities that ensure efficient technology function. It also highlights the expected maintenance events during the design life of the technology.

**Social considerations**

This section is informed by studies relating to the social acceptability of the technology and any relevant legal/region-specific restrictions.

**Cost considerations**

This section covers the expected costs of installation and operations in order to exemplify the level of monetary investment. The quoted values are informed by literature on similar installations, although adequate care should be taken concerning the variability arising from scale, design, location, exchange rates, time relevance and availability/and or non-availability of local technical competence for design, construction, repairs and general maintenance.

# Part 1: Reuse Products

This section presents different reuse products that can be recovered from sanitation and wastewater systems. The reuse products highlighted here should be recovered in a safe manner so that risks are minimised, referring to the cross-cutting section on health and safety guidelines (X.1), and they do not pose any significant health or environmental threat when correctly used. The focus of this document is on the potential to recover plant nutrients and organic matter. This document makes the distinction between fertilisers and soil conditioners. A fertiliser is any material of natural or synthetic origin that is applied to soil mainly to supply one or more of the essential nutrients needed for plants to grow. Soil conditioners, on the other hand, mainly improve the soil's physical condition (e.g., soil structure and water infiltration), thus indirectly affecting plant growth.

On addition, water can also be recovered and energy generated. Due to the diversity of potential uses for recovered water, few water recovery products are included here, but many of the aspects highlighted in the 'Irrigation Water' and 'Aquaculture' sections may be similar for other water uses. In all cases, the use of recovered water should meet appropriate quality standards recommended for that use, e.g., drinking water standards should be met for direct potable use. Similarly, energy generation from sanitation systems includes a variety of energy forms, e.g., electricity, heat, biogas/methane, bioenergy feedstock and hydrogen gas. The generation of energy from sanitation products in the form of, e.g., electricity and heat have not been described in reuse product sheets, since the use of these energy forms is deemed common knowledge. However, production of these energy forms from sanitation technologies is less well known, so the potential to produce energy is referred to in the guide as possible reuse products from treatment technologies, even when actual reuse of the energy is not included as its own information sheet.

The choice of product to produce is contextual and generally depends on the following factors:

- Type, quality and costs of input material available
- Socio-cultural acceptance
- Local demands
- Legal aspects
- Availability of materials and equipment
- Availability of space
- Soil and groundwater characteristics
- Local knowledge and capacity

**Liquid Fertilisers**

**R.1** Stored Urine
**R.2** Concentrated Urine
**R.3** Sanitised Blackwater
**R.4** Digestate
**R.5** Nutrient Solutions

**Solid Fertilisers**

**R.6** Dry Urine
**R.7** Struvite

**Soil Conditioners**

**R.8** Dried Faeces
**R.9** Pit humus
**R.10** Dewatered Sludge
**R.11** Compost
**R.12** Ash from Sludge
**R.13** Biochar
**R.14** Nutrient-Enriched Filter material

**Biomass and Proteins**

**R.15** Algae
**R.16** Macrophytes
**R.17** Black Soldier Fly Larvae
**R.18** Worms

**Water**

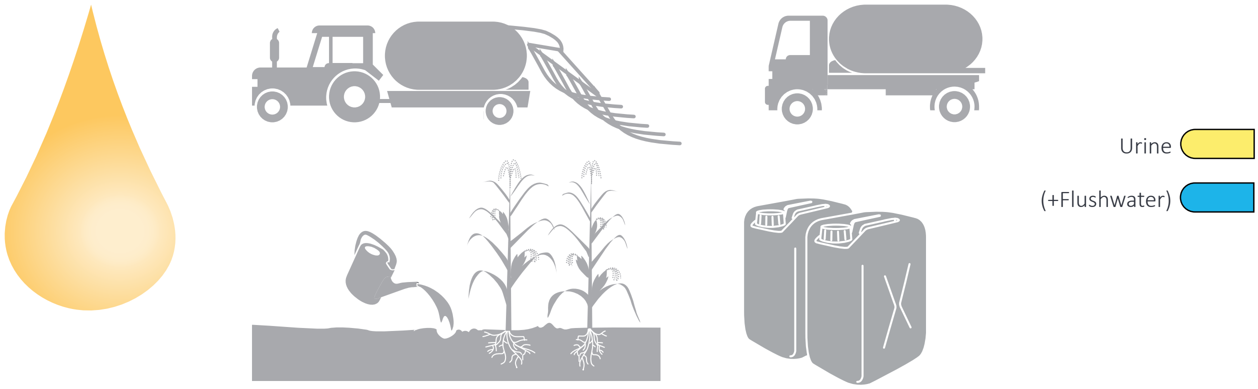
**R.19** Irrigation Water
**R.20** Aquaculture

**Energy**

**R.21** Biogas

# R.1 Stored Urine

| **Intended use:** Liquid fertiliser, Industrial input | **Application level:** | | **Treatment technologies:** |
|---|---|---|---|
| | ** | Household | (U.2 Urine-Diverting Dry Toilet, U.3 Urinal, U.6 Urine-Diverting Flush Toilet, S.1 Urine Storage Tank/Container) |
| | ** | City | |
| | * | Regional | |
| **Technical maturity:** High | | Global | |




***Compiled by:*** *Tilley et al. (2014) and Swedish University of Agricultural Sciences (SLU).*

**Stored urine coming from urine-diverting sanitation systems is a source of nutrients, primarily nitrogen and phosphorus, in their mineralised forms that are directly accessible for plants. It can be applied as a liquid fertiliser in agriculture or as an additive to enrich compost.**

## Characteristics

Urine contains most of the nutrients excreted by the body. Soluble substances in urine include essential plant nutrients such as the macronutrients nitrogen (N), phosphorus (P), potassium (K) and sulphur (S), as well as smaller quantities of micronutrients. Urine is especially beneficial for crops lacking in nitrogen. The nitrogen in urine is in a form readily available to plants, similar to that in ammonia- and urea-based fertilisers, and has comparable results on plant growth. For adults, there is nearly a mass balance between consumption of nutrients and excretion. The nutrient content in urine is thus dependent on diet, and can vary depending on sex, climate, water intake and time of the day when excreted. Roughly 90% of N, 60% of P and 75% of K excreted by the human body will end up in the urine.

## Health and safety considerations

While urine is generally sterile when it leaves the body, cross-contamination with faeces in the toilet means that there can be a significant risk of exposure to pathogens when handling urine during collection and use. The pathogen reduction during storage depends on the time stored and the storage temperature. World Health Organization guidelines recommend that urine in large systems is stored for at least one month before use in agriculture. If the urine is to be applied to food and fodder crops, storage for 1 month at 4°C is recommended, along with incorporation of the urine into the soil. However, if urine is used to fertilise food that will be eaten raw, storage of 6 months at 20°C is recommended.

Urine should be applied close to the ground, thus reducing the possibility of direct contact with the edible parts of plants. As an additional safety measure, urine use could be restricted to non-food crops (e.g., flowers), crops that are processed or cooked before consumption, or crops that allow for a minimum distance between the soil and harvested part of the crop (e.g., fruit trees).

Volatilisation of ammonia from stored urine may pose an occupational health risk if fumes are inhaled. If stored urine is used on a large scale with urine from multiple households/businesses, personal protective equipment such as shoes, gloves and masks is recommended.

### Social considerations

Collection of urine requires the application of source separation technologies that are not conventional sanitation infrastructure and thus may require additional awareness raising and linkages to infrastructure planning for acceptance and development of a system that will collect sufficient volumes of urine for reuse. The potential application of urine in agriculture should be discussed with the affected communities beforehand. Regular training or orientation may be needed in order to support acceptance, ensure proper application and avoid accidental misuse.

Stored urine has a relatively strong odour, and some may find it offensive to work with it or have it nearby. If urine is immediately tilled into the soil, the odour can be reduced. Over time, some minerals in urine will precipitate (especially calcium and magnesium phosphates). Equipment that is used to apply urine may become clogged over time. Most deposits can easily be removed with hot water and a bit of acid (vinegar) or, in more extreme cases, manually chipped off.

### Distribution to market

Urine fertilisation is ideal for rural and peri-urban areas where agricultural lands are close to the point of urine collection. The annual urine volume from one person is sufficient to fertilise around 300–400 $m^2$ of cropland. One can assume that 1 $m^2$ of cropland can receive 1.5 L of urine per growing season (corresponding to 40–110 kg N/ha). Households can use urine on their own plot of land or, if facilities and infrastructure exist, urine can be collected at a semi-centralised location for distribution and transport to agricultural land. The optimal application rate depends on the nitrogen demand and tolerance of the crop and the nitrogen concentration of the urine, as well as the rate of ammonia loss during application.

Stored urine should not be applied directly to plants because its high pH and concentrated form can harm plants. Instead, it can be mixed undiluted into soil before planting; or poured into furrows at a sufficient distance away from the roots of the plants and immediately covered (although this should take place no more than once or twice during the growing season); or diluted several times, whereby it can be frequently used around plants (up to two times weekly).

There is no standard recommendation for dilution, and existing recommendations vary widely, usually between ratios of 1:3 to 1:10, depending on the soil and the type of vegetables. Keep in mind that dilution increases the total volume and thus labour and transport needs. If diluted urine is used in an irrigation system, it is referred to as “fertigation” (see R.19). During the rainy season, urine can be applied directly into small holes near plants, it is then diluted naturally.

Urine application does not need special equipment, and thus additional costs for urine application are low. However, urine application can be labour intensive. If urine needs to be transported over longer distances, transport costs may be considerable and not always economically viable, as urine has a relatively low value per volume. However, urine fertilisation could offer livelihood opportunities, improved yields and the potential to substitute costly chemical fertilisers with a readily available product. Urine should always be stored in a closed container to avoid the loss of nitrogen.

### Advantages (+) and disadvantages (-)

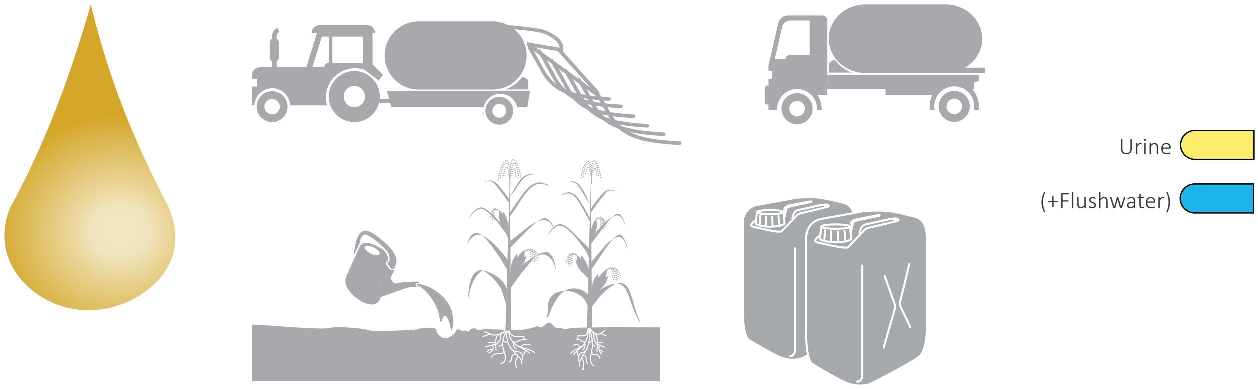
+ May increase income generation by improved yields.
+ Reduces dependence on chemical fertilisers.
+ Low risk of pathogen transmission.
+ Low cost.
- Urine is heavy and difficult to transport, and application is labour intensive.
- Large volumes of urine can be logistically challenging to manage.
- Odour may be offensive.
- Social acceptance may be low in some areas.

### References

References can be found on page 128.

# R.2 Concentrated Urine

| Intended use: | Application level: | Treatment technologies: |
| --- | --- | --- |
| Liquid fertiliser, Industrial input | ** Household<br>** City<br>** Regional<br>* Global | T.24 Nitrification and Distillation of Urine, T.29 Membranes |
| **Technical maturity:**<br>High | | |




***Compiled by:*** *Swedish University of Agricultural Sciences (SLU) and Bastian Etter (Vuna GmbH)*

**Concentrated urine is a nutrient solution obtained by removing water from urine. Water removal is achieved through evaporation, distillation or reverse/forward osmosis of urine. The finished product is between 3 and 7% of the initial volume. In order to ensure that nitrogen is not lost in the process, nitrification or acidification of the urine is done prior to volume reduction. Depending on the pre-treatment process, the majority of the nutrients are retained.**

## Characteristics

Concentrated urine contains the following nutrients: ammonium ($NH_4$), nitrate ($NO_3$), phosphate ($PO_4$), potassium (K), sodium (Na), chloride (Cl), sulphate ($SO_4$), boron (B), calcium (Ca), magnesium (Mg) and zinc (Zn), among others. The nutrients in this liquid fertiliser are in a form readily available to plants, similar to ammonium nitrate-based fertilisers, and with comparable results on plant growth. For fully grown individuals there is nearly a mass balance between consumption of nutrients and excretion. The nutrient content in urine is thus dependent on diet. It may also vary depending on sex, climate, water intake, and time of the day when excreted. Roughly 90% of N, 60% of P and 75% of K excreted by the human body will be captured in the urine.

## Health and safety considerations

Pre-treatment processes, e.g., nitrification and acidification, can remove some pathogens in the concentrated urine. However, the concentration process itself will not remove pathogen nor micropollutants. In order to remove any potential contaminants, the urine concentration process can be followed by activated carbon filtration that will efficiently eliminate pathogens and pharmaceutical residues, thus producing a hygienic and safe fertiliser.

Concentrated urine solutions are thermally and biologically stable. Thus, if properly treated for pathogen removal as described above, it is possible in some countries to certify the product for agricultural use. For example, the concentrated urine product Aurin developed by the Vuna company obtained a full licence covering the use on any crops from the Swiss Federal Office of

Agriculture in 2018.

### Social considerations

Collection of urine requires the application of source separation technologies. With the exception of public urinals for men, urine collection technologies are not commonly used. Thus, collection of urine may require additional awareness raising and linkages to infrastructure planning for acceptance and development of a system that will collect sufficient volumes of urine for reuse. The liquid fertiliser obtained through nitrification and distillation of urine does not smell, thus making it more socially acceptable than stored urine. Studies have found that urine-derived products are relatively well accepted by farmers, although further awareness raising is required for wider acceptance among industry stakeholders and consumers.

### Distribution to market

Depending on where it is produced, concentrated urine can be utilised directly by households or distributed to farmers or fertiliser manufacturing industries. It can be packaged in small volumes for household use or larger jerry cans for agricultural use. At a large scale, this liquid fertiliser requires appropriate equipment for spreading on agricultural fields. Training and capacity building may be necessary for proper dosing and application on agricultural fields.

### Advantages (+) and disadvantages (-)

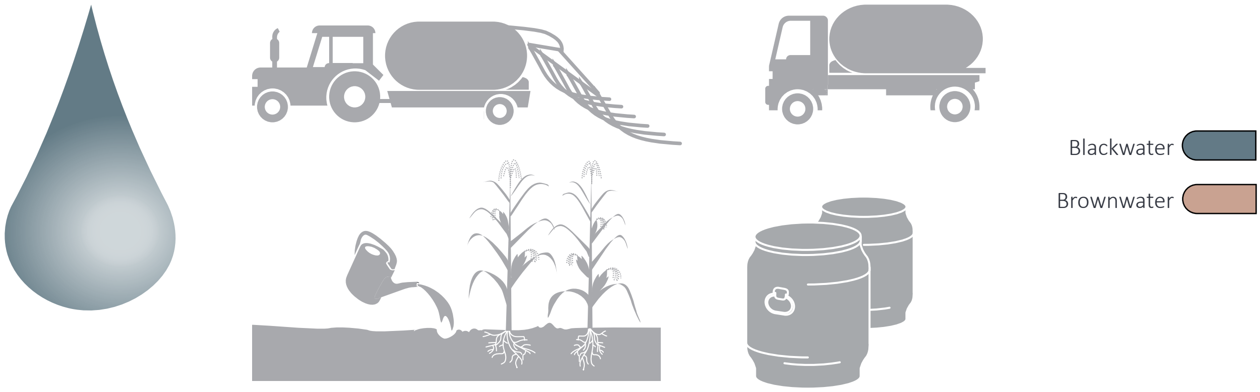
+ It is a complete nutrient recovery product that can be used directly as a fertiliser.
+ Free from pathogens, pharmaceuticals and smell.
+ Reduced volume (as low as 3 to 7% of urine volume) allows for easier transportation.
- Requires specialised equipment for application of liquid fertiliser on fields.
- Production costs for the product are currently quite expensive.

### References

References can be found on page 128.

# R.3 Sanitised Blackwater

| Intended use: | Application level: | Treatment technologies: |
|---|---|---|
| Liquid fertiliser, Agricultural irrigation | ** Household<br>** City<br>** Regional<br>* Global | T.32 Ammonia Sanitisation/Urea Treatment, T.33 Lime Sanitisation |
| **Technical maturity:**<br>High | | |




***Compiled by:*** *Swedish University of Agricultural Sciences (SLU)*

**Sanitised blackwater refers to blackwater that has been treated in order to reduce microbial risks. Since blackwater is toilet waste collected with flushwater, the water content is high. Even with low-flush toilets, the water content is rather high since excreta have a low volume of total solids (TS) (~4%) even without flushwater. Lime treatment can be done by the addition of quick lime (CaO) or slaked lime ($Ca(OH)_2$). Ammonia sanitisation is done by adding urea or aqueous ammonia ($NH_3$) solution to increase the $NH_3$ concentration so that it inactivates pathogens. The addition of urea or ammonia also increases the nitrogen concentration of the blackwater.**

## Characteristics

Depending on the collection and treatment method, sanitised blackwater products differ in characteristics. In general, the solids content before treatment is 2% or less. Adding lime will increase the solids content of the blackwater. With the high water content, the effect of lime is mainly due to the pH increase, and slaked lime is more common in small-scale treatment.

Limed blackwater may have a pH greater than 12, but the alkalinity of the material will decrease over time as it reacts with carbon dioxide in the air to form carbonates. The calcium in the lime may result in phosphorus and magnesium sediments, leading to a separation phase with effluent and settled sludge. The effluent has been reported to reach a neutral pH after one day to two weeks.

Ammonia-sanitised blackwater generally has a pH of around 9 when urea is used for treatment and a pH of 10 if aqueous ammonia solution is used for treatment. If flushwater is kept at a minimum and the blackwater is collected in a closed system, it can be self-sanitising due to the urea coming from the urine. Any ammonia-forming addition will, since the treatment is performed in a closed system, increase the nitrogen content of the blackwater. The increased nitrogen content increases the value of the product as a fertiliser. Common urea additions to blackwater range from 0.5 to 2% by weight, which correlates to a nitrogen concentration increase of 2.5 to 10 kg N/$m^3$. If aqueous ammonia solution is used additions are lower. Particles may precipitate to the bottom of the treatment container, but can be easily resuspended through mixing.

Limed black water gives a liming effect when used on soil, whereas ammonia-sanitised blackwater does not have any permanent liming effect.

### Health and safety considerations

Ammonia treatment also inactivates nematode eggs (e.g., *Ascaris* spp.) if the temperature is at least 20°C and the $NH_3$ concentration is at least 0.7 g/L (see T.32 for treatment details). Lime treatment inactivates bacteria and viruses, but alkaline pH alone has a limited effect on nematode eggs (see T.33 for treatment details). However, if lime treatment is performed in a closed container, the alkaline pH can lead to increased ammonia concentrations, thus resulting in some inactivation of nematode eggs. Thus, sanitised blackwater should be free from pathogens.

Ammonia gas present in the headspace of the treatment container containing lime- or ammonia-treated material may pose an occupational health risk if a user, e.g., a farmer, inhales fumes. If the limed black water still has a high pH, precautions should be taken to protect skin and eyes.

### Social considerations

Collection of blackwater requires the application of source separation technologies, either through a special sewer or a collection system specifically for only domestic sources. Often such specific separate collection systems are not currently practiced, and thus it may require additional awareness raising and dialogue with sanitation actors to establish them. In addition, reuse products originating from excreta may not be fully accepted by farming communities. The product is rather watery, and ammonia may be the most prominent odour. Documented quality control of the blackwater and/or certified sanitisation may increase acceptance. For blackwater that has been sanitized with the addition of ammonia, e.g., by urea, the increased and predictable nitrogen content should also increase acceptance. Further information on the benefits of stabilised blackwater may be required to achieve its full potential in closing the nutrient loop.

### Distribution to market

The primary use of ammonia-sanitised blackwater is in agriculture as a fertiliser. Liming can result in a nitrogen-rich effluent that can be used for irrigation and a sludge that can be used for its liming effect and for being rich in phosphorus and potassium. The benefits of using limed blackwater on agricultural land depend on soil acidity. Since blackwater is mostly composed of water, there will be large volumes produced that are best utilised in nearby communities in order to reduce transportation costs. It is preferable to incorporate urea/ammonia-treated blackwater into the soil upon fertilisation so that nitrogen losses are kept at minimum.

### Advantages (+) and disadvantages (-)

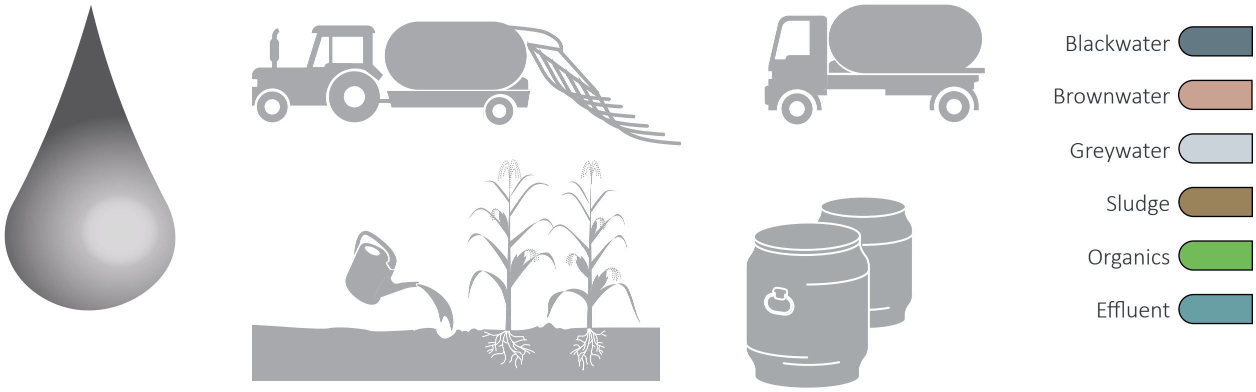
- \+ Production technology is easy to use and implement with readily available materials.
- \+ Nutrient value of ammonia-sanitised blackwater can boost soil fertility.
- \+ The alkaline nature of limed blackwater offers a remedy to acidic soils.
- \+ The stabilisation process prevents the formation of greenhouse gases.
- \- A dilute fertiliser.
- \- This product may not be fully accepted by farming communities.

### References

References can be found on page 128.

# R.4 Digestate

| Intended use: | Application level: | Treatment technologies: |
|---|---|---|
| Liquid fertiliser | * Household<br>** City<br>** Regional<br>* Global | (S.10/T.3 Anaerobic Baffled Reactor ABR, T.11 Upflow Anaerobic Sludge Blanket Reactor UASB, T.17 Biogas Reactor) |
| **Technical maturity:**<br>High | | |




***Compiled by:** Swedish University of Agricultural Sciences (SLU)*

**Digestate is the material remaining after the anaerobic digestion of any feedstock. The feedstock can consist of food waste, agricultural or industrial organic wastes, sludge or wastewater fractions. The digestate discussed in this text is the liquid, non-dewatered digestate from wet fermentation of sludge, possibly mixed with other feedstock(s). Digestate in this form is a mixture of liquid and particles/solids and can also be called "slurry". It is often applied as a fertiliser or soil conditioner in agriculture. To be a soil conditioner, it should contain organic material to increase the soil organic carbon.**

## Characteristics

Digestate quality and composition will differ greatly depending on the source of the substrate (sludge and/or other organic feedstocks) that has been digested. Although the variability is large, digestate generally contains significant amounts of organic carbon, nitrogen, phosphorus and sometimes potassium, which can improve soil quality and provide fertilising effects when applied. Since digestate is produced through an anaerobic process, more nitrogen will remain than in sludge that have been treated using aerobic processes. Depending on the sources of the feedstock, the resulting digestate may contains contaminants, such as heavy metals and pharmaceutical residues (which are present in excreta) and microplastics that primarily come from greywater sources. Digestate derived from domestic sources will generally contain less contaminants than that from industrial wastewater sludge or faecal sludge, although any contaminants present in excreta (i.e., heavy metals and pharmaceutical residues) will also be present in digestate derived from domestic sources. Significant amounts of faecal pathogens may be present in digestate, which necessitate treatment for pathogen reduction prior to application.

## Health and safety considerations

The hygienic quality of the digestate will depend on the substrate and the digestion method used, with the main parameters being treatment temperature and hydraulic retention time, which both affect the pathogen inactivation. Of the treatment technologies listed in the heading, the anaerobic baffled reactor (ABR) is used at ambient temperature, and helminth eggs such as those of *Ascaris* spp. may remain after treatment. The UASB and Biogas reactor can be operated at meso- and thermophilic temperatures that give better pathogen inactivation. However, they require heating and a more technically complex reactor. Read specific treatment technologies information sheets for more details. The World Health Organization (WHO) Guidelines for the Safe Use of Wastewater, Excreta and Greywater should be consulted regarding the security measures needed to protect public and environmental health. Workers should wear personal protective equipment (e.g., clothing, boots and masks).

Depending on the substrate, the digestate may contain high levels of heavy metals or other contaminants. Digestate that originates from large-scale wastewater treatment plants is more likely to be contaminated, as it may receive industrial and domestic chemicals, as well as surface water run-off, which can contain organic contaminants and heavy metals. In addition, in areas where sewers are not available, industries discharge into on-site containments that generate faecal sludge, and thus contaminant levels in faecal sludge are generally difficult to know and control. Digestate from only domestic sources can be considered safer with respect to heavy metals, as it is not contaminated by industrial waste. However, monitoring of contaminant levels in digestate and control of sources are recommended.

### Social considerations

While the use of digestate from manure is relatively common, digestate originating from human excreta may not be fully accepted by farming communities. The product is rather watery and has a specific smell that may be considered offensive to some people (although the smell does not differ greatly from that of digested manure). Documented quality control of the digestate and/or certified sanitisation may increase acceptance. Further information on the benefits of digestate may be required to achieve its full potential in closing the nutrient loop.

### Distribution to market

Distribution and sales of digestate can presents a potential business opportunity. Digestate produced and used on a regional scale is a cheap and readily available fertiliser, although transportation to and spreading on farmland can add significant costs. Since digestate is quite wet, there will be large volumes produced that are best utilised in nearby communities in order to reduce transportation costs. The application of digestate will require special equipment for application of liquid fertilisers. Agricultural use of digestate can contribute to revenue generation by increasing agricultural yields and can save money if it reduces the need for or replaces commercial fertilisers.

### Advantages (+) and disadvantages (-)

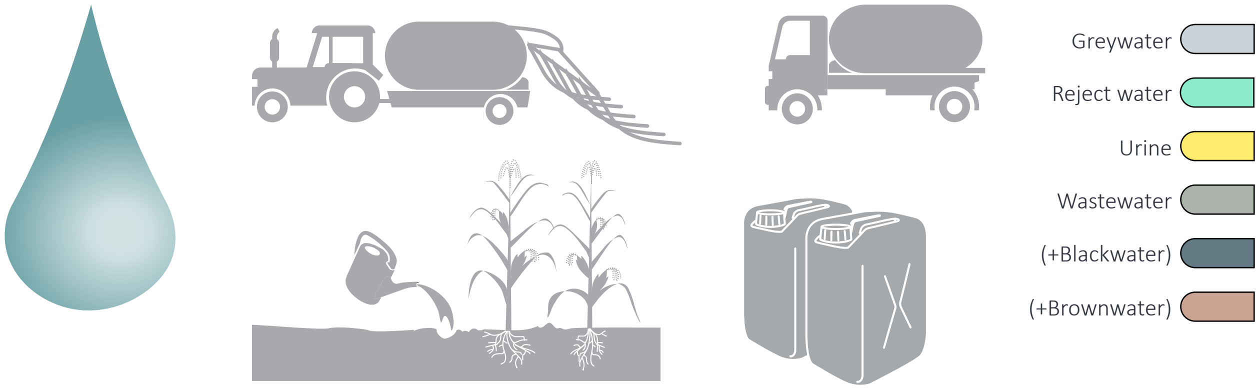
+ Can reduce the use of chemical fertilisers if applied as a fertiliser.
+ If organic matter is high enough, it can increase soil organic carbon and contribute to better soil structure.
+ Relatively more available nitrogen than most organic fertilisers and much more than in dewatered digestate.
- A dilute fertiliser.
- This product may not be fully accepted by farming communities.
- Odours may be noticeable.
- Requires spreading equipment for liquid manure.
- May pose public health risks, depending on feedstock and digestion method.

### References

References can be found on page 129.

# R.5 Nutrient Solutions

| Intended use: | Application level: | | Treatment technologies: |
|---|---|---|---|
| Liquid fertiliser, Aquaculture, Industrial input | * | Household | T.29 Membranes |
| | ** | City | |
| **Technical maturity:** | ** | Regional | |
| Medium | * | Global | |




***Compiled by:** Swedish University of Agricultural Sciences (SLU)*

**Liquid nutrient solutions refer to the concentrated liquid products obtained in either the feed stream or permeate streams from membrane filtration processes. Membrane distillation (MD) and forward osmosis (FO) are the most widely documented technologies to produce these nutrient solutions from urine and wastewater. The nutrient recovery products from membranes are primarily ammonia ($NH_3$), potassium (K) and phosphate ($PO_4$) solutions that can be used as liquid fertiliser or further processed in industry.**

## Characteristics

The nature of the incoming waste stream has a significant effect on the contents of nutrients in the solution, with urine and reject water having the greatest potential concentrations. As a percentage of initial content, ammonia ($NH_3$) recovery from membrane filtration systems for urine has been reported as 41 to 75%, while that from another swine manure and wastewater is as high as 99%. Low concentration of sulphuric acid can be used as a stripping solution to boost the ammonia recovery up to 99%. In the case of using stripping solutions, back-extraction may be required to obtain the pure nutrient solution. The non-volatile inorganic nutrient ions such as potassium (K) and phosphate ($PO_4$), are usually concentrated in the feed stream to facilitate subsequent nutrient precipitation, e.g., through acidification for $PO_4$.

## Health and safety considerations

Liquid nutrient solutions resulting from the permeate (as opposed to the retentate) are free from heavy metals due to the nature of transfer of materials across the membrane. Similarly, contamination of pharmaceuticals in permeate solutions should also be minimal. Ammonia, the most commonly recovered nutrient solution, is volatile and has been linked to irritations, particularly under poorly ventilated conditions, and to burning sensations in the respiratory tract at high concentrations. Potassium and phosphate solutions are considered less hazardous; however, proper safety precautions like gloves and other personal protective equipment (PPE) should be utilised at all times. Nutrient solutions recovered from the permeate stream are pathogen free, whereas nutrient solutions from the feed stream may contain some pathogens from the input.

### Social considerations

Nutrient solutions derived from urine requires application of source separation technologies that are not conventional sanitation infrastructure. There are few reviews on the social implications and acceptability of liquid nutrient solutions, despite their promise as fertilisers. Further research is needed regarding the social acceptability and agronomic efficiency of recovered nutrient solutions.

### Distribution to market

Nutrient solutions are useful as fertilisers and can even be used within aquaculture. The solutions can also be used within food processing industries or as inputs into fertiliser manufacturing industries. Urban farmers and horticulturists can also utilise these solutions in hydroponic systems.

This makes it possible to have decentralised and on-site recovery applications for producing nutrient solutions using membrane technology. However, expert knowledge is needed for optimal operations, and chemicals may be needed to control problems with fouling and scaling of the membranes.

While nutrient solutions can be extracted from mixed wastewater, it can be more effective to extract nutrients from the more concentrated fractions of source-separated urine and blackwater. On-site urine separation linked to membrane filtration/distillation and, subsequently, struvite precipitation holds the best promise for these systems. Thus, decentralised production and distribution of nutrient solutions may be appropriate in certain contexts. It is important to note that source separation may require substantial changes to existing infrastructure.

### Advantages (+) and disadvantages (-)

+ Recovered nutrients require little value addition to make good fertilisers.
+ Nutrient solutions can be easily processed for further nutrient recovery, e.g., by struvite precipitation.
- Membrane technologies are currently relatively high-tech, expensive and difficult to operate.
- Membrane fouling, pore wetting and operations and maintenance (O&M) can affect product quality.
- Fertilising properties will depend on the feed stream composition and recovery technique applied. These solutions will require chemical analysis before their use as fertiliser.

### References

References can be found on page 129.

**R.6**

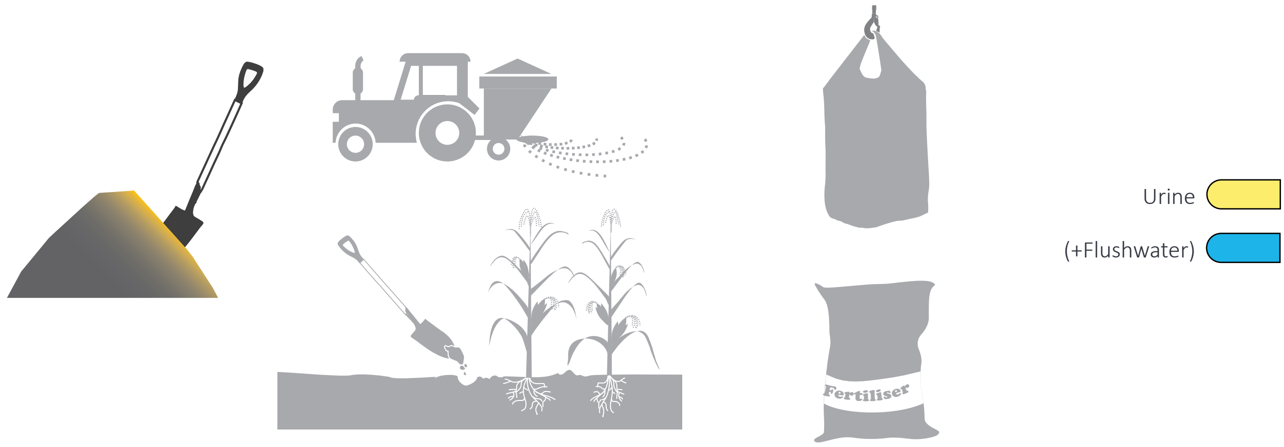
# Dry Urine

**Intended use:**
Solid fertiliser, Soil conditioner

**Technical maturity:**
Low

**Application level:**
** Household
** City
* Regional
* Global

**Treatment technologies:**
T.31 Alkaline Dehydration of Urine




***Compiled by:** Swedish University of Agricultural Sciences (SLU)*

**Dry urine is a nutrient-rich solid fertiliser produced by dehydrating and concentrating human urine in an alkaline substrate (pH > 10). Dry urine's treatment technology, alkaline urine dehydration, can be implemented using different alkaline substrates, which will determine the composition and physicochemical properties of the dried product. The dried urine captures nearly all of the fertilising nutrients in urine.**

## Characteristics

Dry urine is a dry fertiliser powder with <5% moisture. It is a balanced fertiliser containing primary (N, P and K), secondary (Ca, Mg and S), and micro plant nutrients. Typically, the N-P-K composition of dry urine (on a dry matter basis) is >10% N, >2.5% P and >5% K, while it also contains other macronutrients like S (>0.5%), Ca (>5%), Mg (>0.3%) and C (>8%). The urine is commonly dried in alkalising agents such as $Ca(OH)_2$, which can be used either alone or blended with co-substrates such as biochar, sand or ash for drying urine. The substrate used influences the composition of the dried urine. Depending on the end use, dry urine with specific fertilising qualities can be produced by using appropriate drying substrates (e.g., wood ash if high P and K content is required or MgO for high Mg content). Dry urine's pH is >10, and its electrical conductivity is >35 mS $cm^{-1}$.

## Health and safety considerations

Dry urine is a hygienic fertiliser. Due to the alkaline conditions, four days of storage after production of dry urine is sufficient to reach a 6-$log_{10}$ reduction for indicator bacteria and viruses. In areas prone to soil-transmitted-helminths such as *Ascaris* spp., a thermal treatment (≥42°C for 5 days) or a storage treatment in a sealed container (111 days at 20°C or 79 days at 35°C) is recommended in order to meet the World Health Organization (WHO) and U.S. Environmental Protection Agency (USEPA) guidelines for unrestricted reuse of excreta in agriculture. As fertiliser is applied only one or twice in a growing season, storage of the dry urine is a given, and thus storage as a treatment is an ideal option. Research on the fate of pharmaceuticals, drugs such as Phencyclidine (PCP), and hormones in dry urine is still pending (all of which are not currently regulated and are not adequately handled by current wastewater treatment plants).

Dry urine is a moderately caustic irritant (pH > 10) and should be handled with care, avoiding contact with exposed surfaces of the body. Gloves and other protective clothing should be used when handling it.

### Social considerations

Producing dry urine requires source-separated fresh urine, meaning that a collection system with urinals or urine-diverting toilets is needed. These systems may require acceptance and training on the part of the users. As fertiliser, dry urine is an emerging product that may require acceptance by the agriculture sector (farmers and cooperatives) and the food industry (processing industry, supermarkets and consumers), which has to buy the urine-fertilised food. Preliminary studies have indicated a strong preference for dry urine over the application of liquid urine. Dry urine is a powder that can be applied using a mechanical spreader, but it can also be pelletised and applied with conventional farming equipment. The generation of odour during fertilisation with dry urine is expected to be less offensive than that generated by application of stored liquid urine.

### Distribution to market

As a solid fertiliser, dry urine can be easily packaged and transported to market. It is appropriate for large-scale agricultural use, as well as in gardening, horticulture, landscaping or forestry. Depending on the substrate used for drying, it may also act as a soil conditioner for neutralising acidic soils or adding carbon.

Dry urine collection can be performed individually by households and applied in private gardens. For application at neighbourhood or city scales, dry urine needs to be collected by a service provider going door-to-door or building-to-building. This would mean creating a service chain for collection, aggregation and post-processing (e.g., pelletising and storage) of dried urine collected from different households. Dry urine, either bagged or stockpiled, can be stored in open-air containers without changes in composition.

### Advantages (+) and disadvantages (-)

+ Ready-to-use dry fertiliser.
+ Hygienic and meets international safety guidelines.
+ Stable, so can be stockpiled/stored.
+ Can be pelletised and used with conventional farming machinery.
+ <1 000 kg/ha dry urine is required for fertilising cereal crops (90 kg N/ha), compared to 15 000 kg/ha stored human urine.
+ Can be blended to produce specific fertiliser (N-P-K) composition to meet user requirements.
- Collection and post-processing are required for up-scaling, market distribution and quality assurance.
- High energy requirements during drying.
- On application, the smell of dry urine is less offensive than that of stored liquid urine, but it can still be an issue.

### References

References can be found on page 130.

## R.7 Struvite

| Intended use: | Application level: | Treatment technologies: |
| --- | --- | --- |
| Solid fertiliser, Industrial input | * Household<br>** City<br>** Regional<br>* Global | T.25 Struvite Precipitation |
| **Technical maturity:**<br>High | | |


***Compiled by:** Swedish University of Agricultural Sciences (SLU) and Grietje Zeeman (Wageningen University & Research)*

**Struvite, sometimes also called magnesium ammonium phosphate hexa-hydrate (MAP), is a phosphate mineral that occurs naturally in sanitation systems. It is a common precipitate in, e.g., pipes and heat exchangers, and it can also be purposefully extracted from waste streams, for example, through the addition of magnesium to urine. Struvite precipitation can be applied to reduce phosphorus concentrations in effluents while at the same time generating a product that can be applied as a fertiliser or industrial raw material.**

### Characteristics

Struvite is a crystalline mineral with the chemical formula of $MgNH_4PO_4 \cdot 6\ H_2O$. Struvite forms under specific pH conditions when the concentrations of magnesium, ammonium and phosphate are at or above an equimolar ratio 1:1:1. When dried, it forms a powder that can be white, yellow, brown or grey depending on the crystallisation medium.

Struvite is sparingly soluble in neutral or alkaline media, but is readily soluble in acids. Struvite is a thermally unstable compound in which mass loss can occur at temperatures above 55°C. Struvite is commonly used as a fertiliser since it contains three important elements for plants: P, N and Mg. The gradual degradation of struvite leads to a slow release of nutrients after field application, thus limiting the leaching losses of N and P that usually occur when applying conventional nitrogenous fertilisers.

### Health and safety considerations

Struvite formation may be coupled with precipitation of other constituents present in urine and wastewater, such as pathogens and heavy metals. However, the concentrations of these constituents, especially those of heavy metals, are generally below the permissible limits in the precipitated product, particularly if the struvite is precipitated directly from source-separated urine. If the struvite is precipitated from other, more contaminated sources (e.g., blackwater or reject water), heavy metal contamination may become an issue. To minimise pathogen concentration, the struvite filter cakes should be dried at elevated temperatures and/or low relative humidity. However, the temperature should not exceed 40 to 55°C in order to prevent substantial ammonia loss. To eliminate viruses and *Ascaris* spp. eggs, drying should be done until the steady-state moisture content has been reached.

### Social considerations

As with most products recovered from human excreta, there can be acceptance issues with struvite. While it is currently marketed as an eco-friendly fertiliser, there can be scepticism within the population about using it. Educating society may be necessary to gain product acceptance.

However, as a chemical powder, it no longer looks like human excreta and thus may be more acceptable than other recovered products.

### Distribution to market

As a solid fertiliser, struvite can be easily packaged and transported to market. It is appropriate for large-scale agricultural use, as well as in gardening, horticulture, landscaping or forestry. It can also be sold as an additive to commercial fertilisers or other industrial processes.

Currently, it is best marketed at a local or regional level, due to restrictions in legislation. As a potential end-of-waste product, struvite may be registered as a product in one country, but as waste in the other, which is an obstacle for trade across borders.

### Advantages (+) and disadvantages (-)

- \+ Can be stored in a compact form and is easy to handle, transport and apply, especially in a granulated form.
- \+ Slow-release fertiliser that provides plants with nutrients without the risk of burning the roots.
- \+ Has a longer shelf life than urine.
- \- Not a complete fertiliser, as it contains low levels of nitrogen and no potassium.
- \- Thermally unstable compound in which mass loss can occur at temperatures above 55°C.

### References

References can be found on page 130.

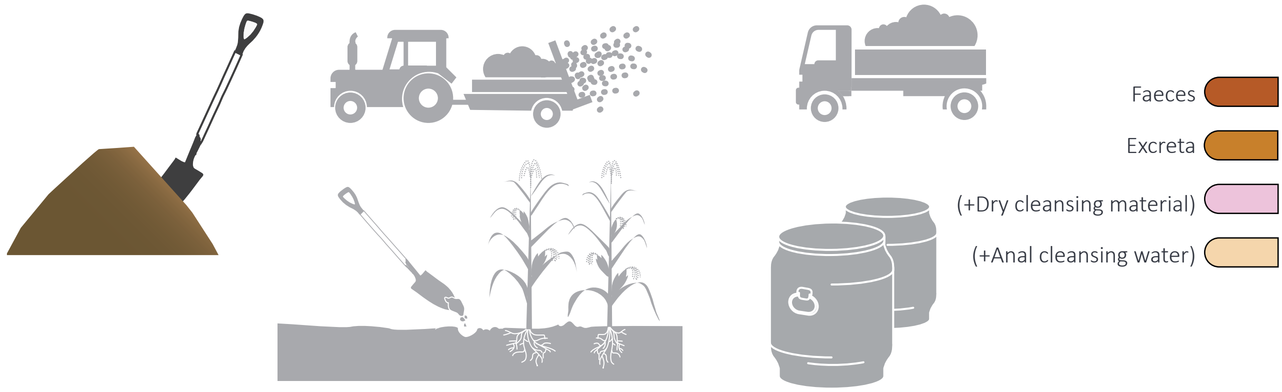
# R.8 Dried Faeces

**Intended use:**
Soil conditioner, Solid fertiliser

**Technical maturity:**
High

**Application level:**
*** Household
* City
* Regional
Global

**Treatment technologies:**
(U.1 Dry Toilet, U.2 Urine-Diverting Dry Toilet, S.7 Dehydration Vaults)




***Compiled by:** Tilley et al. (2014) and Swedish University of Agricultural Sciences (SLU).*

**When faeces are stored in the absence of moisture (e.g., urine or anal cleansing water), they dehydrate into a coarse, crumbly, white-beige material and can be used as a soil conditioner. Dehydration is very different from composting, as the organic material is not degraded or transformed. Instead, only the moisture is removed through the addition of drying materials after defaecation and proper ventilation and time. The dehydrated faeces can be used as an additive in composting or mixed directly into the soil. Extended storage is also an option if there is no immediate use for the material.**

## Characteristics

Through dehydration, faeces can be reduced in volume by about 75%. Completely dry faeces are a crumbly, powdery substance. This material is rich in carbon and nutrients, but can still contain helminth eggs and protozoan cysts or oocysts and other pathogens. The degree of pathogen inactivation will depend on the temperature, the pH (ash or lime addition raises the pH and inactivates pathogens) and the storage time.

## Health and safety considerations

Dehydrated faeces are a hostile environment for organisms, and most pathogens die off relatively quickly (usually within weeks). However, some pathogens (e.g., *Ascaris* spp. eggs) may remain viable even after longer drying periods and therefore a secondary treatment like co-composting, vermicomposting or chemical treatment (e.g., lime or urea treatment) is recommended before dehydrated faeces are applied in agriculture. Dried faeces are usually incorporated into the soil prior to the planting season and the World Health Organization (WHO) Guidelines for the Safe Use of Wastewater, Excreta and Greywater with its flexible multi-barrier approach should be consulted for further guidance. Personal protective equipment (PPE) (e.g., gloves, masks and boots) should be used when removing, transporting and applying dried faeces. It is generally recommended that faeces should be stored and dehydrated for between 6 to 24 months, although pathogens can remain viable even after this time. See the WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater for more specific guidance.

### Social considerations

The handling and use of dried faeces may not be acceptable in some cultures, and the potential use of dried faeces needs be discussed with the affected communities. However, because dehydrated faeces should be dry, crumbly, and odour free, their use might be easier to accept than that of manure or sludge. Offensive odours may be generated if the level of dehydration is insufficient.

### Distribution to market

Application of dried faeces can contribute to revenue generation by increasing agricultural yields and to cost savings if it replaces other fertilisers or soil conditioners. Costs to consider include the potential transport cost from the toilet to the field and costs for labour, agricultural equipment and PPE during spreading.

### Advantages (+) and disadvantages (-)

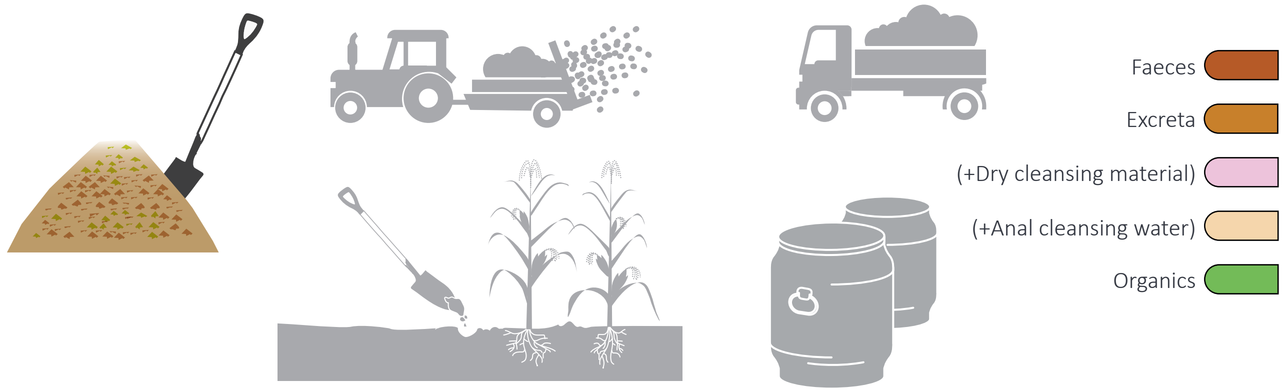
+ Can improve the structure and water-holding capacity of the soil.
+ Contains phosphorous and other fertilising nutrients.
+ Low risk of pathogen transmission.
- Labour intensive.
- Pathogens may exist in a dormant stage (cysts and oocysts) and may become infectious if moisture is added.
- Social acceptance may be low in some areas.

### References

References can be found on page 130.

## R.9 Pit Humus

| Intended use: | Application level: | Treatment technologies: |
|---|---|---|
| Soil conditioner, Solid fertiliser | ** Household<br>* City<br>* Regional<br>Global | (S.4 Double Ventilated Improved Pit Latrine, S.5 Fossa Alterna) |
| **Technical maturity:**<br>High | | |




***Compiled by:** Tilley et al. (2014) and Swedish University of Agricultural Sciences (SLU).*

**Pit humus is the material removed from double pit systems. It is produced passively underground, generally in the absence of oxygen, and thus it has not been composted. If long-term storage recommendations are followed, it can safely be removed from the pits and used as a soil conditioner.**

### Characteristics

Pit humus can be used beneficially to improve the quality of soil. It adds nutrients and organics and improve the soil's ability to store air and water. It can be mixed into the soil before crops are planted, used to start seedlings or indoor plants or simply mixed into an existing compost pile for further treatment. Pit humus is usually applied prior to the planting season. The use of pit humus has even made agriculture possible in areas which otherwise would not have supported crops.

The texture and quality of pit humus depends on the materials that have been added to the excreta (e.g., soil, organic matter) and storage conditions. If enough leaves and soil are added to the pit, there may be enough oxygen to promote some composting, but this will vary. Matured pit humus will be dewatered and consolidated, making it quite difficult to remove mechanically. For technologies that generate pit humus, a minimum of one year of storage is recommended to eliminate bacterial pathogens and reduce viruses and parasitic protozoa. World Health Organization (WHO) guidelines should be consulted for detailed information.

### Health and safety considerations

Pit humus, particularly from double pit systems that are not used correctly, poses a risk of pathogen transmission. If in doubt, material removed from the pit should be further composted before being used. Pit humus should not be applied to crops less than one month before they are harvested. This waiting period is especially important for crops that are consumed raw.

As opposed to sludge, which can originate from a variety of domestic, chemical and industrial sources, pit humus has very few chemical inputs. The only chemical sources that could contaminate compost or pit humus might originate from contaminated organic material (e.g., pesticides) or from chemicals that are excreted by humans (e.g., pharmaceutical residues). Compared to the chemicals that may find their way into wastewater sludge, pit humus can be considered less contaminated. However, caution should always be taken, and direct, unprotected handling should be actively discouraged. Workers should wear appropriate protective clothing.

### Social considerations

Pit humus is an inoffensive, earth-like product. Regardless, people might refrain from handling and using it, particularly in communities that are not familiar with using pit humus. Conducting demonstration activities that promote hands-on experience can effectively show its non-offensive nature and beneficial use. If vegetable production is being promoted, the demonstration gardens should use crops that reflect those grown and consumed in the local context.

### Distribution to market

Pit humus can be bagged and sold or simply transported in trucks from treatment sites to fields, greenhouses or gardens. It has been shown that the productivity of poor soil can be improved by applying equal parts pit humus and topsoil to it. The capital costs for tools to apply pit humus are generally low.

If space is abundant and emptying not desired, the pit humus can be used in an Arborloo (D.1 in the Eawag Compendium). The Arborloo is a shallow pit on which a tree can be planted after it is full, while the superstructure, ring beam and slab are moved to a new pit. In this case, the pit latrine is not lined, and the pit humus is left in the pit. The Arborloo can be applied in rural, peri-urban and even in denser areas if enough space is available. Nutrients from the Pit humus will be taken up by the tree; however, there is a risk of nutrient and pathogen leaching from the Arborloo, especially if the groundwater table is high.

### Advantages (+) and disadvantages (-)

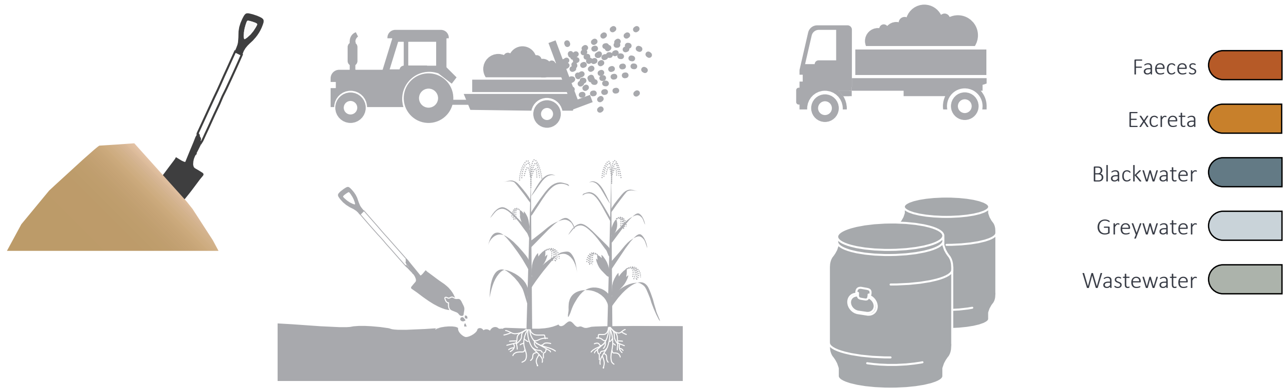
+ Low risk of pathogen transmission if storage recommendations are respected.
+ Can improve structure and water-holding capacity of soil and reduces chemical fertiliser needs.
+ May encourage income generation (improved yield and productivity).
+ Low costs.
- May require a year or more of maturation before being safe to use.
- Social acceptance may be low in some areas.

### References

References can be found on page 131.

# R.10 Dewatered Sludge

| Intended use: | Application level: | Treatment technologies: |
|---|---|---|
| Soil conditioner, Solid fertiliser, Construction, Soil reclamation | ** Household<br>** City<br>** Regional<br>* Global | * Sludge from collection/storage and treatments units that has been dewatered (full list below) |
| **Technical maturity:**<br>High | | |




***Compiled by:*** *Tilley et al. (2014) and Swedish University of Agricultural Sciences (SLU)*

**Dewatered sludge that has been stabilised and treated to remove pathogens can be used in agriculture, home gardening, forestry, landscaping, parks, golf courses, mine reclamation, landfill cover or for erosion control. Although sludge has lower nutrient concentrations than commercial fertilisers (for nitrogen, phosphorus and potassium), it can supplement required nutrient needs. Additionally, organic matter in the dewatered sludge can improve soil properties such as bulking and water retention and provide a slow release of nutrients into the soil as the organic matter is degraded.**

## Characteristics

Dewatered sludge quality and composition will vary greatly depending on the source of the sludge. Although the variability is large, dewatered sludge generally contains significant amounts of organic carbon, phosphorus and sometimes nitrogen, which can improve soil quality and provide fertilising effects when applied. Dewatered sludge from mixed wastewater may contain contaminants, such as heavy metals and pharmaceutical residues (which are present in excreta) and microplastics that primarily come from greywater sources. Sludge from domestic sources will generally contain less contaminants than wastewater sludge or faecal sludge (which may have contributions from industry), although any contaminants present in excreta (i.e., pharmaceutical residues) will also be present in sludge from domestic sources. Significant amounts of faecal pathogens may be present in dewatered sludge, thus requiring pathogen removal prior to application.

## Health and safety considerations

The hygienic quality of the dewatered sludge will depend on the treatment method used to produce it. For the majority of the associated treatment technologies helminth eggs such as *Ascaris* spp. may remain after treatment, with the exception of the technologies that may operate at elevated temperature (T.11 and T.17). Read specific treatment technologies information sheets for more details. The WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater should be consulted regarding the security measures needed to protect public and environmental health. Workers should wear personal protective equipment (e.g., clothing, boots and masks).

Although sludge is sometimes criticised for containing potentially high levels of heavy metals or other contaminants, actual contamination levels depend on the source of the sludge. Sludge that originates from large-scale wastewater treatment plants is more likely to be contaminated, as it may receive industrial and domestic chemicals, as well as surface water run-off, which can contain organic contaminants and heavy metals. In addition, in areas where sewers are not available, industries discharge into on-site containments that generate faecal sludge, and thus contaminant levels in faecal sludge are generally difficult to know and control. Sludge from domestic sources can be considered safer with respect to heavy metals, as it is not contaminated by industrial waste. However, monitoring of contaminant levels in sludge and control of sources is recommended.

### Social considerations

The greatest barrier to the use of dewatered sludge is generally social acceptance. However, even when farmers or local industries do not accept sludge, it can still be useful for municipal projects and can provide significant savings (e.g., mine reclamation through covering abandoned mining sites). Depending on the source of the sludge and the treatment method, dewatered sludge can be treated to a level where it is generally safe and no longer generates significant odour or vector problems. Following appropriate safety and application regulations is important. The WHO guidelines should be consulted for more detailed information.

### Distribution to market

Distribution and spreading of treated and dewatered sludge can presents a potential business opportunity. Dewatered sludge produced and treated at a neighbourhood and/or city scale is a cheap and readily available fertiliser, although transportation to and spreading on farmland can add significant costs. Dewatered sludge can contribute to revenue generation by increasing agricultural yields. The application of dewatered sludge can save money if it reduces the need for or replaces commercial fertilisers.

### Advantages (+) and disadvantages (-)

+ Can reduce the use of chemical fertilisers and improve the water-holding capacity of soil.
+ Can accelerate reforestation.
+ Can reduce erosion.
+ Low costs.
- Odours may be offensive, depending on prior treatment.
- May require special spreading equipment.
- May pose public health risks, depending on its quality and application.
- Social acceptance may be low in some areas.

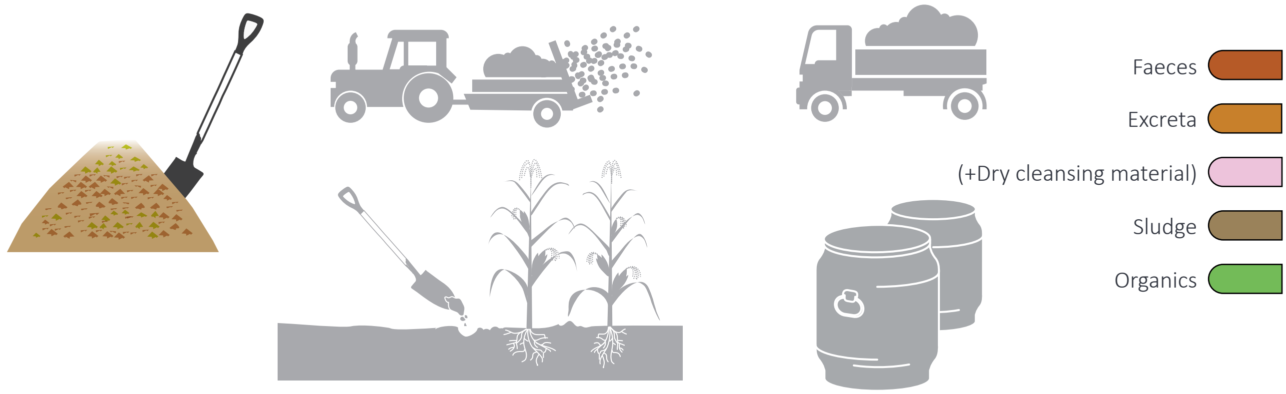
### References

References can be found on page 131.

*** Technologies potentially producing dewatered sludge:** (S.9 Septic Tank, S.10 Anaerobic Baffled Reactor ABR, S.11 Anaerobic Filter, S.12 Biogas Reactor, T.1 Settler, T.2 Imhoff Tank, T.3 Anaerobic Baffled Reactor ABR, T.4 Anaerobic Filter, T.5 Waste Stabilization Ponds WSP, T.6 Aerated Pond, T.10 Trickling Filter, T.11 Upflow Anaerobic Sludge Blanket Reactor UASB, T.12 Activated Sludge, T.13 Sedimentation/Thickening Ponds, T.14 Unplanted Drying Beds, T.15 Planted Drying Beds, T.17 Biogas Reactor)

# R.11 Compost

| Intended use: | Application level: | | Treatment technologies: |
|---|---|---|---|
| Soil conditioner, Solid fertiliser | ** | Household | T.20 Vermicomposting and Vermifiltration, T.21 Black Soldier Fly Composting, (T.16 Co-Composting, S.8 Composting Chamber) |
| **Technical maturity:** | * | City | |
| High | * | Regional | |
| | | Global | |




***Compiled by:*** *Tilley et al. (2014) and Swedish University of Agricultural Sciences (SLU)*

**Compost is a soil-like substance resulting from controlled aerobic degradation of organic material in, e.g., co-composting facilities. Compost is a soil conditioner that contains nutrients and organic matter. It contributes to the formation of humus in the soil, thus improving soil structure and water retention capacity. By adding carbon to the soil, compost also contributes to soil carbon storage capacity, which is beneficially for reducing climate change.**

## Characteristics

Compost can be beneficially used to improve the quality of soil. It adds nutrients and organics and improves the soil's ability to store air and water. It can be mixed into the soil before crops are planted, used to start seedlings or on indoor plants. Compost is usually applied prior to the planting season. The use of compost has made agriculture possible in areas which otherwise would not have supported crops.

## Health and safety considerations

The process of thermophilic composting generates heat (50 to 80°C), which can kill most pathogens present in the material being composted. Achieving this, however, requires active monitoring and control of the composting process, since reaching a high temperature normally becomes more difficult over time. The World Health Organization (WHO) Guidelines for the Safe Use of Wastewater, Excreta and Greywater stipulate that compost should achieve and maintain a temperature of 50°C for at least one week before it is considered safe to use.

Compost should not be applied to crops less than one month before they are harvested. This waiting period is especially important for crops that are consumed raw. As opposed to sludge, which can originate from a variety of domestic, chemical and industrial sources, compost has very few chemical inputs. The only chemical sources that could contaminate compost or pit humus might originate from contaminated organic material (e.g., pesticides) or from chemicals that are excreted by humans (e.g., pharmaceutical residues). However, direct, unprotected handling should be actively discouraged. Workers should wear appropriate protective clothing.

### Social considerations

Compost is generally considered an inoffensive, earth-like product. Regardless, people might refrain from handling and using it, particularly in communities that are not familiar with using compost. Conducting demonstration activities that promote hands-on experience can effectively show its non-offensive nature and beneficial use. If vegetable production is being promoted, the demonstration gardens should use crops that reflect those grown and consumed in the local context.

### Distribution to market

Compost can be bagged and sold or simply transported in trucks from treatment sites to fields, greenhouses, or gardens. It has been shown that the productivity of poor soil can be improved by applying equal parts compost and topsoil to it. The capital costs for tools to apply compost are generally low.

### Advantages (+) and disadvantages (-)

+ Can improve structure and water-holding capacity of soil and reduce chemical fertiliser needs.
+ May encourage income generation (improved yield and productivity).
+ Low costs.
- May require a year or more of maturation before being safe to use.
- Social acceptance may be low in some areas.

### References

References can be found on page 131.

# R.12 Ash from Sludge

| Intended use: | Application level: | Treatment technologies: |
| --- | --- | --- |
| Soil conditioner, Solid fertiliser, Construction material | * Household<br>** City<br>** Regional<br>Global | T.26 Incineration |
| **Technical maturity:**<br>High | | |


***Compiled by:*** *Swedish University of Agricultural Sciences (SLU) and Charles Niwagaba (Makerere University)*

**Incineration ash can be divided into two main categories: incinerator bottom ash (IBA) and air pollution control residue, which is commonly referred to as fly ash. IBA forms at the bottom of an incinerator from heavy components that are neither combustible nor volatile. These residues contain large proportions of phosphorous and potassium, which can fertilise the soil for agricultural purposes if the sludge is not chemically contaminated. It can also be used in construction materials such as roads.**

## Characteristics

Incinerated sludge ash contains significant quantities of potassium and phosphate, predominantly present as tri-calcium phosphate. It may also contain silicon, aluminium, iron and calcium, along with significant levels of heavy metals, depending on their presence in the sludge prior to incineration. The presence of heavy metal constituents in sludge coming from domestic sources is normally low. Consequently, ash from domestic sources is generally more suitable for agricultural applications with minimal or no risk of heavy metal contamination. Ash is also highly alkaline and can act as a soil conditioner for acidic soils.

Due to its high porosity, ash can also be used as a filter material in wastewater treatment or as a soil conditioner. Ash removes pollutants from water through the process of adsorption. The high porosity provides many reactive sites for the attachment of dissolved compounds in contaminated water.

## Health and safety considerations

Fly ash on its own is classed as a hazardous material due to the number of chemicals and compounds found in it, which may leach into the surrounding soils if applied on land. It can also leach into the underground water, depending on the underlying geological formations and depth to the groundwater table. However, with further thermal treatment, the ash can be rendered safe and suitable as a construction material or for agricultural use. Many contaminants in the substrate, such as organic pollutants, insecticides and pesticides, as well as pathogens, are destroyed during the incineration. The content of pollutants in fly ash is generally lower for sludge originating from domestic sources than in that from industrial or mixed wastewater sources.

### Social considerations

Ash from the incineration of sludge has been widely accepted a source of phosphorus, hence its use as a form of fertiliser. Extraction of phosphorus from sludge ash is already implemented industrially, for example, in Germany. Ash is also widely embraced as an additive for construction materials such as bricks and cement. Ash from incineration of sludge originating from domestic sources contains fewer pollutants than ash from industrial sources and therefore has less social and environmental impacts.

### Distribution to market

Incinerated sludge ash is normally used to recover phosphorus in the form of clean commercial products such as mono/di-ammonium phosphates (fertiliser) that is later sold to farmers. There is also, at least in the Netherlands and Denmark, a tendency towards utilisation of incinerated ash as cement replacement material in infrastructure projects (embankments, reclamations, motorways, etc.). The use of ash in large infrastructure projects offer better delivery security for the supplier of bottom ash. Metals can also be recovered from bottom ash and sold to scrap dealers or other recyclers of the relevant metal products.

### Advantages (+) and disadvantages (-)

+ Free from pathogens.
+ It is possible to recover phosphorus from incinerated sludge ash using an acid leaching process.
+ Incinerated sludge ash may be used as an adsorbent for heavy metals in wastewater treatment, due to its exceptionally porous structure and active components.
+ It is used as a source for the production of building materials. Incinerated sludge ash is used as a clay substitute to produce quality bricks as well as an additive in cement manufacturing.
- May contain heavy metals.
- Fly ash may pollute the environment.

### References

References can be found on page 132.

# R.13 Biochar

| Intended use: | Application level: | Treatment technologies: |
| --- | --- | --- |
| Soil conditioner, Water purification, Energy production | * Household<br>** City<br>** Regional<br>* Global | T.27 Carbonisation |
| **Technical maturity:** High | | |


***Compiled by:** Swedish University of Agricultural Sciences (SLU)*

**Biochar is a solid material obtained from pyrolysis, the thermochemical conversion of biomass in an oxygen-limited environment. Biochar derived from pyrolysis of sludge, faeces and/or organic waste may be applied to soils in order to improve soil properties and crop yields, as well as acting as a carbon sink to reduce climate change impacts. Other applications include use as an adsorption material for filters, especially for water purification purposes, or as a feedstock for energy recovery. It is typically called "biochar" when it is used as a soil conditioner and "char" when it is used as a fuel.**

## Characteristics

Biochar is black, lightweight, porous and alkaline in nature due to its ash content. It has a high carbon content that enables it to have an energy value similar to that of coal or charcoal. When used for energy conversion rather than as a soil conditioner, it can be directly substituted for any application that uses coal or charcoal. The high carbon content of biochar increase carbon sequestration in soils when used as a soil conditioner.

The quality and characteristics of the organic material used, and conditions under which the pyrolysis takes place, greatly affect the characteristics of the biochar produced. Low-temperature pyrolysis produces greater volumes of biochar. In contrast, high-temperature pyrolysis produces biochars with a high carbon content, large surface area, and high adsorption characteristics.

Due to its great porosity and high surface area, biochar is used as a treatment filter and for soil conditioning. As a filter, biochar removes pollutants from water through the process of adsorption. The large surface area and porosity provide many reactive sites for the attachment of dissolved compounds in contaminated water. Biochar has an affinity for adsorbing contaminants in soil, keeping them from being taken up by plants. The high porosity and surface area of biochar also provide space for microorganisms that are beneficial for the soil and help in binding of important minerals, thus improving soil quality.

### Health and safety considerations

Contaminants in the carbonised substrate (e.g., sludge) such as organic pollutants, insecticides and pesticides, as well as pathogens, are catalytically or thermally destroyed in the production of biochar. Biochar is thus a safe product. In addition, the remaining heavy metals in the biochar are speciated as insoluble sulphides and should not be available for uptake in plants, thus making the biochar safe for use in agriculture. However, dust arising from initial application of biochar can pose a risk for respiratory diseases. Face masks should be worn when handling biochar.

### Social considerations

Certain socio-cultural barriers to the adoption of biochar projects include the lack of awareness of biochar and a need for education about the benefits of using biochar in agriculture. A research study in Poland found that farmers who were willing to use biochar had often been primed with knowledge about the concept of sustainable agriculture.

### Distribution to market

Biochar has a broad range of application in agriculture, forestry, energy generation and fertiliser production. Around 150 companies, mostly small garden supply and specialty retailers, sell biochar worldwide. The majority of the global market share comes from the United States (65%), followed by Europe (25%), Asia (7%), and Africa (3%). Growth in the biofuel sector coupled with various government rules and regulations has been driving demand for the global biochar market in the last few years. Environmental benefits and availability of cheaper feedstock is expected to further drive the market.

### Advantages (+) and disadvantages (-)

+ Biochar can improve the soil quality and the biological and chemical structure of soil.
+ Application of biochar onto soil is a means of increasing its carbon storage. When the application is carried out in a deliberate manner, the process can result in a carbon-neutral or even carbon-negative environment, thereby having a compensatory effect to anthropogenic $CO_2$ emissions.
+ Because of its high surface-to-volume ratio and strong affinity to non-polar substances, biochar has the potential to adsorb a variety of organic pollutants and heavy metals from water.
+ Biochar has a liming effect that can be used to balance acidic soil towards a neutral pH.
- Dust arising from initial application of biochar can pose a risk for respiratory diseases.
- In some cases, yields may decline because of the sorption of water and nutrients by the biochar, which reduces the availability of these resources for the crops.
- The sorption of pesticides and herbicides by the biochar can reduce their efficacy.
- Nitrogen is lost from the biomass in the production of biochar.

### References

References can be found on page 132.

# R.14 Nutrient-Enriched Filter Material

**Intended use:**
Solid fertiliser, Soil conditioner, Construction material

**Technical maturity:**
High

**Application level:**
** Household
** City
* Regional
* Global

**Treatment technologies:**
T.30 Filters


***Compiled by:*** *Swedish University of Agricultural Sciences (SLU)*

**Nutrient-enriched filter materials are mineral or organic materials that have been charged with nutrients through the process of adsorption. Filter material can be naturally occurring materials, by-products of industrial processes or engineered media. Phosphate ions usually have high affinity for these filters. Once saturated with nutrients, the filters can be recycled as a combined fertiliser for plant production, soil conditioner and liming agent on acidic soils.**

## Characteristics

Different filter materials exist, including both organic and mineral-based substrates. Some are by-products of industrial processes, for example, blast furnace slag that results from the process of extracting iron from iron ore at steelworks.

Mineral-based filter materials include soil, sand, crushed rock (e.g., chalk, calcium silicate), or zeolites (e.g., porous minerals). Organic filter materials include biochar, bark, activated carbon and peat, among others. A common feature of these filter materials is the presence of chemical compounds with lattice structures containing cationic elements (e.g., calcium oxides, iron, aluminium and magnesium) for which soluble reactive phosphate ions have affinity. They have a porous structure that consists of pores of different sizes and shapes. They also have a high pH and, once saturated, can be used as fertilisers due to their nutrient content. Calcium silicate is known for its high sorption capacity for soluble phosphorus and has proven useful for recycling of nutrients in agriculture.

Activated carbon is an excellent adsorbent due to its strong affinity for binding organic substances, even at low concentrations. It has a vast network of pores of various sizes to accept both large and small contaminant molecules, and these pores give activated carbon a very large surface area for binding nutrients. Aside from the potential fertilising value of nutrient-enriched organic filter materials, they also have the advantage of increasing soil organic carbon, which improves soil quality as well as sequestrating carbon in the soils. Use of organic filter material in construction can also sequester carbon, but would not allow for nutrient reuse.

### Health and safety considerations

Pre-treatment of the filter material prior to filtration is necessary to ensure that the nutrient-enriched filter materials have minimal or no pathogen content. Most of the filter materials currently in use have an alkaline pH of 9 to 12, which significantly reduces viruses and bacteria, whereas helminth eggs may not be affected by the pH. The nutrient-enriched filter materials usually have a low metal content, but the content varies with the ionic composition of the filtered fluid.

### Social considerations

Nutrient-enriched filter materials no longer resemble human excreta and are thus potentially more acceptable as products. In addition, they have the added benefits of soil conditioning, which may make them attractive to farmers. Application on farmland would require mechanical equipment for mixing the material into the soils. This may be done manually, but would be labour intensive.

### Distribution to market

Nutrient-enriched filter materials may be sold directly as fertilisers/soil conditioners or used as additives to other products. Nutrient-enriched filter materials can be applied directly on fields or pre-treated prior to application. Materials such as calcium silicate are usually crushed and sieved to a fraction of <2 mm in order to have a homogeneous distribution and enhance the release of P and other elements to the soil. They are appropriate for large-scale agricultural use, as well as in gardening, horticulture, landscaping or forestry. They can also be sold as an additive to commercial fertilisers or construction material. When applied in agriculture, the filter material is first applied on the soil surface and then mixed into the upper soil layer by ploughing or digging.

### Advantages (+) and disadvantages (-)

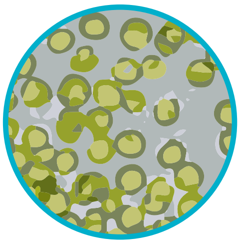
- \+ Most filter material comes from naturally occurring sources.
- \+ Act as low-cost fertilisers due to their relatively high phosphate content.
- \+ Organic filter material can be used as a soil conditioners to increase soil organic carbon.
- \- A shortcoming of the hydrated ash filter material is low concentrations of nitrogen.
- \- The filters may contain metals absorbed from the wastewater, which can be transferred from soil to crops by plant uptake and become hazardous for humans and the environment.

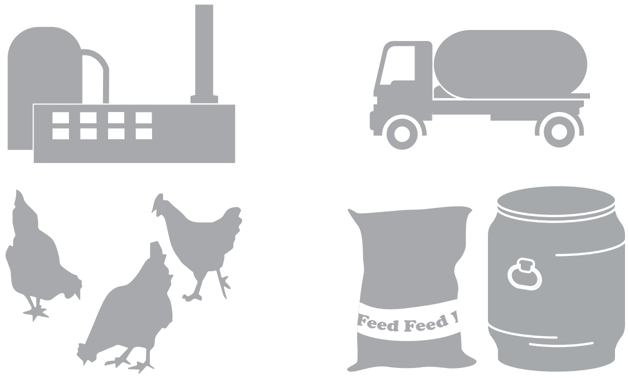
### References

References can be found on page 133.

# R.15 Algae

| Intended use: | Application level: | Treatment technologies: |
|---|---|---|
| Biomass (e.g., animal fodder, biofuels), Soil conditioner, Industrial input (e.g., chemicals, food, pharmaceuticals), Bioremediation | Household<br>** City<br>* Regional<br>* Global | T.22 Algae Cultivation |
| **Technical maturity:** High | | |







***Compiled by:** Swedish University of Agricultural Sciences (SLU) and Eva Thorin (Mälardalen University)*

**Algae are a diverse group of mostly single-celled aquatic organisms, but they include a few multicellular groups and bacteria. Algae are primary producers, i.e., they produce organic material from sunlight and carbon dioxide and release oxygen as they feed on dissolved nutrients in water. They grow in suspension or attached to underwater surfaces from which they can be harvested. As the algae grow, they can treat wastewater by utilising the excess nutrients within it while effectively removing heavy metals and pharmaceuticals. The harvested algae form a biomass with multiple uses. Depending on the type of alga cultivated, it may contain significant amounts of nutrients, proteins and lipids that have uses and applications as biofuels, soil conditioners and additives in the food, chemical or pharmaceutical industries.**

## Characteristics

Algae have no roots, stems or leaves, thus making them easy to process. They contain chlorophyll and other pigments that allow them to carry out photosynthesis. Algae are generally rich in nutrients such as phosphorous and nitrogen. The great diversity of algae means that specific algae can be grown for specific purposes. However, multiple species of algae can co-exist and thus it can be difficult to control exactly which species are cultivated. Algae are commonly used as feed, either for animals or for humans. Algae can be a nutritious feed for fish. In some countries, food products like algae cakes or Chlorella from algae are popular. A higher lipid content in the algae translates to better potential for biofuel harvesting. In addition, algae can contain useful compounds like beta carotene that can be used as a food supplement, as well as other chemicals with potential pharmaceutical properties. Algae can also be used to clean up polluted sites containing hazardous compounds such as heavy metals and organic pollutants.

## Health and safety considerations

Some algae species can absorb heavy metals and other toxic compounds from the water. Concentrations of these compounds in the feed water and algae should be carefully monitored. Some algae species contain bioactive toxins that can be irritants or poisonous to humans. The susceptibility of open ponds to invasion by these species makes this a cause for concern. Algae from cultivated systems should not be released into the environment, as it can lead to decrease in water quality and possibly be fatal to fish in receiving water bodies. Algae growth consumes $CO_2$, which causes an increase in the pH, sometimes up to 9.5 to 10, which has a sanitising effect on viruses and bacteria.

### Social considerations

Consumption of algae as food is practiced in many places. In particular, seaweeds or macroalgae are commonly used. It is also possible to produce food-additive compounds by algae (like beta carotene), although more sensitisation is required to boost uptake of these algal products. Although algae are currently used in the food and pharmaceutical industries, the possibilities of using algae grown on wastewater would need to comply with local health and safety regulations. Algal biofuels are still at this point at a cost disadvantage compared to other, more technically mature fuel options.

### Distribution to market

Algal biomass harvested from treatment ponds is generally dried before being transported to agricultural fields (if used as a soil conditioner/fertiliser), relevant processing industries or energy conversion units. Several start-up companies, particularly in the United States, are striving to commercialise algal biofuels. Algae can also be used as a substrate in digestion processes in order to create biogas in areas that lack other necessary infrastructure for further processing. Existing publications report the costs of producing algal biofuels as being from USD 455 to USD 560 per barrel, while high-value products such as beta carotene cost USD 1 400/kg, and Chlorella, a green microalga used as a dietary supplement, often exceeds USD 100/kg on the market.

### Advantages (+) and disadvantages (-)

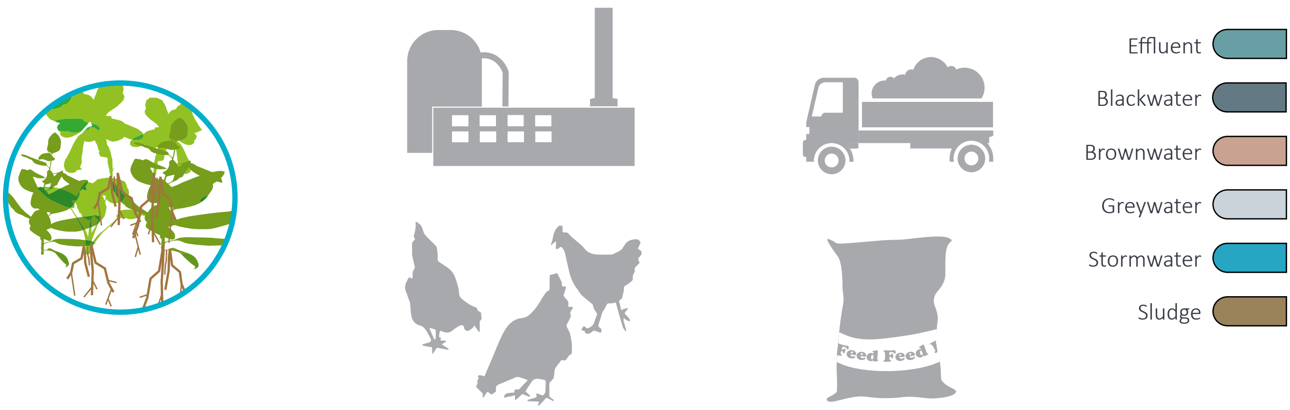
+ Algae species are tolerant to high heavy metal concentrations.
+ Algae production has a positive climate effect by removing $CO_2$ and generating oxygen.
+ Algae can be used as food and animal fodder and for production of precursor chemicals for pharmaceuticals or other chemicals.
+ Algae can be used as a substrate in production of biogas or biofuels.
- Algae ponds may not be aesthetically pleasing.
- Algal biofuel production is currently expensive.
- If algae are to be used for food, fodder or fertiliser, the concentrations of heavy metals in the algae should be monitored.
- It is difficult to guarantee product quality due to variability depending on the extraction technology and the algae species.

### References

References can be found on page 133.

# R.16 Macrophytes

| Intended use: | Application level: | | Treatment technologies: |
|---|---|---|---|
| Biomass (e.g., animal fodder, biofuels) | | Household | (T.7 Free-Water Surface Constructed Wetland, T.8 Horizontal Subsurface Flow Constructed Wetland, T.9 Vertical Flow Constructed Wetland, T.15 Planted Drying Beds) |
| **Technical maturity:** | ** | City | |
| Medium | * | Regional | |
| | | Global | |




***Compiled by:*** *Amadou Gueye (Delvic Sanitation Initiatives), Elhadji Mamadou Sonko (Cheikh Anta Diop University), Ebenezer Soh Kengne (University of Bamenda)*

**Macrophytes are plants that are distinguished by their ability to grow when partially or fully submerged in water. They are commonly used in constructed wetlands and planted drying beds for treatment of wastewater and sludge. There are four types of macrophytes: freely floating, submerged, floating leaved and emergent. When it comes to biomass recovery, emergent macrophytes are generally the best suited because they are the most productive.**

## Characteristics

Many plant species cannot survive without special adaptation to wetland conditions. The plants that can grow in these conditions have the capacity to grow in spaces with high and fluctuating water tables, as well as under lowe oxygen concentrations than those of unsaturated soils. These capacities must be accompanied by high levels of productivity. The total biomass production of wetland vegetation is significantly affected by three main factors: the nitrogen (N):phosphorus (P) ratio, total nutrient supply and morphological and physiological traits of the plants. For biomass production for animal fodder, perennial or annual tropical grasses are commonly used. *E. pyramidalis, P. geminatum* and *P. vaginatum* all appear to be suitable plants for use in planted drying beds (PDB) treating faecal sludge, since they have shown a capacity for sustained biomass production with repeated harvesting based on plant biomass and quality.

The amount of biomass that can be harvested depends on the macrophyte being grown and on operating conditions at the constructed wetland or PDB. For example, the perennial tropical grass *E. pyramidalis* in a PDB can be harvested every 4 to 9 months. The density of the harvest ranges from 125 stems/$m^2$ to approximately 250 stems/$m^2$, depending on the operating conditions and frequency of harvest. Regular harvesting is necessary to maintain the efficiency of the planted drying bed. The management of this plant on an annual three-harvest basis will yield about 100 to 150 dry tonnes/ha of shoots that can be used as fodder for animals if safely managed. Macrophytes can provide a safe and nutritious source of fodder for livestock. For example, *E. pyramidalis* can have a total nitrogen concentration of 719±2.3 mg/kg and a total phosphorous concentration of 118±0.5 mg/kg. It is rich in digestible dry matter (42%), total digestible matter (41%), crude proteins (18%) and metabolisable enzymes (7%).

### Health and safety considerations

There is minimal risk of infection from fodder plants harvested from constructed wetlands. A previous study showed that *E. pyramidalis* macrophytes cultivated in PDB were of a similar or better quality than that of other forages in tropical regions. For health and safety consideration, analyses of samples from plants grown under these conditions show that pathogens such as coliforms, faecal streptococci, helminth eggs and protozoan cysts were not detected in the fractions of plants higher than 60 cm higher above the bed. Based on the results of bromatological analyses of studies carried out in Dakar and Cameroon, the biomass harvested from the planted drying beds did not present any risks for the animals.

### Social considerations

In the context of reuse of the by-products from treatment of faecal sludge and wastewater, social considerations are very important, and these considerations differ greatly from one area to another depending on socio-cultural orientation. For example, a study carried out in Senegal showed that 95% of the actors questioned were ready to use the fodder cultivated from PDB treating faecal sludge, because they believed that the treated sludge has similar qualities to those of other soil amendments. However, 47% of those approving of the use of these macrophytes as fodder still had reservations about the sanitary quality of plants and the potential risks for the animals that consume them. Five percent (5%) of respondents were not in favour of using fodder from PDB, as they doubted the sanitary quality of these products. These results reflect the diverse perspectives of stakeholders, but also concerns about the health quality of the product.

### Distribution to market

The development of urban and peri-urban livestock farming has resulted in a strong demand for animal feed in large cities. This phenomenon has made the fodder trade a booming sector in some cities. Harvesting and transporting fodder is a physically demanding job, since it is often done manually and collected fodder is transported long distances. Fodder transport is often done on foot, by bicycle or using carts and cars. The fodder is then generally sold at a market, although in some cases fodder is delivered and sold directly to livestock producers. In current practices of fodder sales, the people who harvest the fodder are also in charge of transportation and sale at the market. There is generally no organised trade for the fodder, and only local markets and hand cutters are doing the trade. The establishment of markets for macrophytes from treatment plants can potentially work with existing actors to establish distribution systems. However, there are no functional business models yet for full-scale operations for harvesting and selling macrophytes from treatment plants. So, while there is a growing need in many cities to increase local production of fodder, methods for integration of fodder grown as part of a treatment technology in general is still rudimentary. However, economic potential exists. For example, in urban areas of Dakar, Senegal, the fodder supply is ensured by fodder vendors, and on average 500 g of fresh biomass are sold at 50 XOF. The quantities purchased depend on the type of livestock and the number of heads. Among small breeders, they average around 5 kg of fresh biomass per breeder per day. For beef breeders, the quantities are greater. In Dakar, the majority of fodder sellers make this activity their livelihood throughout the year, and 60% of them say that their income covers their needs. However, for others a secondary activity is necessary to achieve their ends. The results of surveys carried out in Cameroon show that the sale of fodder is a profitable activity.

### Advantages (+) and disadvantages (-)

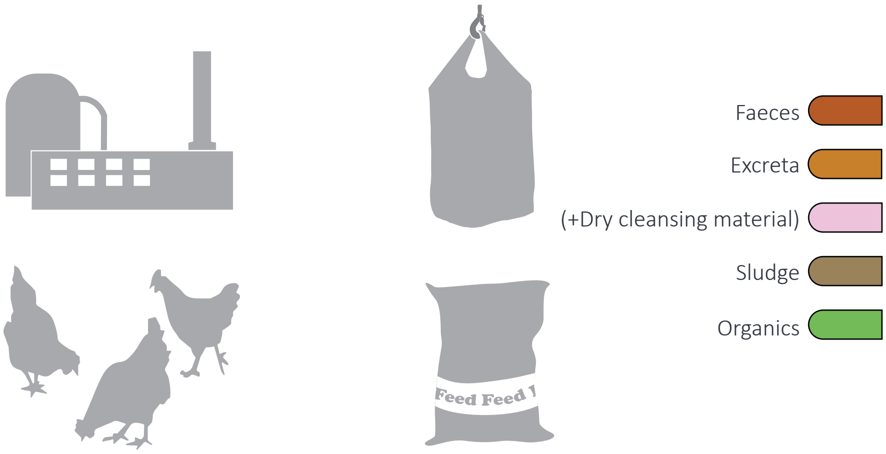
+ Nutritious source of fodder.
+ Local production of livestock feed, which is particularly important in semi-arid areas.
+ Can be used as input to biofuel production.
- Plants can be contaminated by parasites (e.g., *Ascaris* spp. eggs, *Taenia* tapeworm).
- Plants can accumulate heavy metals.

### References

References can be found on page 134.

# R.17 Black Soldier Fly Larvae

| Intended use: | Application level: | | Treatment technologies: |
|---|---|---|---|
| Biomass (e.g., animal fodder, biofuels), Industrial use | ** | Household | T.21 Black Soldier Fly Composting |
| | ** | City | |
| **Technical maturity:** | *** | Regional | |
| Medium | * | Global | |




***Compiled by:** Swedish University of Agricultural Sciences (SLU)*

**Larvae are the main product resulting from treatment of organic waste using black soldier fly larvae (BSFL). Under optimal conditions, it takes three weeks for BSFL to grow from an egg to reach the final larval stage, in which the larvae crawl out of the residue in the search for a dry and dark place to pupate. The larvae can thus be self-harvesting, which means that the larvae and feed do not have to be separated manually. However, large-scale systems primarily use manual or automated separation technologies for harvesting the larvae.**

## Characteristics

The larvae are on average 27 mm long, 6 mm wide and can weigh up to 220 mg in their last larval stage if they have been fed a highly nutritious substrate (e.g., food waste, faeces or slaughterhouse waste). They are whitish in colour in the early stages of their lifecycle and turn blackish brown prior to pupation. The larvae have high protein (42 to 45%) and fat (10 to 40%, greatly varied and depending on substrate) contents. Thus, they make an excellent protein-rich animal feed. The harvested larvae are primarily given to poultry, fish and pigs. Research is ongoing regarding the potential to use proteins and oils in BSFL for bioplastics, biofuels or other industrial processes.

## Health and safety considerations

BSFL composting has a sanitising effect on bacteriophages and bacteria such as *Salmonella enteritidis* and *Escherichia coli*, and studies show reduced concentrations in substrates after BSFL composting. However, these microorganisms may still be in the gut of the larvae when they are harvested. The effect from BSFL composting on *Ascaris* spp. eggs is small. Thus, sanitisation of harvested BSFL needs to be incorporated into any plan for an industrial-scale BSFL production. Drying and powdering the BSFL, heat or UV treatment, high-energy microwaving or pasteurising would reduce the risk of microbial and parasitic contamination.

## Social considerations

While insect use as a feed for livestock is widely accepted in many parts of Asia, Latin America and Africa, there is still cultural resistance in other parts of the world, especially in Europe and North America, where legislation is also an additional hindrance. However, perceptions are changing. In a survey-based study done in Flanders, Belgium, attitudes towards the idea of using insects in animal feed was generally acceptable, most notably for fish and poultry feed. Two-thirds of the respondents were willing to accept the use of insects in animal feed. The foods obtained from animals fed on insect-based feed were widely accepted.

### Distribution to market

At a local level, larvae may be sold directly to farmers as feed for their livestock, either alive or processed. At a regional or global level, processed larvae may be distributed by commercial feed companies. Larvae can be sold dried, frozen or in pellet form. However, there are restrictions in certain markets, such as Europe regarding the bio-waste used to feed the larvae. Use of bio-waste (except for pre-consumer non-animal waste) is currently not permitted for BSFL production as animal feed. Such restrictions limit the distribution of larvae.

### Advantages (+) and disadvantages (-)

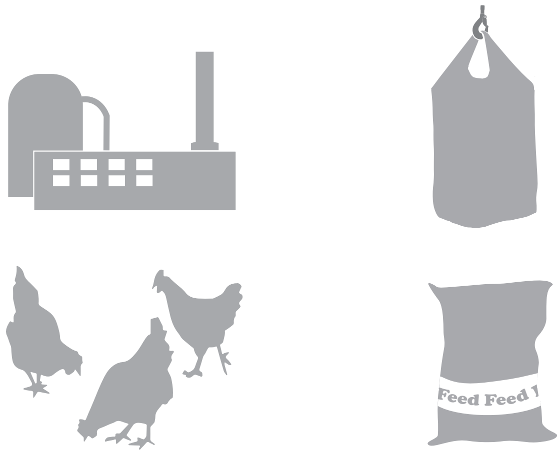
+ BSFL are a good source of protein and oil in animal feed.
+ BSFL can be easily dried for longer storage.
+ BSFL may be a potential input to biofuels or other technical uses.
+ Pesticides and mycotoxins are not bioaccumulated in the BSFL.
- BSFL supplementation of poultry diet could potentially have a negatively impact on the fatty acid profiles of the resulting meat products, decreasing polyunsaturated fats and/or increasing saturated and monounsaturated fats.
- Areas with food policies that prioritise risk avoidance, such as Europe, have stringent rules about insects that must be addressed before they are marketed. In Europe BSFL are not permitted to feed on animal by-products, nor are the BSFL permitted to be given as feed to other animals (with the exception of fish).

### References

References can be found on page 134.

# R.18 Worms

| **Intended use:** | **Application level:** | | **Treatment technologies:** |
| --- | --- | --- | --- |
| Biomass (e.g., animal fodder, biofuels), Industrial uses, Bioremediation | ** | Household | T.20 Vermicomposting and Vermifiltration |
| | ** | City | |
| **Technical maturity:** | * | Regional | |
| High | * | Global | |





***Compiled by:*** *Swedish University of Agricultural Sciences (SLU) and Allan John Komakech (Makerere University).*

**Worms are underground dwelling invertebrates that are generally associated with decomposing waste. They often function symbiotically and in synergy with bacterial communities. Given the optimum conditions of temperature (20 to 30°C) and moisture (60 to 80%), about 5 kg of worms (approximately 10 000 individuals) can process 1 tonne of organic waste into vermicompost in just 30 days. The five most common species of worms used and produced from vermicomposting are *Eisenia fetida*, *Eudrilus eugeniae, Perionyx excavatus, Eisenia andrei* and *Lumbricus rubellus*, with *E. fetida* (the tiger worm) being the most commonly used.**

## Characteristics

Worms have a high nutritional value, i.e., they contain 60 to 70% protein, 7 to 10% fat, 8 to 20% carbohydrates, 2 to 3% minerals, vitamins A and B and 8 or 9 essential amino acids. It is for this reason that they are used as animal and fish feed. Worms also contain compounds with clot-dissolving properties, lytic acid, and immune-boosting properties that are used to make medicine for humans. Industries use stearic acid from worms to manufacture lubricants, cosmetics and additives for other processes. Worms can be used to clean up polluted sites containing hazardous compounds, such as heavy metals and oil from oil spills.

## Health and safety considerations

Worms cultivated in heavy metal-rich waste or soils should be treated with caution if they are to be reintroduced into the food chain, as they tend to retain toxic amounts of these compounds in their tissues. Worms grown in these conditions are better used in industrial processes. Worm composting and worm filters have limited effect on pathogens. Worms may contain pathogens on their skin or in their gut when harvested and should thus be stored, washed and dried before use.

## Social considerations

There is little known adverse reaction to the use of worms. Sensitisation focussed on acceptance by the food industry (consumers and animal feed processing) is required in order to achieve the full benefits of worms. Composting worms do not feed on meat or dairy products, and thus they do not face the same restrictions for use as animal feed that fly larvae do. However, standard safety monitoring for production of feed will need to be followed.

### Distribution to market

Worms can be harvested from vermicompost using mechanical process such as sieving with a wire mesh or with a rotating cylindrical screen. Light and food can also be used to entice worms in certain directions. Strong light will drive worms to the bottom of the compost (they do not like light), thus concentrating the worms in that area of the compost. Worms will also migrate to fresh food sources, and thus they can be attracted to a new container by adding food at one end. The harvesting and processing of E. fetida is challenging due to their sticky nature and tendency to release toxins when disturbed. Complete separation of worms from compost can be difficult, and mechanical separation will need to be done with care.

After harvesting, it is recommended to store the worms outside the feeding substrate for at least 3 hours to allow the worms to excrete the undigested contents in their guts. Some harvesting techniques stress the worms and cause them to release a toxic fluid. Thus, after harvesting and gut evacuation, it is recommended to wash the worms thoroughly before use in animal feed. The worms will also need to be killed by freeze-drying, osmotic shocking or blanching the worm in hot water. Blanching is preferred since it preserves the nutritional value. In order to prolong the shelf life of the animal feed and reduce transportation costs, drying of the worms is recommended.

Worms and worm-derived products have been commercialised in the United States, India, Canada and parts of Asia. In these regions, there are existing markets for worms within farming communities and as supplements to animal feed manufacturers. The worms can be costly to purchase for industrial use, costing USD 30 to 50/kg in the United States, Canada and United Kingdom for the E. fetida worm, whereas in India production costs are approximately USD 4/kg. Worms will reproduce in the vermicompost; thus, if properly operated, worms can be harvested and sold, making a net profit. However, in cases where worms die in the process and/or the compost needs to be reseeded with worms, it is important to know in advance where replacement worms can be sourced.

### Advantages (+) and disadvantages (-)

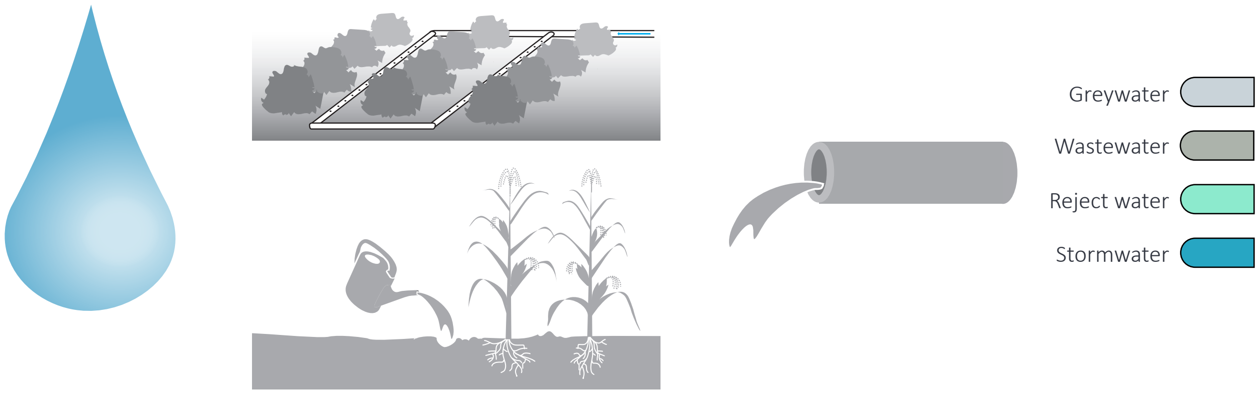
- \+ Worms have a high nutritional value as animal feed.
- \+ Industrial processes can extract useful chemicals from worms, particularly for medicine and pharmaceutical uses.
- \+ Worms can be used in bioremediation of polluted soils.
- \- Harvesting and processing worms can be difficult due to their sticky nature and tendency to release toxins when disturbed.
- \- Worms are relatively sensitive to high concentrations of pathogens, high temperatures, low pH and toxic compounds.
- \- Pests, birds, various insects and rodents can be attracted to the worms and organic material during treatment.

### References

References can be found on page 135.

# R.19 Irrigation Water

| Intended use: | Application level: | Treatment technologies: |
|---|---|---|
| Irrigation | *** Household<br>** City<br>* Regional<br>Global | All technologies that produce an effluent as an output |
| **Technical maturity:**<br>High | | |




***Compiled by:*** *Tilley et al. (2014) and Swedish University of Agricultural Sciences (SLU)*

**To reduce dependence on freshwater and maintain a constant source of water for irrigation throughout the year, wastewater of various qualities can be used in agriculture. However, only water that has had tertiary treatment for pathogen removal (i.e., filtration and/or disinfection) should be used in order to limit the health risks to workers and the risk of crop contamination in horticulture. In addition, high strength effluents, e.g. undiluted reject water from membranes, would be inappropriate for irrigation without dilution.**

## Characteristics

The characteristics of the irrigation water vary considerably depending on the preceding treatment processes. The treated effluent from a conventional centralised wastewater treatment plant contains nitrogen (N), phosphorus (P) and potassium (K) and can serve as a fertiliser and a water source for irrigation.

There are two kinds of irrigation technologies appropriate for treated wastewater: (1) drip irrigation above or below ground, where the water is slowly dripped on or near the root area; and (2) surface water irrigation where water is routed overland in a series of dug channels or furrows. To minimise evaporation and contact with pathogens, flood, spray and sprinkler irrigation should be avoided.

Safely treated wastewater can significantly reduce dependence on fresh water and/or improve crop yields by supplying water and nutrients to plants. Raw sewage or untreated blackwater should not be used, and even effluent from secondary treatment should be used with caution. Long-term use of poorly or improperly treated water may lead to the accumulation of persistent pathogens, excessive/imbalanced addition of nutrients, build-up of salts, accumulation of metals and metalloids and increased concentrations of emerging contaminants in the soils. These, in turn, can cause health risks for farmers and consumers, low crop yields, damage to the soil structure and its ability to hold water and contamination of crops and near water bodies.

### Health and safety considerations

Adequate treatment (i.e., ≥4 $\log_{10}$ pathogen reduction) should precede any irrigation scheme in order to limit health risks to those who are exposed to the water. When effluent is used for irrigation, households and industries connected to the system should be made aware of the products that are appropriate for discharge into the system (e.g., limitations on chemical disposal into the collection system). Drip irrigation is the only type of irrigation that should be used with above ground crops, and even then, care should be taken to prevent workers and harvested crops from coming into contact with the treated effluent. The World Health Organization Guidelines for the Safe Use of Wastewater, Excreta and Greywater should be consulted for detailed information and specific guidance.

Crops such as corn, alfalfa (and other feed), fibres (e.g., cotton), trees, tobacco, fruit trees (e.g., mangos) and foods requiring processing (e.g., sugar beets) can be grown safely with treated effluent. Additional measures (treatment processes and/or management practices) could be needed for fruits and vegetables that may be eaten raw (e.g., tomatoes) because they are exposed to water contact. Energy crops like eucalyptus, poplar, willow, or ash trees can be grown in short rotation and harvested for biofuel production. Since the trees are not for consumption, this is a safe, efficient way of using lower-quality effluent.

### Social considerations

The greatest barrier to the use of treated waste water for irrigation is social acceptance. It may not be acceptable to use irrigation water coming from a water-based sanitation system for edible crops. However, it may still be an option for biomass production, fodder crops and municipal projects such as irrigation of parks, street trees, etc., if it is treated to a level where it no longer generates significant odour or vector problems and appropriate health and environmental regulations are followed.

### Distribution to market

The application rate of irrigation water must be appropriate for the soil, crop and climate, or it could be damaging. To increase the nutrient value, urine or other fertilisers can be dosed into irrigation water; this is called "fertigation" (i.e., fertilisation + irrigation). The dilution ratio has to be adapted to the special needs and resistance of the crop. In drip irrigation systems, care should be taken to ensure that there is sufficient head (i.e., pressure) and maintenance to reduce the potential for clogging (especially with urine, from which struvite will spontaneously precipitate). Overall costs are highly dependent on the system applied. Transport costs of the treated water to the fields must be considered. Irrigation with treated wastewater can generate revenue by increasing agricultural yields and save money if it replaces the need for other fertilisers and water.

Commercial-scale irrigation systems for industrial production are expensive, requiring pumps and an operator. Small-scale drip irrigation systems can be constructed out of locally available low-tech materials and are inexpensive. Ready-made kits are also widely available. A filtration unit before the drip irrigation system is highly recommended to reduce the risk of clogging.

### Advantages (+) and disadvantages (-)

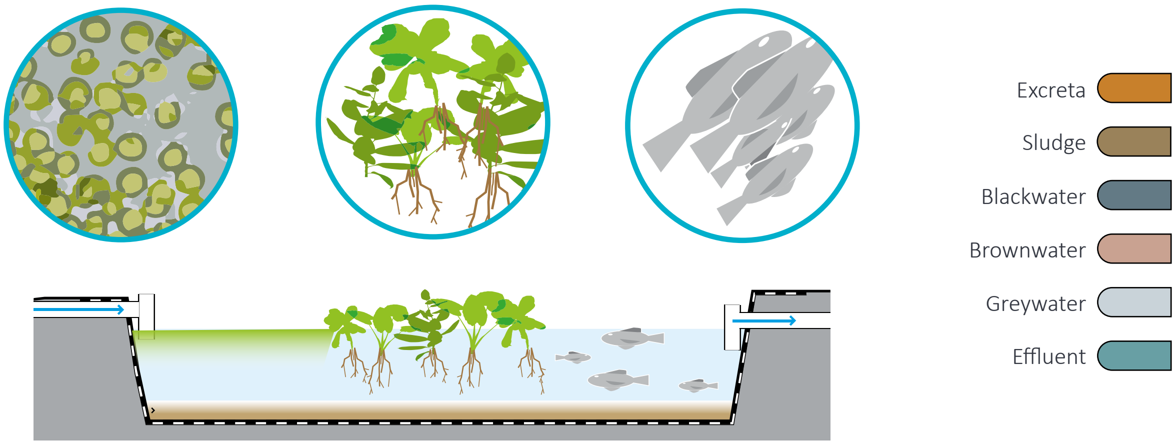
+ Reduces depletion of groundwater and improves the availability of drinking water.
+ Reduces the need for fertiliser.
+ Potential for local job creation and income generation.
+ Low risk of pathogen transmission if water is properly treated.
+ Low capital and operating costs depending on the design.
- May require expert design and installation.
- Drip irrigation sensitive to clogging.
- Risk of soil contamination/degradation.
- Risk of nearby shallow/groundwater body contamination.
- Social acceptance may be low in some areas.

### References

References can be found on page 135.

# R.20 Aquaculture

| **Intended use:** | **Application level:** | **Treatment technologies:** |
|---|---|---|
| Biomass production, Animal feed | Household<br>** City<br>* Regional<br>Global | All technologies that produce an effluent as an output (although dilution may be necessary) |
| **Technical maturity:**<br>High | | |




***Compiled by:** Tilley et al. (2014) and Swedish University of Agricultural Sciences (SLU)*

**Aquaculture, also known as aquafarming, is the farming of fish, aquatic plants, and other organisms. Fish and other organisms can be grown in ponds that receive effluent or sludge, where they can feed on algae and microorganisms that grow in the nutrient-rich water. The fish and aquatic plants remove the nutrients from the wastewater and can eventually be harvested for consumption or use as animal fodder.**

## Characteristics

Three kinds of aquaculture designs function well with effluents from sanitation systems: (1) fertilisation of aquaculture ponds with effluent; (2) fertilisation of aquaculture ponds with excreta/sludge; and (3) practicing aquaculture directly in aerobic ponds (T.5 and T.6).

Fish introduced into aerobic ponds can effectively reduce algae and help control the mosquito population. It is also possible to combine fish and floating aquatic plants in one single pond. For example, duckweed is a fast-growing, high-protein plant that can be used fresh or dried as a food for fish or poultry. It is tolerant of a variety of conditions and can significantly remove quantities of nutrients from wastewater. Fish in ponds do not dramatically improve the water quality, but because of their economic value, they can offset the costs of operating a treatment facility. Under ideal operating conditions, up to 10 000 kg/ha of fish can be harvested. If the fish are not acceptable for human consumption, they can be a valuable source of protein for other high-value carnivores (like shrimp) or converted into fishmeal for pigs and chickens.

Aquaculture is only appropriate where there is a sufficient amount of land (or pre-existing pond), a source of fresh water and a suitable climate. The water used to dilute the waste should not be too warm, and the ammonium levels should be kept low or negligible because of its toxicity to fish. This technology is appropriate for indoor use or tropical climates with no freezing temperatures, and preferably with high rainfall and minimal evaporation.

### Health and safety considerations

The degree of treatment of the incoming effluent into the aquaculture system will determine the level of safety precautions necessary for workers. Workers should wear appropriate protective clothing. World Health Organization (WHO) guidelines on wastewater and excreta use in aquaculture should be consulted for detailed information and specific guidance. There may be concerns about pathogen contamination of the fish, especially when they are harvested, cleaned and prepared. If they are cooked well, they should be safe, but it is advisable to move the fish to a clear-water pond for several weeks before they are harvested for consumption. Aquatic plants such as duckweed can also absorb heavy metals and other toxic compounds, so they should only be grown in wastewater with low concentrations of such compounds.

In cases where excess water in the aquaculture system is discharged to the environment, monitoring of the effluent will need to be established to assure that it meets discharge standards.

### Social considerations

Where there is no other source of readily available protein, this technology may be embraced. The quality and condition of the fish will also influence local acceptance. If aquatic plants are grown, they can make for an attractive pond. A well-designed and maintained aquaculture system can add value and interest to otherwise barren landscapes. However, mosquito problems can develop when the plants are not regularly harvested.

### Distribution to market

Design of the aquaculture system should be based on the nutrient requirements of the fish or other organisms being grown and the water requirements needed to ensure healthy living conditions (e.g., low ammonium levels, required water temperature, etc.). When introducing nutrients in the form of effluent or sludge, it is important to limit the additions so that aerobic conditions are maintained. Depending on the amount of solids that enters the pond, it must be periodically desludged. Trained staff are required to constantly operate and maintain it

Only fish tolerant of low dissolved oxygen levels should be chosen for aquaculture systems. They should not be carnivores and they should be tolerant to diseases and adverse environmental conditions. Different varieties of carp, milkfish and tilapia have been successfully used, but the specific choice will depend on local preference and suitability.

The fish need to be harvested when they reach an appropriate age/size. Occasionally, after harvesting, the pond should be drained so that: (1) it can be desludged and (2) it can be left to dry in the sun for 1 to 2 weeks to destroy any pathogens living on the bottom or sides of the pond.

Floating plants require constant harvesting. The harvested biomass can be used for animal fodder or it can be composted. Depending on the plants grown, harvesting, handling and transport may be labour intensive. For example, duckweed has a high moisture content that increases transport and drying costs. Due to preservation, storage and transportation constraints, plant aquaculture is often restricted to local use.

### Advantages (+) and disadvantages (-)

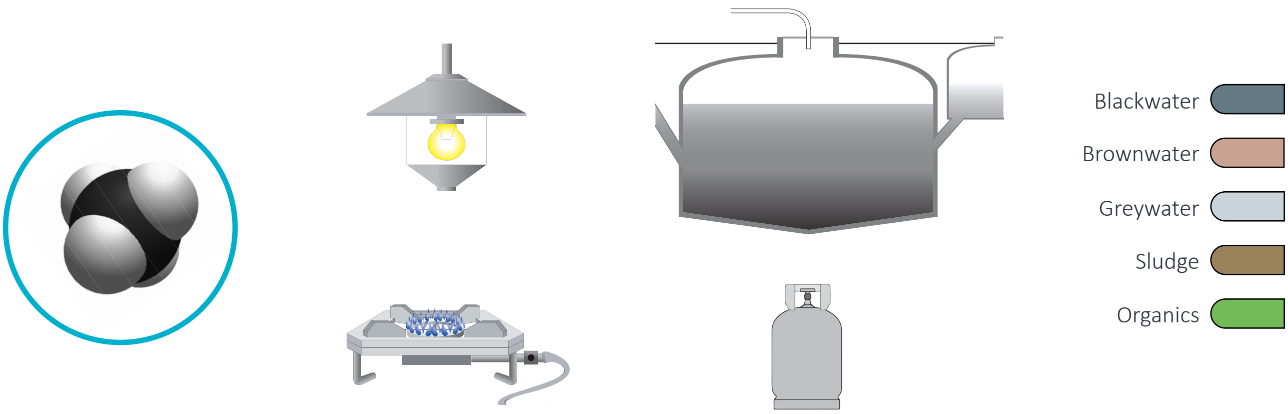
+ Can provide a cheap, locally available protein source.
+ Potential for local job creation and income generation.
+ Relatively low capital costs and operating costs can be offset by production revenue.
+ Can be built and maintained with locally available materials.
- Requires abundance of fresh water.
- Requires a large land (pond) area.
- May require expert design and installation.
- Fish and aquatic plants may pose a health risk if improperly prepared or cooked.
- Social acceptance may be low in some areas.

### References

References can be found on page 135.

# R.21 Biogas

| Intended use: | Application level: | | Treatment technologies: |
|---|---|---|---|
| Heat, Electricity, Vehicle fuel | ** | Household | (S.12 Biogas Reactor, T.11 Upflow Anaerobic Sludge Blanket Rector UASB, T.17 Biogas Reactor) |
| | ** | City | |
| **Technical maturity:** | * | Regional | |
| High | | Global | |




***Compiled by:** Tilley et al. (2014) and Swedish University of Agricultural Sciences (SLU)*

**Biogas is produced through anaerobic digestion of sludge and other organic matter. When produced in household-level biogas reactors, biogas is most suitable for cooking or lighting. Where biogas is produced in large anaerobic digesters, electricity generation or biofuel for vehicles is an alternative. Biogas may be generated from wastewater sludge or fresh excreta; however, the methane potential from faecal sludge is generally low. Addition sources of organic waste may be co-digested to increase biogas generation.**

## Characteristics

The anaerobic digestion process produces a gas mixture that is primarily composed of methane and carbon dioxide, with lesser amounts of hydrogen sulphide, ammonia and other gases. The composition of the produced biogas depends on the substrate that is being digested, the microbial species present in the digester and process control and efficiency. Biogas has an average methane content of 55 to 75%, which implies an energy content of 6 to 6.5 kWh/m$^3$. Biogas is usually fully saturated with water vapour, which leads to condensation. Compared to other gases, biogas needs less air for combustion. Therefore, conventional gas appliances need to be modified when they are used for biogas combustion (e.g., larger gas jets and burner holes). The distance which the gas must travel should be minimised since losses and leakages may occur. Drip valves should be installed for the drainage of condensed water, which accumulates at the lowest points of the gas pipe.

## Health and safety considerations

The gases in biogas pose a number of safety issues. Overall, the risks with biogas include explosion, asphyxiation and hydrogen sulphide poisoning. Risks from pathogens are negligible since pathogens in the substrate are not transmitted to the gas via water vapour.

To prevent blocking and corrosion, the accumulated water has to be periodically emptied from the installed water traps. When using biogas for an engine, it is necessary to reduce the hydrogen sulphide because it forms corrosive acids when combined with condensing water.

Trained personnel must regularly monitor the gas pipelines, fittings and appliances. Training and orientation on biogas safety and system maintenance should be given to support rapid identification of leakages and other potential issues, as such leakages cause a risk for explosion and large greenhouse gas emissions. Proper management of the system and personal protective equipment (PPE) for operators of the system need to be used.

### Social considerations

In general, users find cooking with biogas acceptable, as it can immediately be switched on and off (unlike wood and coal). In addition, it burns without smoke and does not contribute to indoor air pollution. Biogas generated from faeces may not be appropriate in all cultural contexts. In some cases, users will need to learn how to cook with gas. It should also be demonstrated to users that biogas is not dangerous (due to its low concentration of methane). Large-scale production and use of biogas are common practices in wastewater treatment and processing of organic wastes. There are generally no cultural objections to the practice, and biogas even has a positive image as a renewable resource. There can be issues of odour from the treatment plant, and large-scale systems will need to implement odour control measures or be located away from residential areas.

### Distribution to market

For the use of biogas, it is important to consider the calorific efficiency of biogas in different applications, which is 55% in stoves and 24% in engines, but only 3% in lamps. For common household or community level installations, the most efficient use of biogas is in stoves for cooking. For larger installations, the most efficient use of biogas is electricity generation with a heat-power combination. In this case, 88% efficiency can be reached. It is important to strive for high efficiency of biogas use, since this will also mean smaller losses of unburned methane and thus lower emissions of greenhouse gases.

The costs depend on the chosen application for the biogas and the appliance required. At a household level, biogas from a household biogas reactor is generally used for cooking or lightning. Piping from the biogas reactor is required and generally available in local markets. Gas cooking stoves are cheap and widely available. With proper instructions and simple tools, the modifications can be done by a local craftsperson. Many appliances have to be designed specifically for use with biogas, and these are not always widely available. However, conventional gas burning stoves can be easily modified for use with biogas by widening the jets and burner holes and reducing the primary air intake.

Gas demand can be related to the corresponding energy in other fuels. For example, 1 kg firewood corresponds to 200 L biogas, 1 kg dried cow dung corresponds to 100 L biogas and 1 kg charcoal corresponds to 500 L biogas.

Biogas produced from medium and large-scale reactors is commonly converted into electricity, heat or vehicle fuel. This will require investment in processing units, which can be high-tech and expensive. Operation of these processing units will also require skilled technicians.

The following consumption rates can be assumed for biogas: household burners: 200 to 450 L/h; industrial burners: 1 000 to 3 000 L/h; a 100 L refrigerator: 30 to 75 L/h depending on outside temperature; gas lamp, equivalent to a 60 W bulb: 120 to 150 L/h; generation of 1 kW of electricity with biogas/ diesel mixture: 700 L/h and biogas as vehicle fuel: approximately 960 L/km depending on the vehicle.

### Advantages (+) and disadvantages (-)

- \+ Low-cost energy source from renewable resources.
- \+ Can substitute fuel wood and other sources for cooking.
- \+ Comparably few operation skills and little maintenance required.
- \- Biogas can only be stored for several days (low energy density) and needs to be used daily.
- \- Biogas lamps have lower efficiency than kerosene lamps.
- \- Leaked and unburned methane can cause large greenhouse gas emissions.

### References

References can be found on page 136.

# Photos of Reuse Products

Black soldier fly prepupae

Biogas used for cooking

Composted faeces

Digestated blackwater

Pelletised Dry Urine

Nutrient-enriched filter material

Earthworms in vermi compost

Urine diverting double vault (UDDT) compost

# Part 2: Treatment Technologies for Resource Recovery

This section describes treatment technologies in which the primary focus is on safe resource recovery. The technologies described here are generally appropriate for large user groups (i.e., from semi-centralised applications at the neighbourhood level to centralised, city-level applications), although some of them may be applicable for small household-level systems. The technologies are divided into groups based on the primary mode of treatment, e.g., biological, chemical or thermal. Note that the sanitisation processes highlighted here are also chemical processes, but they are highlighted separately because there is no transformation in the treated substrate, as the process primarily aims at pathogen reduction. The technologies highlighted in this document are primarily additional treatment technologies that are not included in the Eawag Compendium of Sanitation Systems and Technologies. There are a number of technologies in the Eawag Compendium that produce recoverable resources, such as sludge or irrigation water. Information sheets for these technologies are not repeated in this document; instead, reference numbers to the Eawag Compendium are referred to where appropriate. In order to avoid confusion with reference numbers, the technologies in this document are numbered starting at T.20.

The operation, maintenance and energy requirements of the technologies within this functional group are generally similar to the Treatment Technologies T described in the Eawag Compendium. Note that the Eawag Compendium also describes processes for pre-treatment or dewatering of liquid waste flows that can be applicable as pre-steps for the technologies included here.

Achieving the desired overall objective of a safe resource recovery treatment process scheme may require a design that logically combines different technologies in multiple-stage configurations (e.g., for pre-treatment, primary treatment and secondary treatment). The choice of treatment technology is contextual and generally depends on the following factors:

- Type and quantity of inputs to be treated (including future developments)
- Desired output product (end use and/or legal quality requirements)
- Financial resources
- Local availability of materials
- Availability of space
- Soil and groundwater characteristics
- Availability of a constant source of electricity
- Skills and capacity (for design, operation, maintenance and management)
- Management considerations
- Local capacity

**Biological**

**T.20** Vermicomposting and Vermifiltration

**T.21** Black Soldier Fly Composting

**T.22** Algae Cultivation

**Biochemical**

**T.23** Microbial Fuel Fell

**T.24** Nitrification and Distillation of Urine

**Chemical**

**T.25** Struvite Precipitation

**Thermal**

**T.26** Incineration

**T.27** Carbonisation

**T.28** Solar Drying

**Physiochemical**

**T.29** Membranes

**T.30** Filters

**T.31** Alkaline Dehydration of Urine

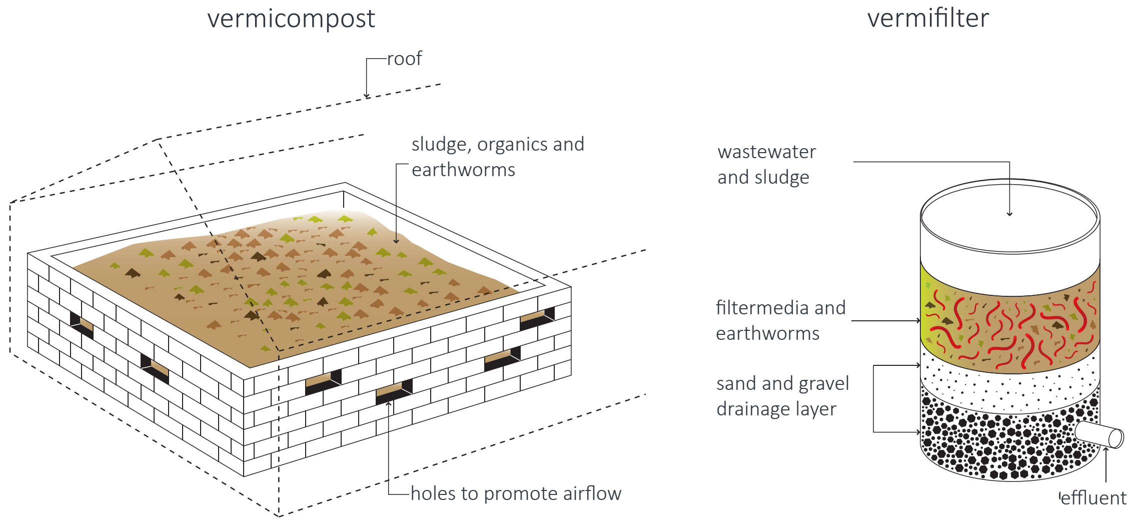
**Sanitisation Processes**

**T.32** Ammonia Sanitisation/Urea Treatment

**T.33** Lime Sanitisation

# T.20 Vermicomposting and Vermifiltration

| **Inputs:** | **Reuse:** | **Application level:** | **Management level:** |
|---|---|---|---|
| Excreta, Blackwater, Sludge, Organics | R.18 Worms, R.11 Compost, (R.19 Irrigation Water) | * Household<br>** Neighbourhood<br>** City | * Household<br>* Shared<br>** Public |
| | | **Technical maturity:** | **Complexity:** |
| | | High | Medium |




***Compiled by:** Gensch et al. (2018) and Allan John Komakech, Makerere University*

**Vermicomposting and vermifiltration are two low-cost options for human and organic waste treatment in which earthworms are used as biofilters under aerobic conditions. The end product is worm cast or compost. Also the worms can be harvested from the system. Depending on the processes, earthworms can reduce the volume of faecal sludge by 60 to 90%. The compost is an nutrient-rich organic fertiliser and soil conditioner. Two parameters are particularly important, moisture content and the carbon to nitrogen (C:N) ratio. By combining human excreta which is high in moisture and nitrogen, with organic solid waste which is high in organic carbon and has bulking properties that promotes aeration, the process and the product can be optimised. The most commonly used method of vermicomposting is the in-vessel method in which the compost is held in an open vessel. Vermifiltration happens in a watertight container that can receive more liquid inputs such blackwater or watery sludge.**

## Design considerations

The design of a vermicomposting facility is similar to co-composting using vessels, but with the addition of earthworms. Vermifilters consist of enclosed reactors containing filter media and worms. These are used on a small scale in worm-based toilets. In vermifiltration systems, the solids (excreta, sludge and toilet paper) are trapped on top of the filter, where they are processed into humus by the worms and bacteria while the liquid passes through the filter. In separating solid and liquid fractions, the quality of the effluent is increased. Using appropriate safety precautions, the effluent water may be used for Irrigation (R.19). Ventilation must be sufficient to ensure an aerobic environment for the worms and microorganisms, while also preventing entry of unwanted flies. The temperature within the reactor needs to be maintained within a range suitable for the species of compost worms used. The specific design of a vermifilter will depend on the characteristics and volume of sludge.

### Applicability

Vermifiltration on a domestic level can be applied anywhere, provided there is access to worms. Labour requirements are comparable to those for operating normal household composts. Vermicomposting requires a high level of organisation and labour to sort organic waste, manage the facility and monitor treatment efficiency. Experience has shown that vermicomposting facilities operate best when they are established as a business venture with compost/worms as a marketable product that can generate revenue to support cost recovery. Sales of compost and worms may partially or fully cover the cost of operations.

### Health and safety

Unlike co-composting, pasteurising temperatures cannot be achieved, as worms and bacteria are sensitive to extreme temperatures; thus, for wastes containing high levels of pathogens (such as raw sewage or septic tank waste), further treatment (e.g., storage) may be required to produce a compost with low pathogen content. Health risks can be minimised if adequate control measures are consistently practiced and workers adopt basic precautions, hygiene practices and wear personal protective equipment. If material is dusty, workers should wear masks. Vermicompost should be stored for at least a year before use or treated to reduce pathogens. If resources exist, helminth egg inactivation should be monitored as a proxy measure of sanitisation.

### Operations and maintenance

A vermicomposting facility requires experienced maintenance staff to carefully monitor the quality and quantity of the input material and the worm health, as well as to manage moisture and oxygen content. Some experiences indicate that worms may be sensitive to high ammonia contents, and thus urine separation should be considered. Organic waste must first be sorted so it is free from plastics and other non-organic materials. Turning must be periodically done either with a front-end loader or by hand using a pitchfork or shovel. A vermifilter has low mechanical and manual maintenance requirements, and if gravity operated requires no energy inputs. Recirculation, if required for improved effluent quality, would require a pump. Prevention against common predators such as ants (black and red), mites, rats, etc. should be undertaken through the adoption of appropriate control methods.

### Social considerations

Before considering a vermicomposting system, the concept needs to be discussed with the involved community beforehand. If the community has experience with separating organic waste and composting, this can be a facilitating factor. Identifying that compost made from human waste is an acceptable product for potential users and ensuring that the compost product conforms to local guidelines and standards are prerequisites.

### Cost considerations

Costs of building a vermicompost facility vary depending on the method chosen and the cost of local materials, and if machinery such as aerators are included in the design. The main costs to consider are the overall operation requirements including labour, transport and supply of faecal sludge and organic solid waste, availability of worms and disposal of compost. The cost of a vermifilter depends on the scale and design of the system. If they are constructed with locally available material and local labour is inexpensive, costs for these systems can be relatively low cost.

### Advantages (+) and disadvantages (-)

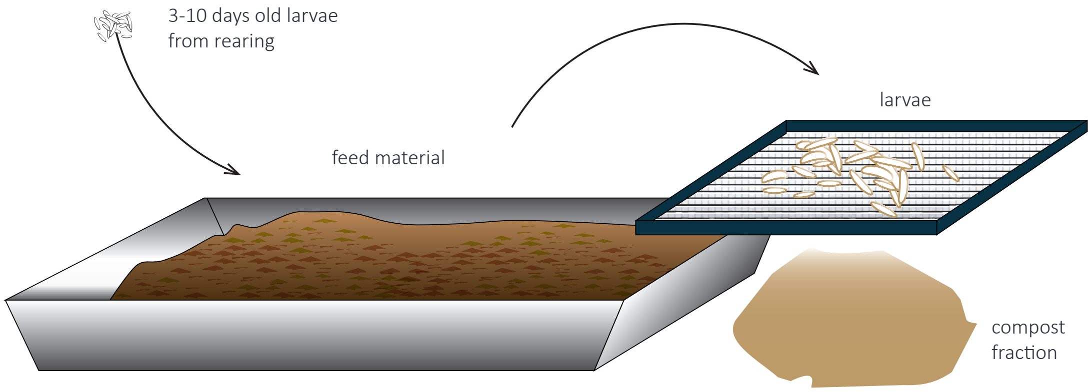
+ Simple robust technology.
+ Can be built and maintained with locally available materials.
+ Relatively low capital costs.
- Vermicomposting requires a large, well-located land area.
- Requires a well-trained and experienced staff to operate it.
- Rodents and other pests can be attracted to the organic material (food waste etc.).
- May require post-treatment.

### References

References can be found on page 136.

# T.21 Black Soldier Fly Composting

| Inputs: | Reuse: | Application level: | Management level: |
|---|---|---|---|
| Excreta, Faeces, Sludge, Organics, (+Dry cleansing material) | R.11 Compost, R.17 Black Soldier Fly Larvae | * Household<br>** Neighbourhood<br>** City | ** Household<br>** Shared<br>*** Public |
| | | **Technical maturity:** | **Complexity:** |
| | | Medium | Low (treatment with larvae) High (production of larvae) |




***Compiled by:** Swedish University of Agricultural Sciences (SLU)*

**The black soldier fly larvae (BSFL) treatment technology is a biological treatment technology that relies on the natural growing cycle of the black soldier fly *Hermetia illucens* (L.), *Diptera*: *Stratiomyidae*. The BSFL feed only during the larval stage, then migrate for pupation and do not feed anymore, even during the adult stage. The larvae feed on 25 to 500 mg of organic matter/larva/day from a wide range of decaying organic materials, such as fruits and vegetables, fish or animal manure and excreta. BSFL reduce the presence of harmful bacteria such as *Escherichia coli* and *Salmonella enterica*; however, parasites are not inactivated in the treatment. As the larvae feed, a fraction of the organic material is converted into larval biomass. The treatment residue, comprised of the larval droppings and undegraded material appears as a compost-like material that can be used as soil conditioner. The larvae can be harvested a source of protein in animal feed**

## Design considerations

BSFL treatment usually takes place in boxes, bins or containers measuring 60 to 100 cm × 40 to 80 cm × 17 to 30 cm. Upon completion of the treatment, the larvae are usually separated from the substrate using a mesh. This can be done manually or automated. For small-scale systems, the growth chambers can be built with ramps to enable the larvae to crawl out of the feeding material at the final larval stage, thus making them self-sorting. The ramps should be built at angles (20 to 45°), and lead from the base plate of the container to the upper end of each shorter side panel. A drainage system or ventilation is required when working with wet material such as household waste or pig manure, or if the system is operated in a humid climate. This to prevent accumulation of stagnating liquids that might create anaerobic conditions. It is necessary for large-scale facilities to rear BSFL at the treatment site to ensure continuous production of larvae.

## Applicability

Treatment of waste using BSFL can be carried out at both household and municipal levels. The larvae can consume most organic feed substrates; however, fibrous feeds may need pre-treatment or should be co-composted with a less fibrous substrate. The larvae can consume large amounts of waste and have been demonstrated to reduce the dry matter content of manure by 58% and that of municipal organic waste by 70%. Large-scale protein production facilities treating up to 200 tonnes of organic waste per day are already in operation, with a focus on protein production.

## Health and safety

The risk of disease transmission to animals and humans when BSFL compost is used as soil conditioners in agriculture is low because BSFL inactivates bacterial pathogens such as *Salmonella* spp. and *Escherichia coli.* However, BSFL have demonstrated to have no impact on the destruction or inactivation of *Ascaris* spp. eggs. Therefore, if the treatment residues are intended for use in food crop production, an additional sanitising treatment step, e.g., ammonia sanitisation (T.32), is recommended. Before using the larvae in animal feed, further processing, such as drying, would be required.

## Operations and maintenance

Usually, 4 to 10-day-old larvae are used for treatment. They are removed from the BSFL rearing units and placed onto the waste in the treatment units. The number of larvae used depends on the amount of waste per surface area. The larvae are usually fed incrementally over a period of about 3 weeks, until they have grown large enough to be harvested. An incremental feeding approach is generally more efficient, but it is possible to feed them all the waste at once as a batch process.

Harvested larvae are either sold alive to farmers or further processed through drying or scalding in hot water to remove any bacteria that may have attached onto the surface of the larvae. The optimal conditions for growth of BSFL include temperature ranging between 29 to 31°C, a relative humidity of 50 to 70% and moisture content ranging from 40 to 75%. A moisture content in this range is important for larval development and residue separation. Care should be taken to ensure that the waste is neither too dry nor too wet, lest the larvae fail to feed.

## Social considerations

Despite some acceptance issues with the use of maggots, treatment of organic waste using BSFL has gained momentum over the last decade, mainly due to the growing demand for locally produced animal feed. This has opened new economic niches for small entrepreneurs. The motivation to use this technology at the household level often comes from the thought of self-sufficiency and to make organic waste management more environmentally and economically sustainable.

## Cost considerations

BSFL technology has low investment costs, as the treatment units can be assembled using relatively cheap, locally available materials, such as metallic sheets. The operating costs, including labour, are likely the largest cost. The end product, larvae, can be sold as animal feed, thus contributing to the economic sustainability of the BSFL system.

## Advantages (+) and disadvantages (-)

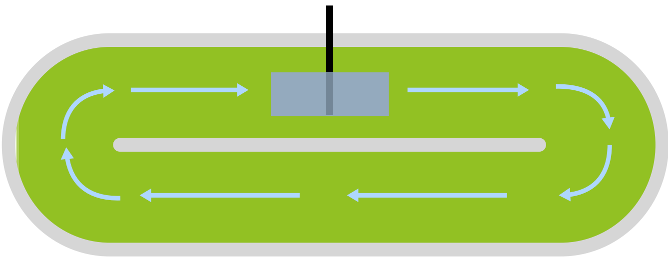
+ Conversion of organic waste into high-protein biomass.
+ Fast volume reduction of organic wastes.
+ Larval movement aerate the material thus preventing anaerobic conditions and greenhouse gas emissions.
+ Adult black soldier flies do not feed and thus are not vectors for disease transmission.
- BSFL require tropical temperatures which may require heating.
- Low feeding rates result in a long treatment time.
- BSFL treatment requires access to eggs, either purchased or reared. Rearing of flies require environmental control and trained personnel.
- Post-treatment may be required if residue is to be applied in cultivation.

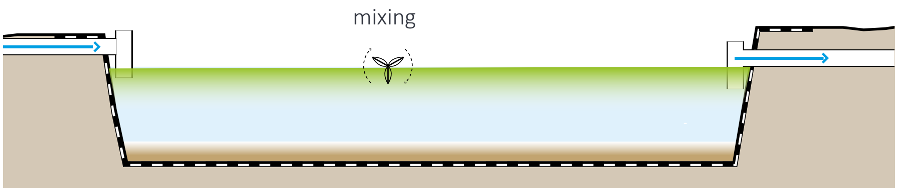
## References

References can be found on page 137.

# T.22 Algae Cultivation

| **Inputs:** | **Reuse:** | **Application level:** | **Management level:** |
|---|---|---|---|
| Reject water, Wastewater, (+Blackwater), (+Brownwater), (+Urine) | R.15 Algae. (R.19 Irrigation Water), (R.20 Aquaculture) | Household<br>* Neighbourhood<br>** City | Household<br>* Shared<br>** Public |
| | | **Technical maturity:** | **Complexity:** |
| | | High | Low |






***Compiled by:*** *Swedish University of Agricultural Sciences (SLU) and Eva Thorin (Mälardalen University)*

**Algae cultivation generates algae biomass from wastewater streams, usually from open shallow ponds or photo-bioreactors, using artificial light or sunlight. Containments are designed for maximum light penetration. For shallow ponds, this means a depth typically within the range of 0.5 to 1.5 m. As the algae grow, they utilise the dissolved nutrients in the water (phosphorus, nitrogen and carbon). Photosynthetic algae will release oxygen into the water while they consume carbon dioxide. The algae are then harvested, dewatered and converted into biomass that can be utilised for biofuel generation, soil conditioning and other applications such as food, supplements and chemical processing.**

## Design considerations

There are two major types of large-scale algae culture systems, open ponds and closed photo-bioreactors. Algae are cultivated in suspension or on attached systems like algal turf scrubbers.

In order to obtain high biomass yields, close control of the growth conditions and potential contaminations (such as fungal infestation) is needed. The selection of the most appropriate cultivation system should consider the microalgae strain used, the geographical location and the desired product. Although open systems are more widely used than closed ones, closed systems allow for greater control of conditions and higher biomass concentrations. There are three types of closed systems: tubular photo-bioreactors, flat plate reactors and bag systems. Optimal parameter ranges for algae cultivation are shown in the table on the next page.

The algal species best suited for oil production are *Scenedesmus* spp., *Chlorococcum* spp. and *Tetraselmis* spp. If the nutrient content of the water is inadequate for algae, growth fertilisers can be added; however, this will increase the costs of cultivation.

Harvesting and dewatering are important steps in this technology. Common harvesting methods include sedimentation, flocculation, centrifugation and filtration. Drying of microalgae can be done by centrifuge, freeze drying or sun drying.

| Parameters | Range | Optimal |
|---|---|---|
| Temperature (◦C) | 12-27 | 18-24 |
| Salinity (g $L^{-1}$) | 12-40 | 20-24 |
| Light intensity (lux) | 1 000-10 000 | 2 500-5 000 |
| Photoperiod (light: dark, hours) | | 16:8 (min) 24:0 (max) |
| pH | 7-9 | 8.2-8.7 |

### Applicability

Algae cultivation is well suited for regions with high solar irradiation that promotes increased algal growth. If open-pond systems are used, sufficient space will be needed for construction. Closed photo-bioreactors require less space; however, they may require an energy source for artificial lighting.

### Health and safety

In open-pond systems, some species of microalgae may provide habitats for mosquitoes that cause malaria. Open systems are also more prone to fungal infestation and contamination. More knowledge is needed regarding the potential health and environmental risks from the use of engineered species and disinfectants and the bioaccumulation of contaminants in algae product and by-products. Depending on what substrate is used for algae cultivation, there may be risks for pathogens exposure.

### Operations and maintenance

Effluent characteristics (such as turbidity, chemical oxygen demand/biochemical oxygen demand (COD/BOD) and nitrogen and phosphorus concentrations) and selection of the microalgae species (e.g., *Spirulina* spp., cyanobacteria or naturally occurring species) are critical in reactor design and operations. Pre-treatment may be required to minimise the total solids content and maximise light penetration into the system. Efficiency of the system is enhanced by optimising operating parameters such as hydraulic retention time, temperature, mixing, $CO_2$ availability and cultivation mode. At times, fertiliser addition may be required to boost the nitrogen and phosphorus concentrations. Aside from functions relating to the above, harvesting of algal biomass is the most intensive operation. There are commercial products available that assist in algae harvesting.

### Social considerations

There is some debate regarding the space and energy efficiency of algae cultivation, which has delayed the acceptance of this technology despite its potential. Further sensitisation is needed to boost the uptake and development of this technology, particularly with regard to energy efficiency.

### Cost considerations

It has been reported that separation of the biomass from microalgae cultures can reach 30% of the total production cost. Cost reductions are expected through research into engineered algae species, harvesting techniques and large-scale production. Although closed systems can optimise biomass production, the total costs of the closed systems are a major limitation on their commercialisation.

### Advantages (+) and disadvantages (-)

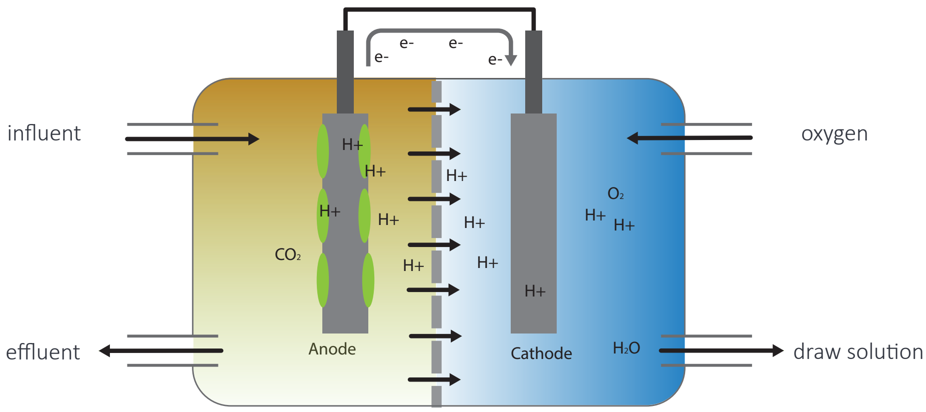
+ Low energy requirements.
+ Low operation and maintenance costs.
+ Environmentally friendly due to $CO_2$ fixation and heavy metal absorption.
- Heavy metal absorption can reduce the suitability of algae as a product or intermediary in some application.
- Current algae harvesting techniques are costly and inefficient.
- Large space requirements.
- Open ponds are prone to contamination that affects quality of the product.

### References

References can be found on page 137.

# T.23 Microbial Fuel Cell

| **Inputs:** | **Reuse:** | **Application level:** | **Management level:** |
|---|---|---|---|
| Urine, Reject water, Wastewater, (+Excreta), (+Sludge), (+Blackwater) | Electricity, (R.19 Irrigation Water), (R.20 Aquaculture) | * Household<br>** Neighbourhood<br>** City | * Household<br>** Shared<br>** Public |
| | | **Technical maturity:** | **Complexity:** |
| | | Low | Medium |




***Compiled by:** Swedish University of Agricultural Sciences (SLU)*

**Microbial fuel cells (MFCs) are a wastewater treatment technology that utilises bacteria to produce electricity through the conversion of chemical energy found in wastewater, while at the same time reducing the pollutant loading in the effluent water. Reduced pollutants include organics, nitrogen, phosphorus, sulphides and heavy metals. An MFC system consists of cathode and anode compartments that are separated by a cation exchange membrane in which oxidation-reduction reactions occur.**

## Design considerations

The main design parameters are the number of chambers, wastewater composition and the selection of electrode material. The performance of MFCs depends on parameters such as pH, temperature, substrate, type of bacteria and internal resistance. MFCs have successfully been integrated into constructed wetlands, anaerobic digesters, activated sludge systems and septic tanks. Depending on choice of integration, the optimum design factors can vary. Adequate attention should be given to matching the MFC to the local conditions.

The simplest MFC is composed of single cathode and anode compartment separated by a cation exchange membrane with graphite/platinum electrodes. The single-compartment MFC removes the need for the cathodic chamber by exposing the cathode directly to air. Multi-compartment MFCs generally produce higher power densities and greater wastewater treatment compared to single-electrode MFCs. However, multi-compartment MFCs are associated with high internal resistance build-up and cathode fouling, and in these cases more concern should be given to organic and hydraulic loading during design.

Higher organic loadings and hydraulic retention times (HRT) have been associated with higher power generation. Bio-electrodes (often with the aid of algae) in the MFC compartments are necessary for the sustainability of large-scale application because they reduce the energy, environmental and cost footprints of the overall technology compared to those of conventional abiotic electrodes. Bio-cathodes eliminate the need for hazardous chemical agents as electron acceptors. Exoelectrogenic bacteria are used in MFCs, and research into engineered microbe strains to boost electrical energy generation has been proposed.

### Applicability

MFCs are applicable in many settings due to their ambient operating conditions and the possibility of integration with existing treatment technologies. MFCs can be integrated into other treatment technologies at all levels, including domestic, centralised or industrial treatment. At a domestic scale, the MFCs can be incorporated into existing septic tanks. They are most applicable within a centralised system due to the technical complexity and high capital costs. However, limited research is available regarding use of MFCs with high-volume reactors and variable feedstock, which creates some uncertainty regarding their applicability in large-scale processes.

### Health and safety

The technology is relatively safe while operating under normal conditions. MFCs have been reported to reduce chemical oxygen demand (COD) by 85% and total nitrogen up to 90%. However, there is a need for more research regarding pathogen reduction and other potential health and safety issues arising from the microorganisms within the MFC.

### Operations and maintenance

MFCs can be operated in batch or continuous processes. They should be operated under ambient conditions, and neutral pH is preferred for an efficient system. Operators should ensure that organic loading rate and microbial activity are kept at optimal levels for efficient functioning of the MFC components. Monitoring the feedstock concentration and feeding rate, as well as the power generation is crucial. It should be noted that MFCs integrated within other treatment processes may present a new set of operational and maintenance issues that need to be given proper consideration.

### Social considerations

No significant social issues are reported, although community sensitisation may be necessary for acceptance of technology, particularly for decentralised installations (e.g., in septic tanks).

### Cost considerations

A major drawback of this technology is the high capital investment, primarily owing to expensive electrode and membrane material. Operation costs generally include pumping of oxygen, process monitoring and catalyst dosing when applicable. In order to reduce capital costs, semi-coke, carbon cloth and activated carbon have been suggested as potential lower cost alternatives for electrodes. Other factors like the HRT, cell configuration and the number of cathodes, anodes and separators also affect the capital cost. For example, increasing the HRT significantly increases the cost of the MFC despite the amount of electricity generated increasing as well.

### Advantages (+) and disadvantages (-)

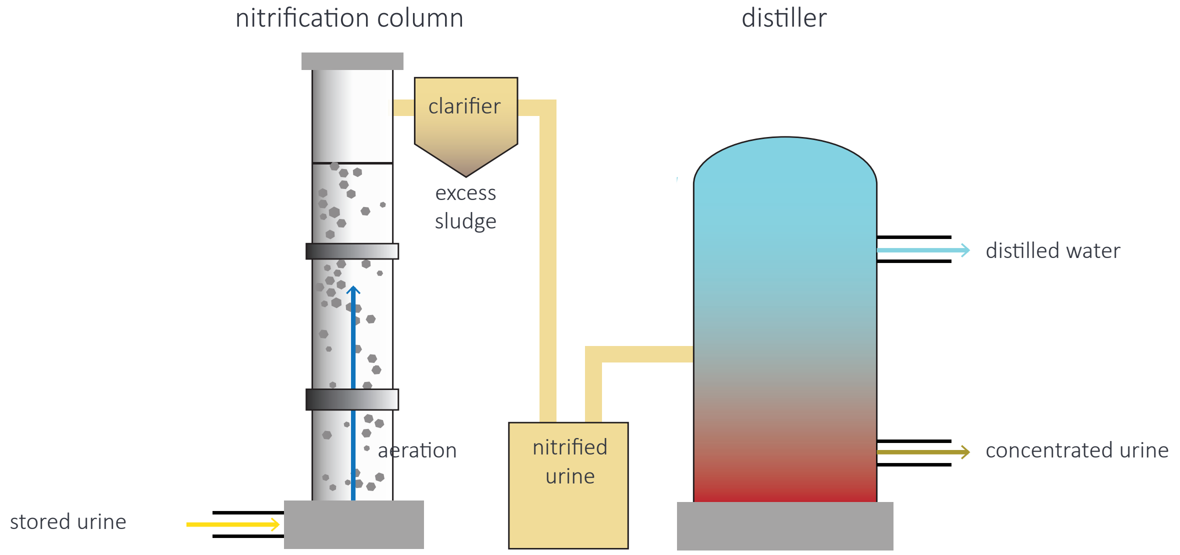
- \+ MFCs can produce clean electricity directly from organic matter in wastewater.
- \+ Possibility of integration with other existing wastewater treatment technologies.
- \+ Low operation and maintenance costs.
- \+ High potential for heavy metal recovery or reduction in wastewater.
- \- MFCs are an expensive technology due to electrode and membrane materials.
- \- Power densities can vary with electrode choice, type of feedstock, HRT, temperature and design configurations.
- \- There remains uncertainty regarding pathogen reduction and operations with variable feedstock.

### References

References can be found on page 137.

# T.24 Nitrification and Distillation of Urine

| **Inputs:** | **Reuse:** | **Application level:** | **Management level:** |
|---|---|---|---|
| Urine | R.2 Concentrated urine (Distilled water) | * Household<br>** Neighbourhood<br>* City | * Household<br>** Shared<br>* Public |
| | | **Technical maturity:** High | **Complexity:** High |




***Compiled by:*** *Swedish University of Agricultural Sciences (SLU) and Bastian Etter (Vuna GmbH)*

**Nitrification and distillation of urine is a complete nutrient recovery technology that yields a liquid nutrient solution through nitrification, purification and distillation of urine. The technology transforms pure urine into distilled water (capturing 93 to 97% of the water) and a nutrient solution containing nitrogen, potassium, sulphur and phosphate, as well as micronutrients (e.g. boron, iron, and zinc).**

## Design considerations

The system consists of the following parts: a urine storage tank, nitrification column with automatic control, activated carbon filter, intermediate storage tank, vacuum distiller and final product storage tanks. The critical components are the nitrification column acting as a bioreactor, the activated carbon column and the distillation unit.

A vacuum distiller is used to produce the concentrated urine, which is marketed as liquid fertiliser (R.2). Current nitrification and distillation systems can treat up to 200 L of urine per day, but the design is easily scalable to higher flow rates.

## Applicability

The technology requires the input of urine, which can be collected from urine-diverting toilets and waterless urinals. It is currently applied on a neighbourhood scale in Durban, South Africa, with decentralised urine collection and treatment at a local treatment plant. It is theoretically possible to scale the technology down for household use or scale it up by having multiple installations citywide. The complete installation of the system has a footprint of approximately 5 $m^2$, whereas the room accommodating it should not be smaller than 10 $m^2$ to ensure proper access and ventilation.

## Health and safety

Formation of ammonia gas in the headspace of urine tanks can be toxic when inhaled. High nitrite concentrations in the reactor can lead to the formation of volatile noxious compounds, which are harmful to humans and the environment. Operators should use masks and appropriate protective equipment if the urine storage tank has to be opened. The treatment unit necessitates sufficient air space and ventilation, like any technical equipment placed in a building.

The treatment process removes pathogens; however, for micropollutant removal it is recommended to include a final polishing step with activated carbon filtration that will efficiently eliminate all pharmaceutical residues. The final product is thus free from pathogens, pharmaceuticals and smell and meets health and safety regulations.

### Operations and maintenance

Efficient functioning of the reactor can be controlled using remote monitoring systems. The operation of the system is fully automated and based on a nitrite sensing technology developed by Eawag and Vuna. The ideal operating temperature conditions in the reactor are 20 to 30°C. Maintenance involves calibration of the pH probe and rinsing of pipes twice a year. General maintenance of piping system and pumps, as well as inspections twice a year, should be done throughout the system's service life.

### Social considerations

Demonstrations and training are essential for appropriate use of the urine collecting technology in order to avoid urine contamination that can affect the concentration process. Recent studies have demonstrated that more than 50% of farmers generally favoured the use of human urine as a fertiliser compared to fertilisers derived from faeces. The produced distilled water has been proposed for several options, such as in toilet flushing, car batteries and irrigation, since it meets the national standards for these activities in several countries. The fertiliser product is fully licenced in Switzerland, with pending applications in further European countries.

### Cost considerations

The bulk of the costs associated with nitrification and distillation of urine come from piping installation, distiller and process control, with medium energy demands of 150 Wh per litre of urine.

### Advantages (+) and disadvantages (-)

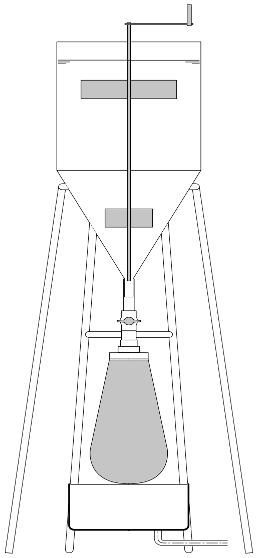
- \+ All nutrients in urine (>99%) are recovered with a malodour-free product.
- \+ Complete pathogen and pharmaceutical reduction.
- \+ Can be installed with minimal retrofitting in urine-diverting toilets.
- \- Requires electricity, especially for efficient distillation and for the required automatic control nitrification.

### References

References can be found on page 138.

## T.25 Struvite Precipitation

| Inputs: | Reuse: | Application level: | Management level: |
|---|---|---|---|
| Urine, Reject water, (Wastewater), (+Blackwater) | R.7 Struvite, (R.19 Irrigation Water), (R.20 Aquaculture) | Household<br>* Neighbourhood<br>** City | Household<br>* Shared<br>** Public |
| | | **Technical maturity:** High | **Complexity:** Low |




***Compiled by:*** *Swedish University of Agricultural Sciences (SLU) and Grietje Zeeman (Wageningen University & Research)*

**Struvite precipitation is a process used to recover phosphorus (P) from either urine or concentrated wastewater. Struvite precipitation occurs under specific pH conditions when concentrations of magnesium (Mg), phosphate ($PO_4^{3-}$) and ammonium ($NH_4^+$) are close to an equimolar ratio of 1:1:1. The resulting product is predominantly a P fertiliser containing Mg and nitrogen (N) and can be used as a slow-release fertiliser.**

### Design considerations

Common reactors for struvite crystallisation are upflow fluidised bed reactors and air-agitated reactors. Feed solutions, typically concentrated wastewater or reject water, enter the reacting zone from the bottom of the reactor. Upward airflow allows for uniform fluidisation of particles to prevent the growing struvite particles from settling. Airflows can also help to maintain a pH of 8 to 9, which is necessary for struvite crystallisation. The pH can also be adjusted by NaOH addition. Magnesium is also commonly added to maximise P recovery. The technology can be operated in batch mode based on demand.

The struvite crystals are then filtered out and dried to produce a solid fertiliser (R.7). Phosphorus capture in these types of processes differs with molar ratios of the struvite constituents, pH and reactor type. However, if designed well, more than 90% P recovery is possible.

### Applicability

Struvite precipitation has been applied widely in wastewater treatment processes to reduce excess phosphorus in the effluent from anaerobic sludge digestion processes. This enables the treatment plants to reduce the cost of operation and maintenance while simultaneously recovering struvite. Reactors for struvite precipitation are normally too large and complex for application on a household scale.

### Health and safety

Struvite precipitation does not inactivate pathogens, nor does it capture a majority of the nutrients in wastewater (e.g. remaining N, potassium (K) and others).

Thus, the effluent will need to be treated to eliminate hygiene risks and prevent aquatic pollution if it is released into water bodies. The struvite precipitate itself may also need sanitising. This may be done by exposing the precipitate to high salinity during dewatering, drying and storage. The levels of organic contaminants and heavy metals detected in struvite are usually below the permissible limits, but they vary with composition of the input stream.

### Operations and maintenance

Struvite recovery is controlled by the solution's supersaturation point, pH, molar ratio of nutrients ($Mg:NH_4:PO_4$), temperature, reaction time and mixing conditions. To ensure a high recovery rate, these factors have to be monitored closely. For crystallisation to occur, the solution should be supersaturated with respect to struvite. Supersaturation may be created by increasing the solution content in $NH_4^+$, $Mg^{2+}$ or $PO_4^{3-}$, and/or raising the pH. Theoretically, struvite is formed at a molar ratio of 1:1:1 for $Mg:NH_4:PO_4$. In practice, the optimum ratio is usually different due to the presence of competing species that form by-products.

Struvite can be formed within the pH range of pH 8 to 10. At a pH of >10, struvite formation is inhibited due to the formation of other compounds, such as $Mg_3(PO_4)_2$ and $Mg(OH)_2$, that consume $Mg^{2+}$ and $HPO_2^{4-}$ ions. Under optimal conditions, struvite crystallisation can occur rapidly. In precipitation reactors, it occurs within 10 to 60 minutes of stirring.

At low temperatures (5 to 20°C) the solubility of struvite increases, resulting in smaller particles. The struvite crystal structure is stable below 55°C. Struvite is optimally dried at temperatures between 30 and 50°C to avoid mass loss.

### Social considerations

Struvite precipitation from urine requires large volumes of urine, and transporting the urine to the struvite production site can be costly. Therefore, it is advisable to produce struvite close to the source of urine production, e.g., from areas using urine-diverting toilets. When conducting struvite precipitation on P-rich side streams at a centralised wastewater treatment plant (WWTP), these issues are mitigated

### Cost considerations

Struvite precipitation can require chemicals to increase the pH to values above 8.5, and to supply the necessary Mg to reach the needed

molar concentrations. This increase in operational costs, which may be reduced by using alternative low-cost Mg sources such as bittern, pre-treated magnesite or magnesite rock. Cost incentives for recovering struvite recovery should take into account environmental benefits, rather than purely looking at the fertilising value of the recovered product.

### Advantages (+) and disadvantages (-)

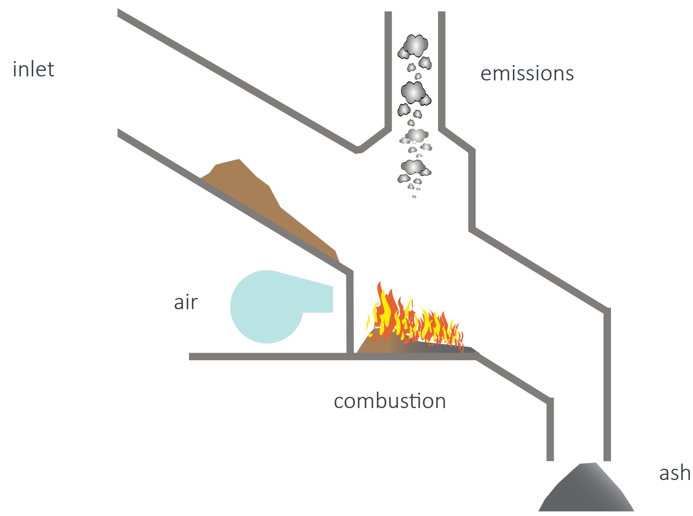
+ Struvite recovery removes P and N from wastewater, thus reducing nutrient emissions to receiving surface waters.
+ The system can operate with or without electricity.
+ Reactors for struvite precipitation can be constructed with local materials and be operated in batches.
- May require addition of a soluble Mg source.
- The effluent requires further treatment for pathogen and nutrient reduction.
- The majority of the nitrogen in the input stream is generally not recovered.

### References

References can be found on page 138.

# T.26 Incineration

| Inputs: | Reuse: | Application level: | Management level: |
|---|---|---|---|
| Excreta, Faeces, Faecal sludge, Sludge, (+Dry cleansing material), (+Organics) | R.12 Ash from sludge, Electricity, Heat | Household<br>* Neighbourhood<br>** City | Household<br>Shared<br>*** Public |
| | | **Technical maturity:**<br>High | **Complexity:**<br>High |




***Compiled by:** Swedish University of Agricultural Sciences (SLU) and Charles Niwagaba (Makerere University)*

**Incineration is the controlled combustion of waste. The heat produced can be recovered as an energy source in district heating systems or for electricity and heat production utilising steam turbines. The incineration process includes three main parts: combustion, energy recovery and air pollution control. Incineration combusts organic matter and evaporates water from the feed substrate (e.g., sludge), leaving an inorganic ash. The ash can be used as a soil conditioner, solid fertiliser (the majority of phosphorus (P) and potassium (K) remain in the ash) or construction material.**

**Usability of the ash will depend on the quality of the input substrates. If the substrate is contaminated, the ashes may need to be landfilled. Incineration works best with dewatered, semi-dry or dry substrates. When semi-dry inputs are used, the energy to dry them can be harnessed from the combustion process, thereby minimising external energy inputs.**

## Design considerations

Incineration can be set up as either mono-incineration (i.e., incineration of one substrate) or as co-incineration (i.e., incineration of several mixed substrates). The prevailing technologies for mono-incineration of sludge are fluidised bed combustors (FBCs) and multiple heat furnaces (MHFs), with the most common being the FBC.

The combustor design should account for input substrates with variable composition, e.g., various water contents depending on the substrate used. Adequate ventilation is necessary for complete combustion, so airflow is a key design parameter. If the substrate is wet, there will be evaporation water that needs to be removed from the system. The exhaust gas from the combustion process should be cleaned, e.g., with an air scrubber, before it is released to the environment.

### Applicability

Incineration of sludge and other wastes is currently applied in many industrialised countries for the purpose of volume reduction and, increasingly, for energy recovery. The process is mainly applied on a large scale. It is suitable for industrialised contexts and areas that have strict limitations concerning sludge landfilling and agricultural reuse. The technology is also applicable when distances to alternative reuse or disposal sites are long or space at the treatment plant is limited.

### Health and safety

Incineration effectively eliminates pathogens in the substrate due to the high temperatures. A majority of organic pollutants and pharmaceuticals will also be destroyed. However, most of the heavy metals in the input material will accumulate in the ash, which may limit the potential for direct reuse of the ash. The quality of the ash produced will need to be monitored to determine appropriate usage/disposal. Technologies exist for extracting value resources such as metals and phosphorus from the ash.

Air pollution is a major problem for incineration. In modern incinerators, advanced pollution control systems (electrostatic precipitators, acid gas scrubbers, etc.) are designed to minimise pollution and to ensure compliance with environmental standards.

### Operations and maintenance

Under normal operating condition, excess air must be added to an incinerator in order to ensure complete combustion of the sludge. Besides enhancing contact between fuel and oxygen in the furnace, relatively high rates of excess air are necessary to compensate for variations in both the organic characteristics of the sludge feed and the rate at which it enters the incinerator. Preheating of the incoming air and/or pre-drying of high-moisture feed is generally required in order to reach the required incineration temperature of about 800°C. In general, incinerators require a high skill level to design, construct and maintain the systems, which may initially be problematic in low-income contexts. Incinerators experience significant downtime for routine maintenance and therefore require redundancy, backup or possibilities for waste storage.

### Social considerations

One major constraint for the widespread use of incineration is public concern about possible harmful emissions. However, new technologies for controlling gaseous emissions, such as gas scrubbing, can minimise these adverse effects.

### Cost considerations

The incineration process needs to deal with large quantities of polluted exhaust gases. The costs of an efficient and adequate gas treatment system are very high. Co-incineration of human excreta and sludge with municipal solid waste may have cost advantages over mono-incineration, depending on supply and transport factors.

### Advantages (+) and disadvantages (-)

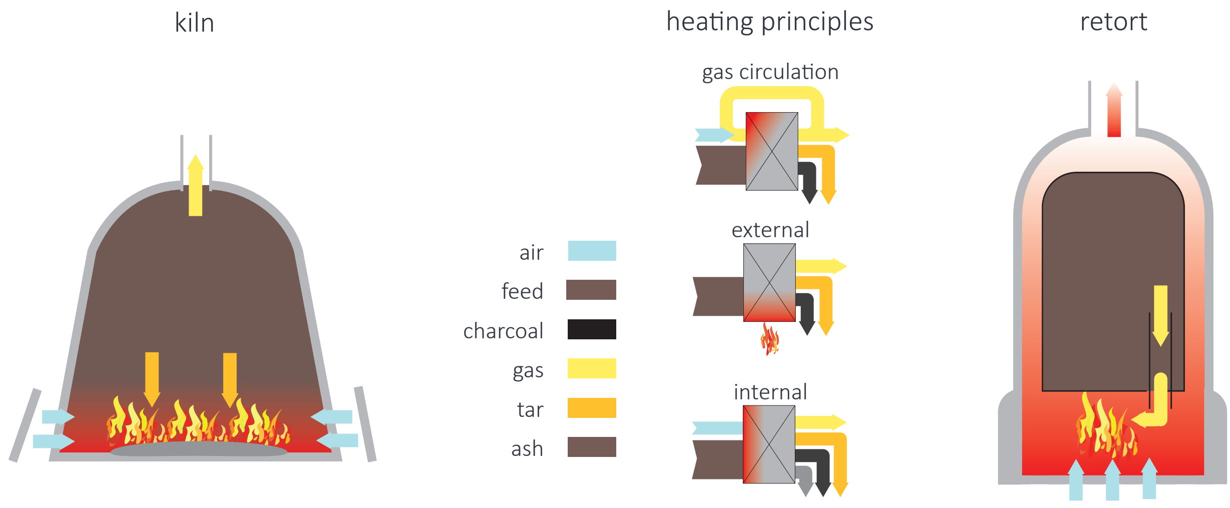
+ Fast treatment- generally only hours.
+ Large reduction of waste volume.
+ High temperatures destroy pathogens and potentially organic contaminants such as pharmaceutical compounds.
+ Recovers energy, e.g., for district heating or for electricity production.
+ Possibility of P recovery from leaching the ash.
- Wet biomass requires drying before it can be used as a feedstock.
- Control measures are needed to assure the capture and treatment of exhaust gases.
- Input feeds should be monitored and controlled to limit the amount of heavy metals that accumulates in the ash.
- The carbon footprint of incineration has been shown to be considerably higher than those of other sludge management options.

### References

References can be found on page 139.

# T.27 Carbonisation

| Inputs: | Reuse: | Application level: | Management level: |
|---|---|---|---|
| Excreta, Faeces, Faecal sludge, Sludge, (+Organics), (+Dry cleansing materials) | R.13 Biochar, Bio-oil, Syngas, Heat | * Household<br>* Neighbourhood<br>** City | * Household<br>* Shared<br>** Public |
| | | **Technical maturity:**<br>High | **Complexity:**<br>High |




***Compiled by:*** *Swedish University of Agricultural Sciences (SLU) and Christian Zurbrügg (Eawag)*

**Carbonisation is a process of thermal decomposition of organic material at high temperatures without oxygen. The organic inputs are transformed into a solid carbon material resembling charcoal that is commonly referred to as biochar. There are several different types of processes for carbonisation, including dry pyrolysis, gasification and wet pyrolysis, also known as hydrothermal carbonisation (HTC). Carbonisation allows for significant energy and nutrient recovery. In addition to biochar, carbonisation can produce bio-oil and syngas. The potential to recover these additional products varies with the process and the substrate that is used. Each carbonisation technique uses different temperatures, heating duration, or reactor pressure to produce different quantities and qualities of the end products.**

## Design considerations

Feedstocks for carbonisation include organic matter such as municipal solid waste, sludge, wood and crop residues from agricultural fields. The drier the feedstock, the better the conversion efficiency and yield. Pyrolysis reactors are classified as kilns or retorts. Kilns are traditional reactors that focus on char production, with less emphasis on resource recovery from the gas products. Retorts are spherical distillation reactors with downward-pointing necks that are capable of recovering products from the liquid and gas by-products.

Carbonisation processes are controlled by temperature, time and oxygen availability. In general, the process should be operated without or with little oxygen. Heating the incoming biomass to high temperatures (generally greater than 200°C) changes the chemical structure of the biomass, increasing its carbon density.

Carbonisation can be performed using batch or continuous feed processes. For higher energy efficiency and consistent end product quality, continuous reactors are used. The energy required to drive the carbonisation process can be supplied from an external fuel source, directly from the heat produced from exothermic reactions of pyrolysis (more suitable for community scale) or from combustion of pyrolysis fuel gases derived from by-products of pyrolysis (more suitable for household and single farm scale). A gas filtering system, such as a bag filter, should be incorporated into the reactors to reduce harmful environmental gas emissions.

### Applicability

Carbonisation of sludge is usually done at a centralised level, where sludge can be dried prior to the thermal treatment. The drying process may be an integral part of the wastewater treatment plant or can be pre-treatment of the proposed installation for the carbonisation of sludge. Co-pyrolysis of sludge with other feedstocks such as wood, sawdust or coffee husks may be done to reduce moisture and increase the carbon content.

### Health and safety

The contents of organic chemicals or pathogens are significantly reduced during carbonisation due to the high-temperature conversion process. In addition, the remaining heavy metals in the resulting biochar are generally not available for uptake in growing plants. Accidents at carbonisation plants can be greatly reduced by use of safety devices such as safety helmets and by safe working habits.

Safety devices include pressure relief doors, automatic temperature shutdown and electric power failure devices, among others. Failure of the filter bags to work efficiently may expose the workers and the environment to noxious emissions.

### Operations and maintenance

Feedstock is loaded manually for batch processes, whereas for continuous processes, it is done mechanically using conveyor belts. An oxygen-free environment should be maintained during carbonisation. Accidental introduction of air into the pyrolysis reactor, for example, through leaks in the reactor, may create unstable combustion and result into explosions or fires. Regular inspection and maintenance of filter bags and safety devices are a necessity to minimise accident occurrences.

### Social considerations

Construction of carbonisation plants near residential areas may result in protests from locals because of fear of possible airborne emissions, odours or smoke.

### Cost considerations

The type of reactor used affects the cost of construction, as well as the cost of operation. For example, in batch reactors, the feedstock must be heated to the reaction temperature using an external fuel source, and this may lead to high operating costs despite the fact that batch reactors have a low capital cost. Continuous reactors tend to have a high capital cost compared to those of batch and semi-batch reactors. Costs for electricity are incurred if mechanical equipment is used for feedstock loading, air pollution control and process control/ monitoring equipment. Manual labour costs are also incurred if the loading is not mechanised.

### Advantages (+) and disadvantages (-)

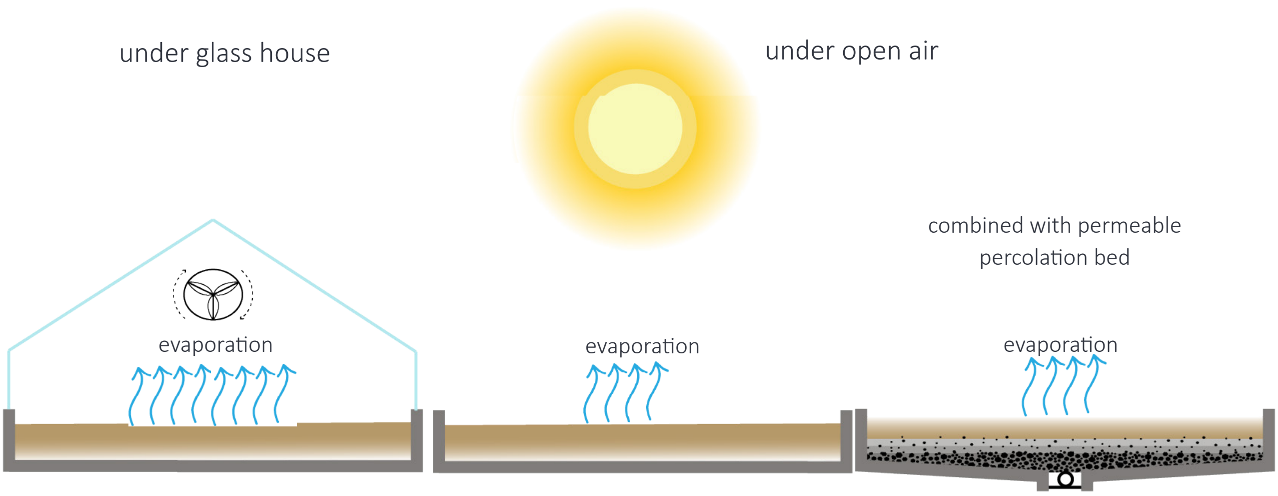
+ Fast treatment time - generally only hours.
+ Carbonisation allows significant energy and nutrient recovery.
+ High temperatures destroy pathogens and organic contaminants.
+ Significant volume reduction of solid residues.
+ A source of revenue when biochar or other products such as energy and oils are sold.
- Self-ignition of biochar may occur due to oxidisation during storage or transportation.
- Wet biomass requires drying before it can be used as feedstock.
- Control, recovery and management of noxious combustion gases are expensive.
- Input feeds should be monitored and controlled to limit the amount of heavy metals in the biochar.

### References

References can be found on page 139.

# T.28 Solar Drying

| Inputs: | Reuse: | Application level: | Management level: |
|---|---|---|---|
| Excreta, Faeces, Sludge, Faecal Sludge, Blackwater, (+Organics) | R.8 Dried Faeces, R.10 Dewatered Sludge | * Household<br>** Neighbourhood<br>** City | * Household<br>** Shared<br>** Public |
| | | **Technical maturity:** High | **Complexity:** Medium |




***Compiled by:** Swedish University of Agricultural Sciences (SLU)*

**Solar drying is a treatment technology that utilises solar energy to stabilise waste, usually within a tunnel-type greenhouse following mechanical dewatering. Solar energy in the form of heat raises the ambient temperature, which in turn increases evaporation that reduces the moisture content of the waste and inactivates pathogens. The dry product has a reduced mass and volume that eases its cost of storage, handling and transport. Heat transfer is often aided by fans and ventilation to renew the humidified air above the waste.**

## Design considerations

Sludge from wastewater, on-site systems and blackwater after dewatering to about 20% total solids (TS) is preferred for solar drying. Solar drying can be done using covered or open drying beds with either batch-type or continuous operations. The covered bed is generally more efficient than the open one due to better control of drying conditions. Covered beds may be fitted with fans for ventilation to facilitate drying. In contrast, open drying beds rely on wind and solar effects.

Covered drying beds generally utilise a greenhouse construction. The greenhouse should be of glass or transparent material with an impervious concrete floor. The greenhouse takes up a large amount of space, in some cases up to 1 500 $m^2$, and is often divided into bays about 5 m in width and 20 m in length, although the size depends on the volume of sludge to be dried.

The critical design parameters for dimensioning a solar drying system are those that affect the evaporation process, e.g., solar radiation levels and the ambient dehydrating conditions (i.e., air temperature, humidity and its superficial velocity). Increasing any of these parameters favours the drying process. Highly light-transmitting material should be used for construction of the greenhouse. Design parameters should be based on values of ambient conditions during rainy/ cold season to ensure a conservative design.

In colder regions, auxiliary heating sources like infra-red lamps and floor heating systems can be installed to facilitate the heating process. Another important design aspect is surface renewal by turning, which can be done by hand or mechanically. Mechanical turning often uses machines mounted on two parallel concrete walls along the drying bed. Liming (often 15% of the dry solids (DS) is also used to aid the dehydration and sanitisation effect.

### Applicability

Solar drying technology is best applied under a centralised system and is most suitable for tropical regions with sufficient solar radiation year-round. However, with additional heating systems, it can be adopted in colder climates. It is not ideal for areas with space restrictions.

### Health and safety

Solar drying is generally a safe technology, although there are problems associated with odour and air quality resulting from the heat and emissions of gaseous ammonia ($NH_3$) and volatile organic compounds (VOC). These conditions also attract disease vectors. However, biofilters can be used to treat the air released from covered drying beds. Pathogen inactivation is related to the level of dryness that is achieved. Helminth eggs in particular may survive with as little as 5% moisture. The dried sludge product is odour free and can be classified as a U.S. Environmental Protection Agency (USEPA) class B biosolid if it meets regulations for pathogen reduction. Heavy metals in the incoming substrate will not be removed. There are limited data on the efficiency of removal of other hazards like pharmaceutical residues.

Usual personal protective equipment in the form of overalls, gas masks and gumboots are encouraged during operations, particularly if hand tools are used to turn the waste.

### Operations and maintenance

The operational activities involve spreading the waste evenly on the drying beds and turning. The waste is applied in thick layers and turned over once or several times a day by hand or mechanical processes. Specialised machinery for turning the sludge can be obtained from private companies.

### Social considerations

Solar drying has predominantly been used for food preservation, and its application for waste treatment requires further education and familiarity with it was a possible technology. This will build confidence in using the dried sludge product as an odourless and pathogen-free soil conditioner.

### Cost considerations

Recent publications place the CAPEX and OPEX costs of a covered plant in Nicaragua at roughly 800 USD/tonne and 50 USD/tonne of untreated sludge respectively. The CAPEX includes cost of installation of covered drying bed (1 460 $m_2$ in this example) in terms of construction, ventilators and turning machines, but excludes land acquisition. The operation costs include the electrical power requirements for ventilators and turning equipment. Of course, manual turning or uncovered drying beds would significantly reduce the costs. However, this would come with increased health risks for workers and reduced drying efficiency.

### Advantages (+) and disadvantages (-)

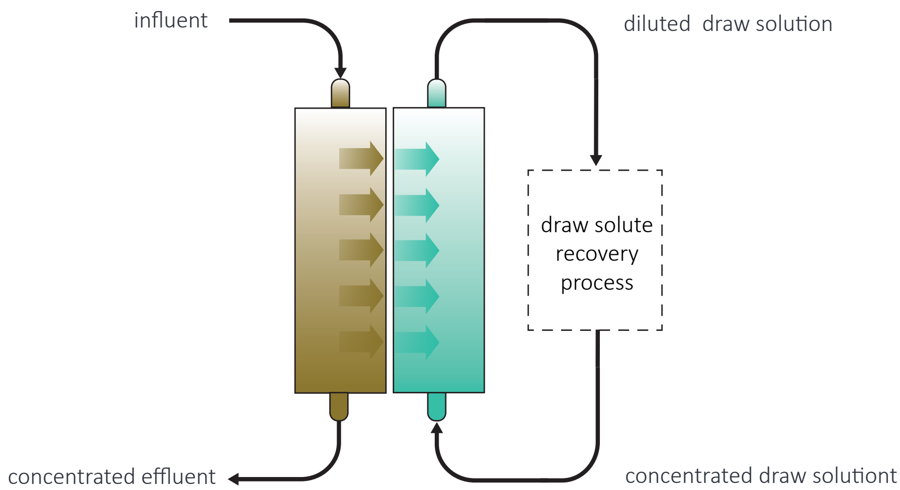
- \+ Low energy requirements.
- \+ Simple and durable installation.
- \+ Relatively safe dry product is produced as sludge is dried, classified at least as USEPA Biosolids Class B.
- \- High space demands.
- \- Relatively long drying time in cold climates if no additional heating is used.
- \- Drying efficiency may vary with weather conditions.

### References

References can be found on page 140.

# T.29 Membranes

| Inputs: | Reuse: | Application level: | Management level: |
|---|---|---|---|
| Greywater, Reject water, Urine, Wastewater, (+Blackwater), (+Brownwater), | R.5 Nutrient Solutions, (R.19 Irrigation Water), (R.20 Aquaculture) | Household<br>* Neighbourhood<br>** City | Household<br>* Shared<br>** Public |
| | | **Technical maturity:** High | **Complexity:** High |




***Compiled by:** Swedish University of Agricultural Sciences (SLU)*

**Membranes are semi-permeable materials designed for selective filtration of liquids. Membrane application in the field of wastewater treatment aims to reduce organic and nutrient content in the wastewater stream and/or resource recovery. Membranes separate solids, nutrients and liquid fraction using concentration gradients (e.g., osmosis) or physical barriers that create pressure gradients (e.g., microfiltration). Advanced membrane technologies such as nanofiltration (NF), reverse osmosis (RO), forward osmosis (FO), and membrane distillation (MD) have shown great potential for wastewater treatment and reuse. Forward osmosis is the most widely used membrane in wastewater treatment.**

## Design considerations

The main design aspects of membranes include the feed and draw solutions, draw solute recovery process, membrane material, orientation and placement within the treatment process. The draw solution is the source of the driving force in FO, with brine (NaCl) and magnesium chloride ($MgCl_2$) being the most used. Draw solutions should be non-toxic, easily recoverable and cheap. Membrane materials should be dense, porous and selectively permeable.

Membranes are made with two layers: a selective layer and a supportive layer. The selective layer is commonly oriented to the feed side (input flow). Orientation facing the permeate side is associated with higher membrane fouling, although there are reports of higher water flux compared to the feed side orientation.

Membranes, particularly FO membranes, are often considered a pre-treatment technology but can be integrated into other wastewater treatment technologies. For example, they can concentrate organics in feed flows to anaerobic digestion, thus increasing methane yield and minimise heating requirements. Membranes can be used to recover concentrated nutrient solutions (e.g., calcium/

magnesium phosphates and struvite) and clean water.

### Applicability

Due to the high technical complexity and capital investments of current membrane technology, it is most applicable at higher management levels in centralised systems. Membrane technology is widely applicable to a number of waste streams and can easily be integrated into existing treatment options as discussed above.

Nanofiltration membranes are best suited for urine treatment due to their high rejection of pharmaceuticals and endocrine disruptors, which tend to persist in other treatment options. MD is well suited to removing heavy metals from waste.

### Health and safety

Studies concerning the use of membrane technology consider it a relatively safe technology during operation. Contaminant accumulation like that of trace organic compounds hampers the quality of the recovered resource in membranes and can lead to membrane fouling. Handling of hazardous cleaning chemicals needed for maintenance of the membranes can pose a significant health risk and necessitates proper staff training and the use of personal protective equipment (PPE).

### Operations and maintenance

Membrane technology can operate in continuous flow or batch operations. The osmotic process of the FO membranes is a naturally occurring phenomenon that does not require any external energy provided the draw solute is available without energy input. Depending on the physical driving forces used in other membrane processes (e.g., pressure, heat or electricity), the operation of membranes may require a considerable amount of energy input.

MD systems require heating of the feed solution to 45 to 90°C depending on the nature of feed solution and system design. For long-term operation, there are issues of salinity accumulation, membrane fouling and product purity. Granular activated carbon (GAC), adsorption and ultraviolet (UV) oxidation are effective in mitigating fouling issues on the membrane. However, the choice of draw solution and membrane material significantly affect the effectiveness of such mitigation strategies.

### Social considerations

No significant social issues are reported with acceptance of membrane technology. However, it is technically complex to design and operate and will require trained staff to assure proper operation and maintenance.

### Cost considerations

The refreshing of the draw solution dictates the energy consumption of the entire system. FO and MD systems have significant potential in this regard due to the possibilities of utilising thermal energy from solar or waste heat. Membranes may have high investment costs and moderate operation costs due to the maintenance of membranes and draw solutions, including chemical inputs. Optimisation of membrane materials and draw solutions will likely lower costs.

### Advantages (+) and disadvantages (-)

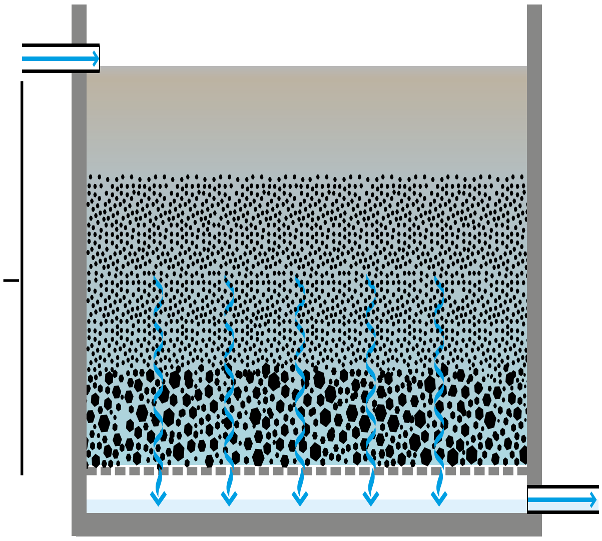
+ FO has low energy requirements, provided that a draw solution is freely available (e.g., in locations close to salt water).
+ Extraction of clean water when hybrid system processes are used, i.e., RO and MD.
+ High nutrient recovery potential (e.g., ammonium, struvite, and calcium phosphate) with correct choice of design.
+ MD can be run with low-grade thermal heat from other processes (e.g., industrial waste heat, solar, or biogas).
+ MD has higher separation efficiency and is less prone to fouling compared to other membrane technologies.
- High capital investment costs.
- Problem of potential accumulation of contaminants in the draw solution.
- When membranes eventually foul costly replacements and/or hazardous regeneration chemicals will be necessary.

### References

References can be found on page 140.

# T.30 Filters

| **Inputs:** | **Reuse:** | **Application level:** | **Management level:** |
|---|---|---|---|
| Urine, Wastewater, Greywater, Stormwater, (+Blackwater), (+Brownwater) | R.14 Nutrient-Enriched filter material, (R.19 Irrigation Water), (R.20 Aquaculture) | ** Household<br>** Neighbourhood<br>* City | ** Household<br>** Shared<br>* Public |
| | | **Technical maturity:** High | **Complexity:** Low |




***Compiled by:** Gensch et al. (2018) & Allan John Komakech, Makerere University*

**Filters use the mechanisms of straining (filtering), adsorption and biodegradation to remove target contaminants from wastewater. The filter material can be made of organic materials or minerals. When wastewater flows through a filter, normally by gravity, particles are filtered and retained on the surface, bacteria degrade organics and other contaminants (e.g., phosphate or ammonium) are absorbed in the material and thus removed from the water. Depending on the type of filter material, the material can become enriched with phosphates and other nutrients and may therefore be used as a solid fertiliser.**

## Design considerations

Filter material can be organic or mineral-based. Mineral-based filter materials include soil, sand, crushed rock (e.g., chalk or calcium silicate) or natural or synthetic porous mineral (e.g., zeolites). Organic filter materials include biochar, bark, activated charcoal and peat, among others.

It is also possible to use hydrated ash. The performance of the filter material in removing organic pollutants depends on the type of filter material used and on how the filter was designed in terms of particle size, distribution or surface area, depth of filter and hydraulic and organic loading of the feed. Smaller particle diameters of filter material usually have a larger surface area and higher absorption capacity, while coarser materials have a lower capacity. The removal efficiency for organics improves with increasing filter depths of ≥0.6 m.

The sorption process occurs in three steps: (1) external mass transfer of solute molecules (e.g., phosphate ions) from the feed solution to the sorbent particle surface, followed by (2) diffusion within the particle internal structure, where (3) rapid uptake at sorption sites occurs. The sorption capacity depends on both the number and affinity of sorption sites. Once the available adsorption sites are filled, the removal efficiency is significantly diminished.

Activated charcoal and biochar are excellent adsorbents due to their strong affinity for binding organic substances, even at low concentrations. These materials have a vast network of pores of various sizes that give them a large surface area for binding both large and small contaminant molecules. Calcium silicate is also known for its high sorption capacity of soluble phosphorus.

### Applicability

This technology is most suitable for areas with low population density and non-sewered localities where on-site wastewater treatment (OWT) is widely practiced. To treat wastewater using filters, the solids concentration in the influent should be low because fouling and clogging often results from high organic loading.

### Health and safety

Filter materials with small particle sizes can remove high levels of microorganisms, e.g., bacteria, by filtration. Alkaline filter materials, e.g., calcium silicates and chalk, have a high pH at the beginning of their use. These high pH values can inactivate microorganisms and significantly reduce their numbers and prevent the spread of pathogens from wastewater in the environment. However, high organic loading can result in clogging and short-circuiting in the filter, which will reduce the removal efficiency. In addition, filter materials may have pathogen content at the end of their lifetime, and precautions should be taken when replacing filter material and prior to reuse of the material.

### Operations and maintenance

Pre-treatment is important to achieve optimum contaminant removal and increase the lifespan of filters. Solids removal using a screen, prefiltration or a septic tank may help avoid clogging of the filters when in situ.

Operating the filter beds intermittently or at a relatively high hydraulic conductivity also reduces the risk of clogging. Regular inspection and analysis of effluent is necessary to ensure that it meets the disposal standards.

For on-site wastewater treatment, effluent usually enters the filter system using a pipe from the septic tank, where it is distributed over the filter bed. The wastewater is treated as it flows through the filter, after which the water is infiltrated into the ground or discharged to a receiving water body, such as a wetland. It may also be used for irrigation.

### Social considerations

Filter technologies to treat wastewater is widely accepted and used, especially in suburban and rural areas, due to their ease of operation and convenience.

### Cost considerations

Some of the filter materials are naturally occurring in certain areas, making them readily available and inexpensive. For example, soil, sand and crushed stones are available everywhere. Zeolites are abundant throughout the western United States, while calcium silicate is abundant in Poland. Biochar is widely available in low-income countries that use charcoal for cooking and heating.

Filters are relatively cheap to operate due to their low maintenance. They have no moving parts, so nothing can break. However, they need to be monitored to ensure that no clogging occurs and that the filters are functioning well. Replacement of the filter material will be necessary when it has been saturated.

### Advantages (+) and disadvantages (-)

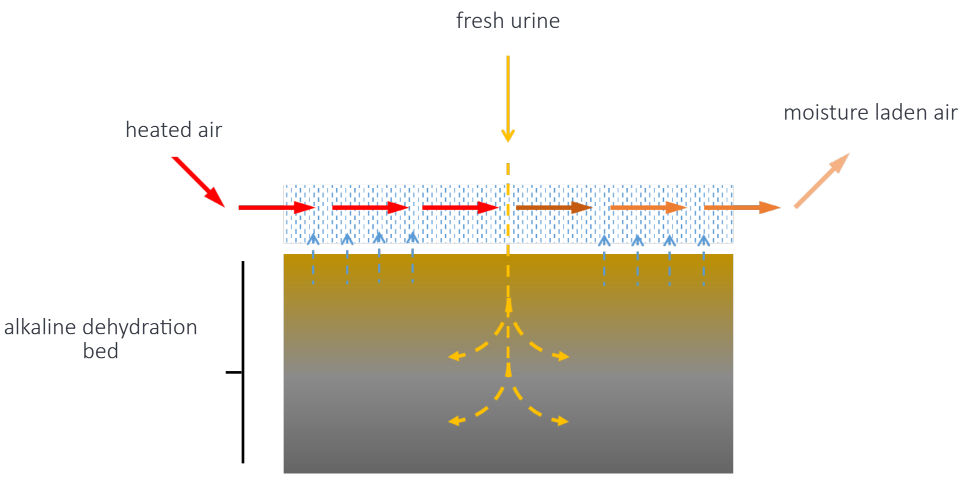
+ In alkaline filter materials, the initial effluent wastewater may have a pH of 9 to 12. These high pH values can significantly reduce the presence of microorganisms.
+ Filters have low operational costs.
- Heavy organic loading can lead to blockage of the micro-pores, which can reduce treatment efficiency.
- Use of the filter technology may be limited in some areas due to limited abundance of source materials and a lack of awareness or knowledge of their use.
- The high pH of the effluent during the first weeks of treatment may pose a risk to aquatic fauna if the recipient is a small water body.

### References

References can be found on page 141.

# T.31 Alkaline Dehydration of Urine

| Inputs: | Reuse: | Application level: | Management level: |
|---|---|---|---|
| Urine | R.6 Dry Urine | ** Household<br>** Neighbourhood<br>* City | ** Household<br>** Shared<br>** Public |
| | | **Technical maturity:**<br>Medium | **Complexity:**<br>Low |




***Compiled by:*** *Swedish University of Agricultural Sciences (SLU)*

**Alkaline urine dehydration is a post-urine diversion treatment technology that coverts liquid urine into a dry, solid fertiliser. It is a two-step, on-site treatment technology. First, fresh human urine collected from a urine-diverting toilet or urinal is added to an alkaline substrate (e.g., lime or wood ash). The high pH of the substrate prevents the biochemical degradation of urea (the main form of nitrogen in urine) to ammonia (which is volatile). Subsequently, the alkaline urine and substrate mixture is dehydrated by forced ventilation to yield a dry end product (R.6 Dry Urine).**

## Design considerations

The alkaline urine dehydration unit should be located as close to the toilet as possible. Any pipe transport will increase the degradation of urea and cause odour issues. Critical elements for design of a urine dehydrator are the properties of the drying substrate (elemental composition, pH and EC, solubility, etc.), and the dehydration conditions (air flow, humidity and temperature). For the process to function, the pH of the alkaline substrate must be kept above 10. Locally sourced substrate could be ash, biochar and/or lime.
The operating conditions dictate how often the alkaline substrate needs to be replaced; e.g., a family-scale dehydrator with 6 kg of wood ash substrate treating 6 kg urine per day can be used for 1 month. Urine dehydration rates can be increased by: (1) increasing the surface area of drying substrate; (2) increasing air-flow; (3) increasing air temperature; and (4) reducing air humidity. Warming the inlet air, by either solar or other means, would increase dehydration rate by increasing the water-holding capacity of air.

## Applicability

Alkaline urine dehydration is appropriate in all settings with assured electricity supply. In settings without electricity or with limited supply (informal settlements and rural areas), a passive urine dehydrator needs to be designed, but this may require large surface areas, especially in areas with high relative humidity. Like all toilets, the airflow should be directed upward, with a chimney to disperse any odours that may be generated.

### Health and safety

Few pathogens are excreted via the urine; however, during excretion and collection of the urine in urine-diverting toilets, cross-contamination from faeces occurs. Dehydrated urine in an alkaline medium inactivated both bacteria and viruses after just four days of storage at 20°C. For helminth eggs, a thermal treatment (≥42°C for 5 days) or a storage treatment in a sealed container (111 days at 20°C or 79 days at 35°C) is recommended in order to meet the WHO and U.S. EPA guidelines for unrestricted reuse of excreta in agriculture.

Care should be taken not to inhale vapours directly from the treatment unit as they may contain low concentrations of ammonia. At higher concentrations (>50 ppm) ammonia can be an irritant to the eyes and lungs. Such risks can be managed with good ventilation. The alkaline substrate used in the treatment can be a skin irritant and cause damage to the eye. Handling of the substrate should be performed outdoors or in a well-ventilated area and using personal protective equipment.

### Operations and maintenance

As the system's performance is dependent on the ambient air conditions, installations need to be adjusted to the local climate. After the initial adjustments, maintenance should include: (1) cleaning the pipes with an alkaline solution (to prevent biofilm building up); (2) regularly changing the dehydration substrate; and (3) checking the system components (fans). The volume of urine treated by the system will dictate the frequency of maintenance. For example, for a system in an office serving 25 people, (1) is performed once a week, (2) is performed once a month, and (3) is performed once a year.

The nutrient-rich dried urine can be used on-site as a fertiliser or collected and transported in the same way as municipal solid waste (MSW). A service provider catering to this can operate either by door-to-door collection or by collection at transfer stations where users deposits their dried urine. Regardless of service model, further cost optimisation, economies of scale and/or density can be created if the collection and transportation of dried urine is combined with that of MSW. Multi-compartment trucks for collection of source-segregated wastes or optical sorting of differently coloured bags in a mixed collection system would help make this possible.

### Social considerations

The technology requires source-separated fresh urine, meaning that toilet users need to use urinals or urine-diverting toilets (which requires acceptance and training). A social acceptance survey is needed to assess if private homeowners would rather change the substrate themselves or allow personnel into their house to do it for them. The preference may be different in different regions. Recent studies have demonstrated that several regions would generally accept the use of human urine as a fertiliser.

### Cost considerations

The treatment unit can be assembled by the user using off-the-shelf materials, since it does not require sophisticated components. The simplest variant can be built for less than USD 50. Establishing a whole service chain (to support collection of the dried urine and maintenance of the system) will require a minimum number of users and minimum investments (costs of which would be site specific). Depending on local temperature and climate, the energy consumption for forced ventilation can be significant.

### Advantages (+) and disadvantages (-)

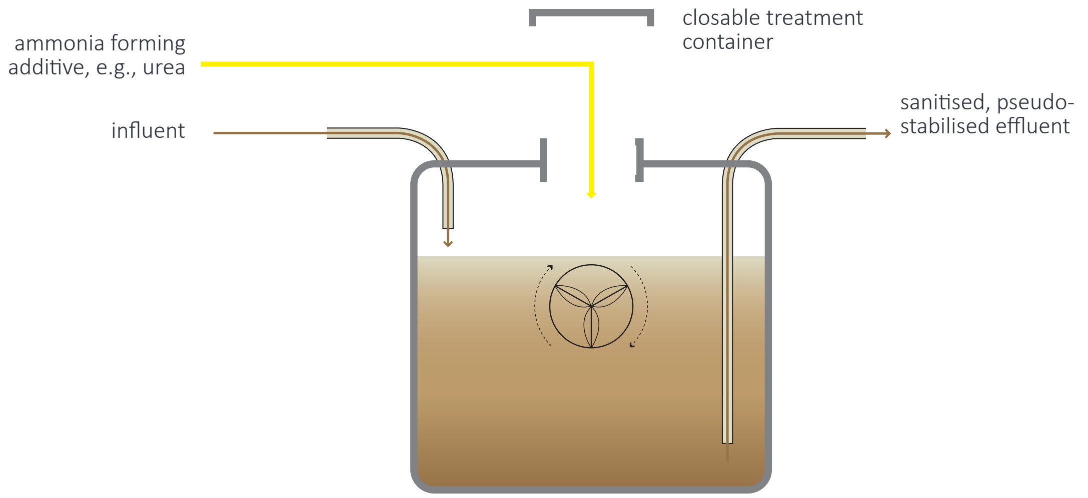
- \+ Recovers all macronutrients (>95% nitrogen) and micronutrients normally present in urine.
- \+ Compact and fits into existing bathrooms with minimal retrofitting.
- \+ Can be assembled using off-the-shelf materials.
- \- Requires connection to a urinal or urine-diverting toilet.
- \- Usually requires an electricity supply.

### References

References can be found on page 141.

# T.32 Ammonia Sanitisation/Urea Treatment

| **Inputs:** | **Reuse:** | **Application level:** | **Management level:** |
|---|---|---|---|
| Blackwater, Brownwater, Excreta, Faeces, Sludge, Urine | R.3 Sanitised Blackwater | Household<br>** Neighbourhood<br>* City | Household<br>* Shared<br>** Public |
| | | **Technical maturity:** | **Complexity:** |
| | | High | Medium |




***Compiled by:** Gensch et al. (2018) and Swedish University of Agricultural Sciences (SLU)*

**Ammonia sanitisation is a technology that is used mainly to remove pathogens from waste flows with human excreta. The addition of urea ($CO(NH_2)_2$) results in increased ammonia concentration and an alkaline environment in the storage device and thereby sanitises the material and make it pseudo-stable, thus preventing formation of greenhouse gases. When urea is added to faecal sludge, it is catalysed by the enzyme urease, which is present in faecal material, to decompose into ammonia and carbonate. Urea decomposition results in an alkaline pH, which favours the formation of ammonia. The un-ionised ammonia ($NH_3$) acts as the main sanitising agent, inactivating pathogens.**

## Design considerations

A critical design parameter is that the sanitisation process should be done in a closed container. If the container is not closed, ammonia will be lost to the atmosphere, thus greatly reducing the efficiency of pathogen inactivation. Urea is usually added at a ratio of 2% of the overall sludge wet weight. Urea can be added to the storage vessel prior to the sludge or afterwards and mixed in.

The size of the vessel may differ depending on the amount and frequency of the sludge to be treated. If the storage vessel is large, a pump or stirring rod is used to circulate the sludge within the storage vessel to ensure adequate contact between the urea and sludge. Urea decomposition requires a minimum of 4 days, and hence a retention time in the closed vessel of around 1 week is recommended, but depends on temperature.

## Applicability

Ammonia sanitisation has been shown to be effective in urine, sludge and compost. Ammonia sanitisation may be a suitable treatment option both for emergency situations and established treatment systems, due to its short treatment time, relatively simple process and the use of readily available materials.

## Health and safety

Pathogen inactivation by uncharged ammonia has been reported for several types of microorganisms, bacteria, viruses and parasites. Thus, the final product after treatment should be free from pathogens.

Urea may act as an irritant when in contact with skin or eyes, ingested or inhaled. However, it is commonly available in pelletised form that makes management dust free. Ammonia gas is toxic, and precautions are needed when removing sludge from the tank. Personal protective equipment, e.g., masks, gloves, aprons and long-sleeved clothing, must be worn when handling urea to prevent irritation to eyes, skin and the respiratory system.

## Operations and maintenance

Regular maintenance of pumps and other equipment used for mixing is required. Due to potential health risks when handling urea, the process requires skilled personnel following health and safety protocols and using proper personal protective equipment (PPE).

The process depends on the temperature and partial pressures of ammonia gas above the liquid.

Hence, ventilation and headspace in the vessel also influence the process conditions. It is recommended that treatment be undertaken in a sealed vessel to minimise the amount of ammonia gas that escapes and to force the equilibrium towards soluble ammonia. The treatment should be done as a batch process to ensure consistent sanitisation in the sludge.

## Social considerations

Appropriate health and safety protocols must be in place and include the provision of PPE and training for involved staff.

## Cost considerations

Ammonia sanitisation is a relatively cheap treatment option. Costs vary depending on the availability and costs of local materials and urea. To treat 1 $m^3$ of faecal sludge, 20 kg of urea is required. Urea is usually available and affordable.

## Advantages (+) and disadvantages (-)

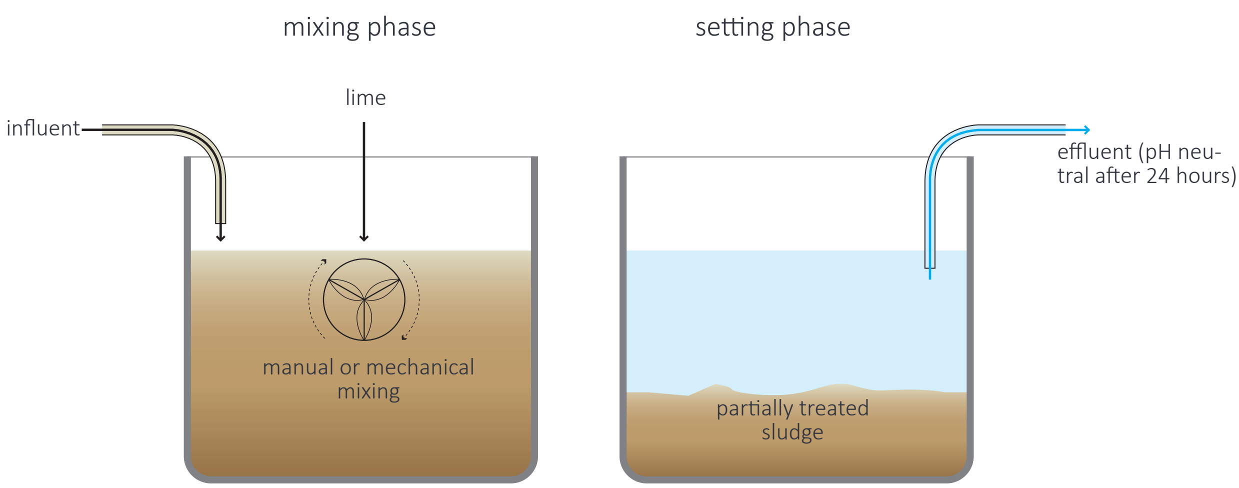
+ Treatment time ≈ 1 week (4 to 8 days, depending on temperature).
+ High level of pathogen removal (6 $\log_{10}$ removal of *Escherichia coli*).
+ Simple process that uses readily available material: urea and sealed containers.
+ Treated product has a high nitrogen content that is beneficial for agricultural application.
- High chemical input.
- Mixing is essential for the process.
- Additional sludge storage and treatment in sealed containers may be required.
- Potential health risks if not handled properly.

## References

References can be found on page 142.

## T.33 Lime Sanitisation

| **Inputs:** | **Reuse:** | **Application level:** | **Management level:** |
|---|---|---|---|
| Blackwater, Brownwater, Excreta, Sludge, (+Greywater) | R.3 Sanitised Blackwater, R.10 Dewatered Sludge (if dewatered), (R.19 Irrigation Water) | Household<br>** Neighbourhood<br>* City | Household<br>Shared<br>** Public |
| | | **Technical maturity:** High | **Complexity:** Medium |




***Compiled by:** Gensch et al. (2018) and Swedish University of Agricultural Sciences (SLU)*

**Lime sanitisation is a cost-effective chemical treatment for pathogen reduction. It uses hydrated lime ($Ca(OH)_2$) or quicklime ($CaO$) as an additive to create a highly alkaline environment, creating a non-viable habitat for pathogens. It is a robust technology that can be used to treat both solid and liquid sludge. Addition of lime increases the dry solids content of the sludge and improves its dewatering properties. Thus, it can be easier to dewater the sludge following lime treatment. After treatment, the pH falls towards neutral, usually within 24 hours (although it can take 2 weeks). Following pH neutralisation, the supernatant can be pumped off and safely infiltrated into the soil or used for irrigation or landscaping purposes.**

### Design considerations

Lime sanitisation should be carried out in a leak-proof cistern or tank. If the tank is located below ground, care should be taken to ensure it is watertight to avoid the leakage of highly alkaline effluent into the soil. In areas with high groundwater level or in flood prone areas it is recommended to use above ground tanks. Separate tanks may be needed for preparation of the lime slurry and for post-neutralization of the treated effluent respectively. The treatment process will be more efficient if the tank is covered so that ammonia remains in the tank, thus increasing pathogen inactivation.

### Applicability

Lime sanitisation is a simple process and uses readily available materials. With trained and skilled staff, it allows for safe, cost-effective and rapid treatment of faecal wastes. The resulting treated sludge can be safely used as a soil conditioner and the effluent water in irrigation if environmental conditions permit.

### Health and safety

Lime is a powder and is corrosive to skin, eyes and lungs. Therefore, adequate personal protective equipment (PPE) must be worn when handling lime to prevent irritation to eyes, skin, the respiratory system and the gastrointestinal tract. Protection from fire and moisture must also be ensured. CaO is an alkaline material that reacts strongly with moisture. Staff must be carefully trained to follow health and safety protocols.

### Operations and maintenance

Lime is corrosive in nature due to its alkalinity, and regular maintenance of the pumps used for mixing will be required. Due to the potential health risks when handling hydrated lime, skilled staff are required who follow appropriate health and safety protocols. Depending on the buffering capacity of the sludge, the optimum dosage to reach a recommended pH of above 12 should be between 20 to 40% lime per unit of dry solids, or 10 to 20 kg/$m^3$. A contact time of at least 2 hours is recommended. The exact amount of time required depends on the quality of the lime and the characteristics of the blackwater or sludge being treated. Treatment effectivity can be enhanced by increasing the contact time or dosage. The treatment should be undertaken as a batch process. Above pH 10, hydrated lime also acts as a coagulant with precipitation of $Mg(OH)_2$ and allows for effective separation of sludge and supernatant for liquid sludge with <3% dry solids. To increase the precipitation of solid particles, magnesium sulphate can be added.

### Social considerations

Proper health and safety protocols should be in place and include the provision of PPE and respective training for involved staff.

### Cost considerations

Lime sanitisation is a relatively cheap treatment option. Costs may differ depending on the availability and costs of local materials, chemicals and lime. As part of an appropriate health risk management, costs for PPE and staff trainings need to be considered.

### Advantages (+) and disadvantages (-)

+ Simple process that uses commonly available material.
+ For liquid sludge, a sanitised and stabilised effluent is created that is suitable for irrigation water.
- High chemical input.
- Mixing is essential for the process.
- Potential health risks if not handled properly.

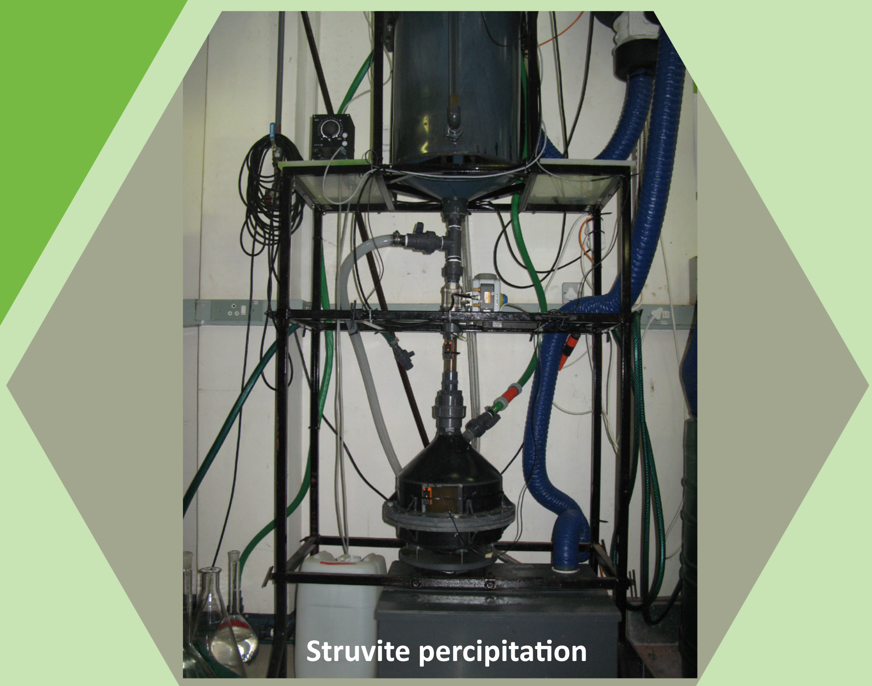
### References

References can be found on page 142.

# Photos of Treatment Technologies

Construction of biogas dome

Biogas installation



Struvite percipitation


Algae cultivation


Nitrification and
distillation of urine


Black soldier fly composting


5 days old black
soldier fly larvae

# Part 3: Cross-Cutting Issues

The selection and implementation of resource recovery from sanitation systems is not only a question of selecting the best technology. There are a number of issues related to socio-cultural, economic and institutional aspects that need to be considered in all cases of resource recovery. These cross-cutting issues include aspects related to health and safety, fertilisation, acceptance, design of appropriate business models and policy. This section presents several important cross-cutting issues that are of particular relevance for resource recovery and reuse.

**X.1** Pathogens and Safe Reuse of Products

**X.2** Medication Residues and other Emerging Contaminants

**X.3** Fertilising with Reuse Products

**X.4** Issues of Acceptance

**X.5** Business Models

**X.6** Policy Implications

## X.1 Pathogens and Safe Reuse of Products

**Compiled by: Annika Nordin (SLU)**

### Multi-barrier approach

When utilising resources in excreta, one major concern is to safeguard human and animal health, since pathogens (disease-causing microorganisms) can be excreted at high concentrations even without any symptoms of disease. This aspect is very important for the social acceptance of sanitation systems, particularly for acceptance of resource recovery sanitation systems. Note that risks from medical residues and other contaminates are described in section X.2. The 2006 ***WHO Guidelines for Safe Use of Wastewater, Excreta and Greywater*** provide a comprehensive framework for managing health risks associated with the use of human wastes in agriculture and aquaculture, and the ***Sanitation safety planning - Manual for safe use and disposal of wastewater, greywater and excreta*** (2016) provides guidance for implementation of the 2006 guidelines. The WHO Guidelines (2006) give sanitisation recommendations based on the goal that the additional burden of disease from excreta reuse should not exceed a loss of $10^{-6}$ disability-adjusted life years (DALYs) per person and year. It has been argued that this is a very high requirement and that $10^{-4}$ DALYs/person/year may be a more reasonable target in relation to the global incidence of diarrhoeal disease.

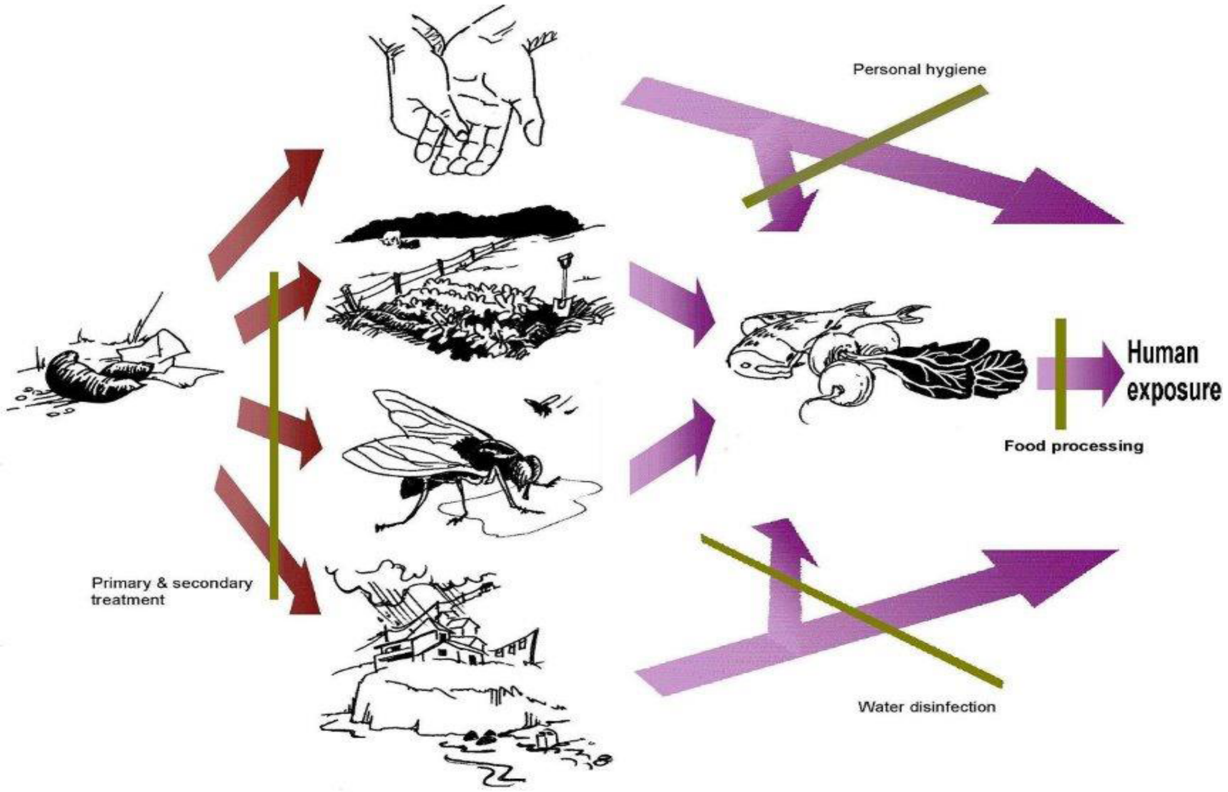



***Figure 3.*** *The 5-F diagram showing transmission routes for faecal-oral disease transmission with different barriers that can reduce or block the transmission pathway (from Nordin, 2010).*

For safe reuse, the WHO guidelines recommend reducing the potential pathogen load by 8 $\log_{10}$ compared with fresh faeces. For urine, the reduction is set to 4 $\log_{10}$, since pathogens in urine mainly originate from faecal contamination and thus are at a lower concentration than that in faeces. However, the pathogen reduction does not have to be achieved by treatment only but can be the result of several health protection measures combined; for example, having one month between fertiliser application and harvest is estimated to reduce pathogen exposure by 2 $log_{10}$. Barriers others than treatment can be restrictions on crop to be fertilised, post-harvest processing, food hygiene, etc. (Figure 3). A multi-barrier approach can allow safe reuse even if treatment alone does not give sufficient pathogen reduction. However, containment and treatment hold a special position as a barrier by preventing environmental dissemination which may be of concern, e.g., regarding parasite eggs that survive a long time in the environment.

## Pathogens in sewage

Pathogens in sewage belong to the groups bacteria, viruses, protozoa and helminths (intestinal worms). Pathogens in sewage mainly originate from the faeces, which are the main route of excretion for most gastrointestinal pathogens. However, a few pathogens have urine as their main route of excretion (e.g., *Schistosoma haematobium*). Pathogens causing blood-borne diseases have short survival times outside the body and thus, e.g., menstrual blood does not pose any hazards. Some pathogens may enter the sewage through the greywater originating from food preparation. Some pathogens are widely spread around the world and are regularly detected in sewage (e.g., *Salmonella* spp. and *Campylobacter* spp.), whereas some are related to, e.g., poor sanitation status (soil-transmitted helminths) and may not be a relevant hazard in all contexts. Most gastrointestinal pathogens are spread through the faecal-oral route, i.e., by ingestion of contaminated crops or water or by accidental ingestion. Some pathogens do, however, spread by skin contact (such as hookworms) or through eating meat from intermediate hosts (e.g., pig, fish and cow meat). When applying ditch and pond systems in the sanitation system, the breeding of vectors such as mosquitos will need to be prevented.

Most pathogens in sewage originate from faeces, so this fraction, if collected separately, holds high concentrations of pathogens and any co-collection with other fractions would contaminate of these fractions but dilute the pathogens in the faeces. Containment, collection and treatment methods may affect how the pathogens are distributed in the sewage fractions, where, e.g., parasite eggs may sediment or adhere to particulate matter and may be present in higher concentrations in sediments and sludge compared to those in the effluents. The exposure to a pathogen depends on the concentrations as well as on the quantities of products used; for example, in crop production, irrigation water will be applied in larger quantities than fertilisers. What is considered a safe concentration of pathogens in the material therefore depends on the use.

## Sanitising and stabilising treatments

Sanitisation is a treatment aiming to reduce pathogens to a safe level, and it can also give stabilisation of the material, i.e., easily degraded material is consumed and odours are decreased. Sanitisation does not necessarily mean stabilisation, as, e.g. drying, ammonia treatment and lactic acid fermentation give a pseudo-stabilisation by hampering microbial activity as long as the sanitising conditions are maintained. Similarly, stabilisation does not necessarily mean sanitisation, e.g., mesophilic digestion and liming achieves stabilisation but not total pathogen inactivation. A stabilised material is less prone to have regrowth if pathogens remain or re-enter the material, since most of the nutrients and energy are consumed and not available for growth. Treatments giving a pseudo-stabilisation often aim to maintain the conditions until material is used as a resource. It may be beneficial to combine treatments that have different benefits; for example, a treatment efficient in volume reduction but not achieving full pathogen reduction may be combined with a sanitisation step.

Even if different barriers together can fulfil the pathogen reduction requirements for safe reuse, containment and treatment prevent environmental transmission. Many factors affect pathogen inactivation, e.g., nutrient competition, redox potential, oxygen and energy content. However, treatments that build on treatment parameters with a clear relation to pathogen reduction make treatment more reliable and pathogen inactivation predictable.

Of treatment parameters with an established relation to pathogen inactivation, temperature is a factor that is efficient towards all pathogen groups. Thermal sanitisation is utilised in thermophilic composting and thermophilic anaerobic digestion and potentially in sun drying. Temperatures above 50°C have the potential to inactivate most pathogens. Alkaline conditions, often from addition of lime, create harsh conditions, and a pH of 10 and above is efficient against bacteria and viruses. An alkaline pH of 10 can be reached in algae cultivation by the natural growth process. Helminth eggs, nematode eggs in particular, can withstand very high pH and alkaline pH alone is not sufficient for inactivation. Ammonia sanitisation requires an alkaline pH but is based on the activity of $NH_3$. Ammonia can inactivate all pathogen groups, but the temperature needs to reach 20°C to have an effect on nematode eggs as *Ascaris* spp. Drying can inactivate all pathogen groups, but helminth eggs are tolerant to desiccation, and a moisture content of 5% may have to be reached to achieve inactivation. Vermicomposting and black solider fly composting are biological systems functioning at ambient temperature and have limited effect on pathogens.

For assessing the treatment reductions and end product quality, faecal bacteria such as *Escherichia coli* and *Enterococcus* spp. can be used. *E. coli* has traditionally been used to detect faecal contamination, but for it use as a reference organism it may best represent other bacteria. It holds value as an indicator of regrowth, and high numbers can then indicate that a product has not been properly managed after treatment. Bacteriophages (viruses that infect bacteria) are also always available in excreta and can be used as model organisms for viruses. When helminths are endemic, they are directly monitored in the sewage fractions to evalúate treatment efficiecy and end product quality.

## References

References can be found on page 143.

# X.2 Medication Residues and other Emerging Contaminants

**Compiled by: Sahar Dalahmeh (Uppsala University)**

We use a growing number of organic chemicals in society today, many of which can enter our sanitation systems. Organic pollutants that are frequently found in sanitation systems include dyes, petroleum, surfactants, pesticides, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) and pharmaceuticals. These contaminants can enter the sanitation system through (1) industrial effluent from production processes (e.g., manufacturing of active ingredients, production and packing), (2) release via human excreta after ingestion (e.g., medications or pesticide residues on food), (3) residues released to greywater through washing (e.g., dyes, surfactants, and pesticides), and (4) disposal of the medicine leftover and other waste into sanitation systems (e.g., flushing of drugs, medicines and other products down the toilet). When reusing resources recovered from sanitation systems, we need to be aware of the potential for contamination with unwanted chemicals. Unfortunately, we are still learning about how many of the chemicals used in society break down and spread within our bodies, sanitation systems and the environment. Further research is needed in this area, particularly regarding risks.

An example of medical residues can illustrate the difficulties in quantifying and monitoring the impacts of organic contaminants. Medicines are composed of pharmaceutically active substances (PhACs). In the human body, PhACs may undergo metabolism, i.e., chemical changes, which results in a number of different chemicals that may be more water soluble than the original substance. In general, PhACs are not designed to accumulate in the human body due to the risk of toxicity. Thus, more than 90% of the substances may be excreted via urine and faeces, either in their original form or as metabolites (e.g., the chemicals resulting from metabolism of the parent compound). The remainder of the substance will be either fully metabolised in the body or released via the skin. Researchers have reported high concentrations of different types of PhACs in human excreta. After their excretion and release into a sanitation system and/or the environment, both parent compounds and metabolites can undergo further structural changes by a variety of biotic and abiotic processes. Thus, even if input chemicals and concentrations are known, it can be difficult to trace the decomposition/metabolism process of these substances to know in which form and concentration they are released into the environment, and thus what the potential impacts may be.

Pharmaceutical compounds from sanitation systems have been linked to adverse effects such as antibiotic resistance, genotoxicity, endocrine disruption and the potential to bioconcentrate and/or bioaccumulate in aquatic organisms, particularly in fish. The majority of the research regarding negative impacts from PhACs is related to aquatic environments. Much less is known about how these compounds behave in soil and terrestrial ecosystems, which are in general more complex, with greater opportunities for these substances to chemically break down and/or bind with other material.

The main source of PhACs in sanitation systems is toilet excreta, even though greywater also can be important, especially for PhACs applied on the skin, e.g., some hormones and painkillers. The concentration of PhACs in sanitation flows is dependent on degree of dilution. Thus, concentrations of PhACs are higher in excreta from dry sanitation systems than that in blackwater, which is in turn higher than the concentrations of PhACs in mixed municipal wastewater. This can be important to know for designing resource recovery system, e.g., where the pollutant is, but also for designing contaminant removal, e.g., it will be easier to remove from material with higher concentrations and lower volumes.

The origin of the sanitation products is also of importance. Certain types of facilities are more likely to result in effluent containing high concentrations of PhACs. Facilities in which many people use medications on a daily basis (e.g., elderly houses, hospitals and health service facilities) will result in effluent with larger amounts of and likely higher concentrations of PhACs than residential developments or retail developments. Disconnecting these types of facilities from resource recovery systems may be one method for controlling unwanted chemicals in the reuse products.

## References

References can be found on page143.

# X.3 Fertilising with Reuse Product

**Compiled by: Håkan Jönsson (SLU)**

## Fertilisers and soil conditioners

Many of the reuse options highlighted in this document refer to the potential fertilising value of the recovered products. It is thus important to define what a fertiliser is and how it can be used. This document makes the distinction between fertilisers and soil conditioners. A fertiliser is any material of natural or synthetic origin that is applied to soil mainly to supply one or more of the essential nutrients needed for plants to grow. Thus, the main purpose of fertilisers is to directly affect plant growth by improving the supply of nutrients in the soil, and thus the fraction of directly plant-available nutrients in them is normally high. Soil conditioners, on the other hand, mainly improve the soil's physical condition (e.g., soil structure and water infiltration), thus indirectly affecting plant growth.

There is often confusion about the use of terminology regarding fertilisers and soil conditioners. This is due to the fact that soil conditioners usually also contain nutrients and thus may act as a fertiliser. However, the proportion of directly plant-available nutrients in soil conditioners is normally low. In order to simplify the distinction, in this document we refer to solid and liquid fertilisers as material that is primarily a source of nutrients and that does not significantly alter the soil's texture quality. Reuse products that contain a high concentration of organic matter, e.g., compost and dewatered sludge, are generally considered soil conditioners in this context. These are used to improve soil structure and provide phosphorus, but their plant-available nitrogen and phosphorus contents are relatively low. It is important to note that that this definition does not mean that soil conditioners are poor fertilisers, but rather that their primary function is improving soil structure and as fertilisers their effect is slow.

The fertilising value of the recovered product depends on the inputs and the treatment processes used. Urine, faeces, and blackwater are complete fertilisers, as the human excreta leaving the body have a balance between nitrogen, phosphorus and potassium that closely matches the nutrients removed by harvested cereal crops. Provided that the urine, faeces and blackwater are collected, stored and treated with only insignificant nutrient losses (implying that they are stored in closed, non-ventilated containers), they can then act as balanced fertilisers for replacing the nitrogen, phosphorus and potassium removed by the harvested crop, thus maintaining the existing fertility of the soil. The soil conditioners and some of the other fertilisers in this book contain less nitrogen (sometimes much less) compared to phosphorus than the complete fertilisers. The reason for this is usually that nitrogen has been lost, often as ammonia due to ventilation or as ammonium due to dewatering, during the handling and treatment processes. If the aim is to recover complete fertiliser products, care should be taken to design the handling and treatment processes in such a way that nutrient losses are minimised. When using fertilisers and soil conditioners benefits should be maximised and risks to environment minimised.

## Surface erosion

The risks to the environment when using sanitation-derived fertilisers and soil conditioners are similar to those when using other fertilisers and soil conditioners, except that the sanitation-derived products might, especially if the health and safety recommendations are not followed, carry increased risks associated with pathogens and micropollutants like pharmaceuticals (see X.1 and X.2). This means that the fertilisers and soil conditioners should be stored and spread in such a way that the risk of losses due to flooding and surface erosion are minimised. Thus, they should not be stored or spread on sloping ground when there is a significant risk of rain causing surface erosion. When used on sloping ground, where there might be a risk of erosion, it is important that the fertiliser or soil conditioner does not remain on the soil surface but is incorporated into the soil as quickly as possible in order to minimise nutrient loss, thus minimising run-off of nutrients to surface water if erosion does occur.

## Ammonia emission

Excreta, especially urine, are rich in nitrogen, initially in the form of urea, which normally degrades quickly to ammonium/ammonia. For non-nitrogen-fixing crops, nitrogen is usually the most important nutrient for reaching a high yield. Nitrogen is also the nutrient in excreta representing the largest monetary value. Thus, it is important not to lose nitrogen. However, nitrogen is easily lost, as ammonia is volatile. If the collection system for urine or blackwater is ventilated, ammonia will be lost to the air. Essentially all nitrogen can be lost in this way. Thus, the airflow above urine, blackwater and other ammonia-rich products should be minimised, and preferably eliminated.

The same applies when spreading urine, blackwater and similar ammonia-rich fertilisers. Air contact should be minimised, i.e., products should preferably be spread close to the ground and not sprayed high into the air. Ammonia emission will be less if the fertiliser is liquid and has a low viscosity so that it easily infiltrates into the soil. Minimising the ammonia emission is not only important for getting the best fertilising effect, but also for minimising negative effects to environment, as emitted ammonia can potentially cause eutrophication both in water and on land, as well as acidification.

## Leaching of nitrogen and phosphorus

When water is available in soil in such amounts that water continues down below root depth, that water will contain similar concentrations of nitrogen and phosphorus to those present at root depth. These concentrations are affected by an interaction between the fertilisation and the properties of the soil, and this interaction is very different for nitrogen than that for phosphorus.

The nitrogen in sanitation fertiliser and soil conditioner products can be present in three forms, namely ammonium, nitrate and organic nitrogen. Which form the nitrogen is available in significantly influences both how susceptible the nitrogen is to leaching and how available it is to plants. In urine, blackwater, digestate and non-nitrified wastewater, most of the nitrogen is in the form of ammonium. In nitrified wastewater and in the nitrified and concentrated urine fertiliser, approximately half of the ammonium will be nitrified to nitrate. Both ammonium and nitrate are very water soluble, while organic nitrogen is contained in the organic matter of the excreta and wastewater. Water-soluble organic matter containing nitrogen is relatively quickly degraded to ammonium, whereas a large fraction of the solid, particulate, organic matter containing nitrogen is not that easily degraded. Thus, in solid sanitation recycling products such as dewatered sludge, dried faeces and pit humus, most of the nitrogen is normally organic nitrogen.

As ammonium and nitrate are very water soluble, they are transported by water infiltrating into the soil. If the water flow is great enough for water to infiltrate deeper than the root zone, these nutrients can leach from the field. This risk is large in sandy soils, especially if there are heavy rains after fertilisation and before the plants have taken up the nitrogen. For nitrates, this risk is also large in clay soil. The risk for ammonium loss in clay soils is much smaller, since the positively charged ammonium particles will adhere to the negatively charged clay particles. However, the ammonium will normally be oxidised to nitrate in the soil within one to a few weeks, depending on the temperature and biological activity in the soil, thus leading to leaching if the fields have been over fertilised. The risk of leaching solid organic nitrogen is insignificant.

Phosphorus in sanitation reuse products can be in the forms of dissolved phosphate ions ($PO_4^{3-}$), which are present mainly in urine; solid phosphate compounds like struvite ($MgNH_4PO_4$) and different calcium phosphate compounds (e.g., $Ca_{10}(PO_4)_6(OH)_2$); and organic phosphorus (i.e., phosphorus in solid organic substances). Leached phosphorus is in the form of phosphate ions. The risk of leaching significant amounts of phosphorus is very small for most soils in the world, as the solubility of phosphate is very low in soil water. This is true even if the fertilisation is done with urine containing mainly dissolved phosphate ions. The reason for this is that the phosphate ions will quickly attach to soil particles and then only slowly dissolve into the soil water. The concentration of phosphate ions in soil water is so low that it often is only enough to supply the crop with the phosphorus needed during one day or so. The phosphorus concentration in the soil water is kept at a low but fairly constant level by an intricate and complicated balance between different dissolution and precipitation processes, in addition to microbial processes in the soil. Thus, the risks of large losses of phosphorus are normally through surface erosion or internal erosion in cracks in the soil, not through leaching.

## Plant availability

Both nitrogen and phosphorus are taken up by plants in their ionized forms. This means that nitrogen is taken up as ammonium or nitrate, with nitrate being the form preferred by many plants. Organic nitrogen is not taken up by plants. Organic nitrogen has to be degraded to ammonium before it is available for plants. The ammonium is then often oxidised to nitrate before it is actually taken up by the plants.

Phosphorus is taken up from the soil water in the form of phosphate ions. As described earlier, the concentration of phosphorus in the soil water is regulated by an intricate balance of different dissolution and precipitation processes, which are controlled largely by the soil type and only to a small extent by fertilisation during the present growth season.

***Figure 4.*** *Red onions fertilised with stored urine (left) and grown without fertilisers (right).*

## Dosing

If possible, the fertiliser dose should be based on local recommendations for the crop and soil in question. When following the recommendations, it is recommended that the calculation of the dose is based on analyses of the soil and fertiliser used. If local fertilising recommendations are not available, general recommendations per crop can be followed. It is very important to note which chemical forms or unit referencing that are used in the fertilising recommendations and the different analyses. For nitrogen, common units are nitrogen (N), ammonium ($NH_4^+$), ammonia ($NH_3$) and nitrate ($NO_3^-$), where 1 kg N corresponds to 1.29 kg $NH_4^+$, 1.22 kg $NH_3$ and 4.43 kg $NO_3^-$. Organic nitrogen is normally given as the corresponding amount of nitrogen (N). For phosphorus, the most common units used are phosphorus (P), phosphate ($PO_4^{3-}$) and (di)phosphorus pentoxide ($P_2O_5$), where 1 kg phosphorus (P) corresponds to 4.94 kg $PO_4^{3-}$ and 2.29 kg $P_2O_5$. In many countries, fertiliser recommendations are given in kg phosphorus pentoxide ($P_2O_5$) per ha, while soil and sanitation product analyses often give the phosphorus content in units of phosphate ($PO_4^{3-}$).

Most crops are nitrogen regulated, which means that the effect of fertilising with nitrogen is large for crops other than those that fix nitrogen themselves in symbiosis with microbes, e.g., beans and peas. Crops grown on organic soils (e.g., peat) are an exception, as the degradation of the soil organic matter will often release sufficient nitrogen for the crop. In mineral soils, the recommended nitrogen dose for different cereal crops is fairly similar between different locations. Normal recommendations range between approximately 40 and 250 kg N/ha, depending on whether the expected grain harvest is fair (2 to 4 tonnes dry matter per ha) or extremely high (12 tonnes dry matter per ha or more). These recommendations are given in kg of mineral nitrogen (N).

If a large proportion of the nitrogen fertiliser is in the form of organic nitrogen, then the fraction of nitrogen that is degraded during the growth season has to be estimated, as it is only this fraction of the organic nitrogen that will be become available to the crop. This fraction differs depending on the sanitation product (how easily degradable it is) and local factors like temperature, moisture, air supply, etc. Thus, this fraction is best estimated from previous measurements and experience. If no previous experience is available, the amount of artificial mineral nitrogen that can be replaced by nitrogen from organic nitrogen degraded during the growth period can be estimated by the following equation:

$N_{replaced} = N_{tot} \times (87\% - 5\% \times \text{C/N ratio})$

$N_{tot}$ is the total nitrogen in the product and the C/N ratio is the ratio between total carbon (C) and total nitrogen (N) in the product.

This equation was developed by Delin et al. (2012) in Sweden, which means it is applicable at moderate soil temperature, good soil moisture availability and a crop growth period of 90 to 120 days. A higher temperature and longer growth period will increase the amount of organic nitrogen degraded.

For most sanitation fertilising products and most crops, the risk of toxic effects from high nitrogen dosing is very low. Normally, at doses of nitrogen least four times as large as to those given above can be spread without toxic effects to the crops. Over fertilisation will increase the amount of leached nitrate ($NO_3^-$) and of nitrogen lost as nitrogen gas ($N_2$) and nitrous oxide ($N_2O$). However, even in the case of serious overdosing, the amounts of emitted nitrate to water and nitrous gas will normally be smaller than the amounts emitted if these sanitation products were instead deposited in non-sealed pits or treated in wastewater treatment plants.

Plants take up phosphorus in the form of phosphate from the soil water. The concentration of phosphate in the soil water is controlled by complex chemical and biological processes in the soil. Since phosphate availability in the soil is controlled by soil chemistry, fertilising with phosphorus seldom results in large effects during the cropping season when it is spread. However, placing the phosphorus fertiliser in such a way that the roots can access the phosphorus before it is affected by soil processes increases the effect of phosphorus fertilisation on the current crop. Apart from this, fertilising with phosphorus has a larger effect on the soil than on the crop. Phosphorus fertilisation is important to maintain the phosphorus status of the soil and thus its fertility. Thus, the recommended dosing depends more on the soil than on the crop. For soils very rich in phosphorus, e.g., those in areas where large doses of manure have repeatedly been supplied over decades (e.g., parts of Sweden and the Netherlands), no fertilisation with phosphorus is recommended for most crops. This recommendation is to bring down the amount of phosphorus in the soil and thus to reduce the risk of losing excess phosphorus through erosion or leaching.

In soils poor in phosphorus or that are phosphorus fixing (e.g., soils that actively bind phosphorus in insoluble forms), very large doses of phosphorus can be applied without any risk of significant phosphorus losses through leaching. A good crop of wheat (6 tonnes/ha) removes approximately 20 kg/ha of phosphorus with the harvested crop from the field. If you have a good and fertile soil, you normally dose the phosphorus to balance the removal by the harvest. You do not have to make sure it balances each year, but over a period of five to 10 years, it ought to balance reasonably.

If you have a soil poor in phosphorus, which ought to be verified with a soil analysis, you can spread several hundred kilograms of phosphorus without significantly increasing the risk of phosphorus leaching. After doing this 2 to 3 times, a new soil analysis ought to be done to check the phosphorus status of the soil and thus verify the fertilisation need and risk of leaching.

Due to the balancing effect of the soil processes, there is no risk of toxic effects due to too much phosphorus being supplied. Thus, phosphorus-rich fertilisers or soil conditioners can be spread in doses several times larger than those given in this text. This may increase the risk of phosphorus losses due to erosion and leaching. However, phosphorus emissions to water from fields fertilised with sanitation products will generally be smaller than if the same phosphorus flows were sent to a wastewater treatment plant with primary and secondary treatment. This is also generally true if comparing field emissions to those from wastewater treatment plants with phosphorus removal as a tertiary treatment, since most soils are very good at removing phosphorus from percolating water.

***Figure 5.*** *Brassica rapa fields fertilised with stored urine applied with a trailing hose spreader.*

## References

References can be found on page 144.

## X.4 Issues of Acceptance

**Compiled by: Melissa A. Barton**

Successful implementation of resource recovery technologies and use of their end products (particularly fertilisers, soil conditioners, and wastewater irrigation) requires social acceptance, particularly when changes are highly visible and require people to change their habits—for example, by installing and using a urine-diverting toilet, making the decision to use fertilisers derived from human excreta to grow crops or consciously purchasing the resulting food products. Acceptance issues are relevant not only to consumers, but to actors in the sanitation, agricultural and food production systems, as well as to regulators and planners. Previous research suggests that the average person does not typically have a high level of knowledge about sanitation, agriculture or food production, but opinions and beliefs about appropriate handling of human excreta are often strong. Acceptance or lack of acceptance is thus shaped by both cognitive (knowledge-based) and psychological factors. New technologies and systems must also be perceived as being at least as convenient, comfortable, clean and safe as the current status quo. Previous studies indicate that the relative importance of different factors in shaping acceptance, and how these factors are perceived, differs greatly according to context; it is thus key to understand the local context before developing communication or implementation strategies.

### Cognitive factors

Cognitive factors are based on or can be addressed through factual information. First of all, people must perceive the benefits of resource recovery as exceeding its costs. Which potential benefits are most compelling depends on local context, which includes the existing sanitation and hygiene infrastructure or lack thereof, availability and safety of water resources and the availability and cost of other fertilisers.

In addition to potential economic costs related to, for example, significantly altering an existing sanitation system, perceived health risks are a common barrier to acceptance. Perceived risks to human and/or environmental health have been generally found to be negatively associated with acceptance of reuse products such as urine-based fertilisers, sludge and recycled wastewater. It is important to note that perceived risk does not necessarily correlate with actual risk. For example, in some contexts with minimal sanitation infrastructure, children’s faeces are perceived as less hazardous to health than those of adults; however, children’s faeces are actually more likely to contain transmissible pathogens and children are more susceptible to faecal-oral infection. Other risk-related concerns include potential negative effects on the environment or on crops (e.g., from hormones or pharmaceutical residues). Knowledge or belief that these risks can be mitigated through treatment or processing is often associated with increased levels of acceptance.

Clear and adequate regulations to ensure safety and protect against liability claims are also crucial for adoption on a systemic level. Regulatory clarity is particularly important for farmers using wastewater irrigation or fertiliser products derived from human excreta, but it is also relevant to manufacturers and installers of new technology, as well as to consumers. The regulatory process is often driven by the efforts of industry and advocacy groups, which may have different concerns from those of the public in general.

### Psychological factors

While cognitive factors are important, they do not solely determine acceptance. Many people, particularly in communities with strong social taboos around human waste, cognitively recognise the benefits of resource recovery from sanitation, but are still reluctant to practice it. Such psychological and social factors include general feelings of disgust or repulsion towards human waste, but also cultural and religious prohibitions and personal values related to recycling and environmental health. Concern about the smell of human faeces and urine has been mentioned almost universally in surveys and social studies regarding ecological sanitation and fertiliser recovered from human excreta. In addition, studies often find greater acceptance for reuse that is spatially or socially removed from the individual, e.g., people are generally more comfortable with their neighbours using urine as fertiliser than with using it themselves, and more comfortable with its use on crops for animal consumption than on crops for human consumption. Similarly, human excreta are often perceived differently from animal excreta, although acceptance of different types of animal excreta in agriculture also varies widely.

These perceptions are often linked to cultural and religious beliefs about proper handling and disposal of waste. Such beliefs can be complicated and seemingly contradictory—for example, many religions promote the importance of hygiene, but perception of toilets and human excreta as unclean or impure can discourage practitioners from using indoor toilets even after they have been installed, resulting in less hygienic practices of open defaecation. As with other factors, local context can differ greatly. For example, some Muslim communities have shown strong resistance to the use of urine as fertiliser, while in others acceptance has been relatively high. Public trust in religious leaders is often higher than that in politicians, and religious leaders can thus influence social norms. How psychological factors are handled while introducing resource recovery to a community can be the difference between acceptance and rejection.

***Figure 6.*** *Field trial with diffrent fertilisers including sanitation recovery products.*

### Increasing acceptance through intervention

While pro-environmental attitudes have been hypothesised to affect the acceptance of resource recovery from sanitation, the environmental benefits are not always readily apparent to the public and may be perceived as insufficient compared to risks or negative impacts. Users of new toilet technologies have generally been more accepting when they understand the overall end goal of the change, e.g., to reuse human excreta as fertiliser. Therefore, one direction for interventions is to focus on explicitly communicating how adoption of sanitation resource recovery technologies and products supports a specific reuse goal and is consistent with values held by the targeted groups. These values may be related to environmental protection, local economic independence, avoiding resource wastage, etc. Two mechanisms for shifting acceptance are particularly promising: demonstration/trial projects and interventions based on social norms (the perceptions of what others are doing or think should be done).

Successful pilot or trial projects can demonstrate that risks can be avoided and that benefits are worthwhile in reality, not only in theory. For example, a collaborative experiment in Uganda on improving soil fertility using human urine allowed farmers to discover beneficial effects on crops first-hand and opened discussion on how collection systems could be developed without violating social taboos. Although the handling of human waste is a complex topic, social norms and taboos are not necessarily inflexible and can be shifted. Collective, community-driven efforts like that in the Uganda experiment can facilitate negotiation and reframing of social norms and, through peer group support, reduce the negative social risks individuals might face if they adopt technology on their own.

Finally, social norms—the perceptions of what others are doing (descriptive norms) and of what others think “should” be done (injunctive norms)—have been shown to affect people’s behaviours in many environmental contexts. Social norms can be shifted in several ways, including by demonstration and early adoption—as more people adopt a technology or behaviour, it becomes more familiar and less threatening—but also by education, legislation and public investments that make a given behaviour easier (such as subsidising installation of new technology). The relationship between social norms and policy is cyclical, where policy influences social norms and behaviour and those in turn inform policy. Thus, even long-standing social norms can shift abruptly at a “tipping point” when a crucial percentage of the population has accepted a practice. Such strategies have been used previously in many recycling and public health campaigns.

### References

References can be found on page 144.

# X.5 Business Models

**Compiled by: Jennifer McConville (SLU)**

When planning and designing for resource recovery sanitation systems, it is important to clearly define a business model, both for public and private actors. A business model is the term used to describe how an organisation (or organisations) creates and delivers economic, social or environmental value. It includes a plan for operating, sources of revenue and financing structures, as well as the customer base and products or services to be provided. In the case of sanitation, business models are generally structured along the sanitation service chain, with one or more organisation(s) collaborating to provide access to toilets, emptying, treatment and reuse/disposal (Figure 6). Business models that are focussed on resource recovery are reliant on the other steps in the sanitation service chain to assure access to reliable quantities and qualities of input products for reuse.


**Figure 7**. *The sanitation service chain is the backbone for any sanitation business model (adapted from Otoo et al. 2018).*

The International Water Management Institute (IWMI) and others have identified a number of key components in business models and applied them to the sanitation service chain (Figure X.2). Core elements of a business model should include identification of a value proposition, customers, infrastructure, financial aspects and trade-offs. The value proposition in resource recovery systems is often related cost recovery or cost saving through sales and/or reusing recovered products, e.g., fertilisers, biomass, water or energy. However, the value proposition can also be structured around maximizing societal good, such as environmental protection or public welfare through, e.g., community-based programs that provide resources to low-income families or stimulate local business through access to subsidised local fertilisers. Thus, these value propositions account for external effects of, e.g., reduced carbon emissions or job creation. The value proposition can also be related to providing access to sanitation and safe management, with increased revenues from reuse being factored in to subsidise financial aspects of sanitation service provision.

A business model should clearly define the target customers—who is being served and how? The customers will be different at each step of the sanitation service chain. Each organisation active within the service chain will need to clearly identify who their target customers are and which part of the sanitation service chain they are serving. The business model should also specify how interactions with the customers will be done, e.g., what channels will be used to deliver the value proposition to the customers and what type of relationship the business will have with the customers (e.g., direct contact, distributers or through subsidiaries). Communication strategies will also be critical for informing about the value proposition and managing customer relationships, including conflict resolution.

The infrastructure components of the business model should include not only activities and resources that are available for the business, but also key partners who can support the business. This is particularly the case for business models which focus on resource recovery, since ensuring a safe reuse product requires proper management along the entire sanitation service chain. This means that the business model should either (1) include the entire service chain with activities from toilet provision to reuse, or (2) partner with other stakeholders who are already involved in these activities. Several container-based sanitation services are using the first model by providing household toilets, emptying them and treating the excreta to extract reusable products, all within the same business. Examples of the second type of business model are organisations that contract with local utilities to treat collected waste and/or convert treated waste into reuse products such as compost or char briquettes. As there are often multiple actors operating in the sanitation service chain, identification of other local actors, networks and resources will be a key part of developing the business model.

Finally, the business model should include financial aspects and recognition of potential trade-offs. Financial aspects include defining full supply costs and structures for covering them, including capital, operation and maintenance costs, as well as interest payments. Revenue flows are the cash generated by the business from each customer segment, e.g., through taxes or tariffs. It should be noted that revenues from sales of sanitation reuse products are generally not enough to cover costs. The majority of resource recovery business models in sanitation rely on additional revenue flows from activities performed in another part of the service chain (e.g., provision of and/or emptying of toilets), or fees collected from another actor for treating waste products (e.g., removal and management of sludge from treatment plants).

All business models should recognise both the potential social and environmental benefits of the activities and the costs. Many traditional business models focus only on the supply costs of capital and operational costs. However, full economic costs will include opportunity costs and environmental and/or economic externalities, i.e. impacts on third parties not directly related to the costs. For example, urine diversion and separate treatment will reduce nitrogen loading at the central wastewater treatment plant, potentially reducing the need for costly nitrogen removal and/or reducing eutrophication in the recipient waters. These costs can and should be included in a full cost analysis. Prior to implementing a business model, it is recommended to identify and evaluate potential trade-offs/opportunity costs and such externalities. There are a number of tools for doing so, including cost-benefit analysis, environmental and social impact assessments, market analysis and SWOT analysis (strength, weakness, opportunities, and threats). Regular monitoring of business activities and adjustment of business models in response to results from updated trade-off assessments is also recommended.

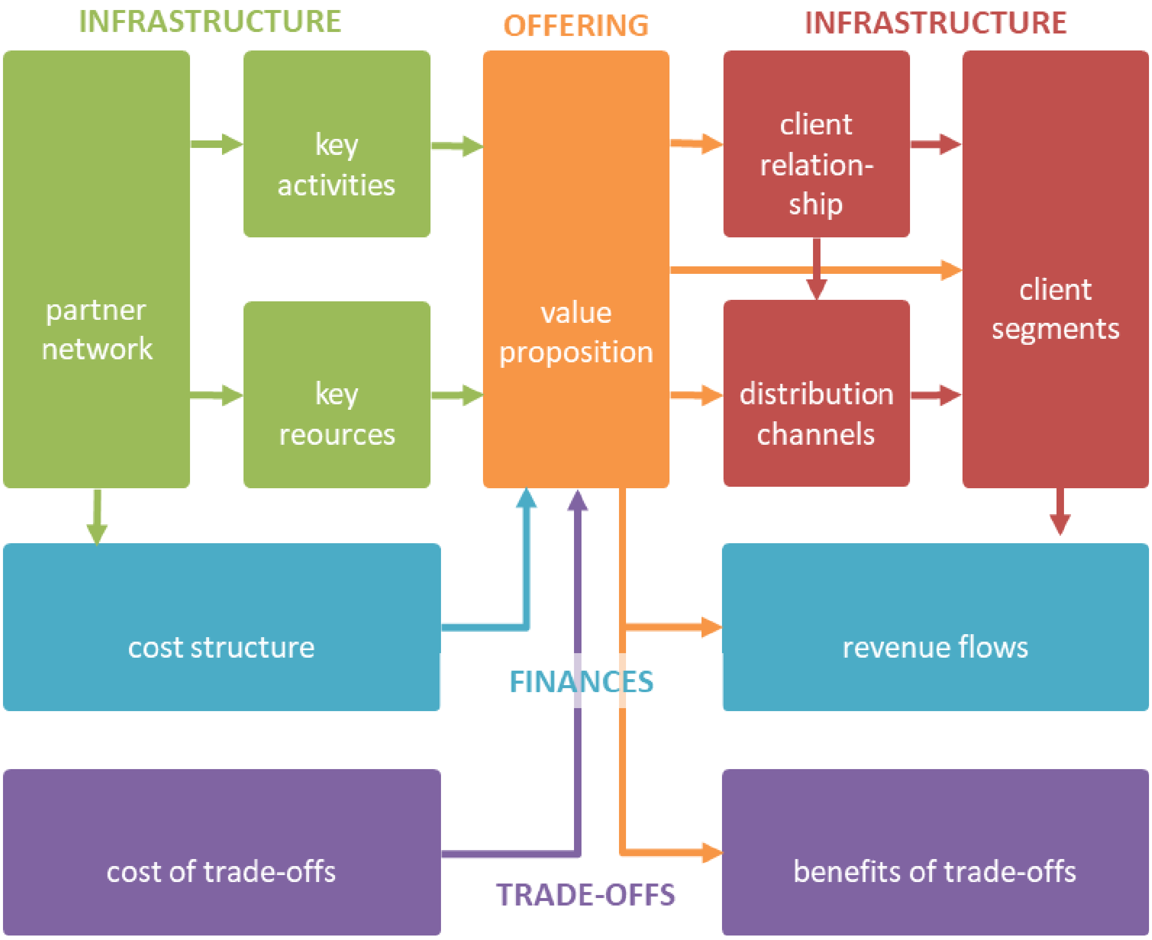



**Figure 8**. *Components and interlinkages of the generic business model canvas (adapted from Otoo and Dreschel 2018).*

## References

References can be found on page 145.

# X.6 Policy Implications

**Compiled by: Jennifer McConville (SLU)**

Sanitation policies and regulatory frameworks are important tools and key elements of an enabling environment when promoting and implementing resource recovery sanitation systems. Without the existence or parallel development of policy that supports resource recovery, many initiatives will never be implemented or will fail to produce the expected outcomes. However, the existence of supporting policy is not enough to drive a transition to resource recovery. It needs to be coupled with political will to enforce existing legislation, incentives for different actors to get involved and capacity development to enable action. The policy situation can vary vastly depending on the local context and country. Therefore, it is difficult to give specific recommendations regarding policy development and implementation. Instead, we offer a framework for developing and working with policy and regulations for resource recovery from sanitation (Figure 8). Since resource recovery involves stakeholders from multiple sectors, implementation of the framework should be done using a transdisciplinary and multi-stakeholder approach.

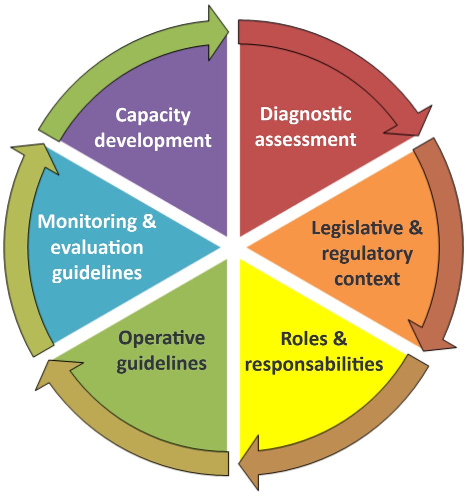



**Figure 8.** *Framework for guiding a multi-stakeholder approach to development of policy and regulations for resource recovery (adapted from Javathilake et al. 2019).*

The diagnostic assessment should place resource recovery within the context of the existing sanitation situation and that of the users of the recovered resource and include problems, specific stakeholder needs and expectations. How can resource recovery sanitation systems fit within the existing sanitation context? What are the needs and expectations from potential end-users? Are there opportunities for win-win solutions? What are the potential trade-offs? What are the current expectations for and acceptance of resource recovery systems? Is it possible to develop a consensus on a vision for resource recovery from sanitation?

Assessment of the legislative and regulatory context should identify existing and missing regulations related to resource recovery. First, it is important to determine if the existing legislation enables or prohibits action on resource recovery to be taken. The review should include policies, guidelines, strategies, plans and initiatives at national, regional and local scales and identify in which contexts resource recovery is allowed and in which contexts it is prohibited. This will help to identify where action can be taken immediately and where changes in policy are needed to allow for future resource recovery.

Assessment of roles and responsibilities should look for gaps and overlap between existing roles and responsibilities in management of the sanitation service chain, as well as mapping how implementation of resource recovery systems will affect these roles. An organisational chart delineating the existing situation and additional roles and responsibilities needed for resource recovery is useful here. Clear definitions of roles and responsibilities will be critical for establishing and maintaining a supportive policy environment for resource recovery.

Operative guidelines should include technical guidelines, licencing or certification arrangements for monitoring and reporting performance and financing reforms and incentive systems. Technical guidelines may include technical specifications for construction and operation of different reuse options, health and safety standards to be met or decision support tools for assessing technical and financial viability of various options. The U.S. Environmental Protection Agency (USEPA) Standards for the Use or Disposal of Sewage Sludge is an example of standards for sludge-based resources. Safe resource recovery requires monitoring of the reuse products to assure that quality standards are met. Certification programs and/or licencing arrangements can be established to ensure that consistent monitoring and reporting is performed. Examples of such certification programs are the Swedish systems for REVAQ certification for improved quality of recycled sewerage sludge or SPCR 178 for quality assurance of source-separated wastewater fractions. Finally, developing a supportive policy environment for resource recovery may require a review of the current system of subsidies and financial structures for sanitation. Do current economic models allow resource recovery systems to access the same level of subsidies as conventional systems, or are economic incentives needed to promote investment in the sector? Can subsidies, tariffs and taxation policies be reformed to at least allow equal opportunity for resource recovery options?

Policy measures should not be static, but should be continual reviewed, adapted and updated as needed. A supportive policy environment should include a regular review of polices and guidelines, with the aim to continuously update and improve guidelines to enable more sustainable sanitation.

Finally, policy development is not only about guidelines, frameworks and regulations; it is directly impacted by the capacity of relevant stakeholders. Ongoing efforts should be made to develop institutional capacities for resource recovery. Capacity development will need to reach all stakeholders within the sanitation service chain, plus sectors involved in the resource recovery, and at all levels of governance—local, regional and national. Reaching all stakeholders means developing targeted programs for education, training, research and awareness raising at multiple levels.

In many cases, policy changes are necessary for the scaling up of resource recovery in sanitation systems. At the same time, it is important to recognise that in many countries, permitting policies and legal frameworks are in place but are not effectively implemented. Establishing an enabling legislation and regulatory framework should go hand-in-hand with the creating of political will to support resource recovery, providing incentives to local actors and developing capacity in local stakeholders to take action.

## References

References can be found on page 145.

# Connecting Technologies in the Eawag Compendium

This document is written as a supplement to the Eawag Compendium of Sanitation Systems and Technologies[1]. The treatment technologies that are listed below have previously been described in the Compendium and are included here in order to ease in referencing. In this document, we use reference numbers corresponding to the 2nd version of the Eawag Compendium. There is also a version that is designed for use in emergency sanitation, the Compendium of Sanitation Technologies in Emergencies[2]. The reference numbers for technologies included in the Compendium for Emergencies are noted in parenthesis ( ) when different.

## U User Interface

**U.1** Dry Toilet

**U.2** Urine-Diverting Dry Toilet (UDDT)

**U.3** Urinal

**U.4** Pour Flush Toilet

**U.5** Cistern Flush Toilet (U.4)

**U.6** Urine-Diverting Flush Toilet (UDFT)

## S Collection and Storage/Treatment

**S.1** Urine Storage Tank/Container

**S.2** Single Pit (S.3)

**S.3** Single Ventilated Improved Pit (VIP) (S.4)

**S.4** Double Ventilated Improved Pit (VIP)

**S.5** Fossa Alterna

**S.6** Twin Pits for Pour Flush (S.6)

**S.7** Dehydration Vaults

**S.8** Composting Chamber

**S.9** Septic Tank (S.13)

**S.10** Anaerobic Baffled Reactor (ABR) (S.14)

**S.11** Anaerobic Filter (S.15)

**S.12** Biogas Reactor (S.16)

## C Conveyance

**C.1** Jerrycan/Tank

**C.2** Human-Powered Emptying and Transport (C.1)

**C.3** Motorized Emptying and Transport (C.2)

**C.4** Simplified Sewer (C.3)

**C.5** Solids-Free Sewer

**C.6** Conventional Gravity Sewer (C.4)

**C.7** Transfer Station (Underground Holding Tank) (C.6)

## T (Semi-) Centralized Treatment

**PRE** Pre-Treatment Technologies

**T.1** Settler

**T.2** Imhoff Tank

**T.3** Anaerobic Baffled Reactor (ABR) (T.2)

**T.4** Anaerobic Filter (T.3)

**T.5** Waste Stabilization Ponds (WSP)

**T.6** Aerated Pond

**T.7** Free-Water Surface Constructed Wetland

**T.8** Horizontal Subsurface Flow Constructed Wetland

**T.9** Vertical Flow Constructed Wetland

**T.10** Trickling Filter (T.7)

**T.11** Upflow Anaerobic Sludge Blanket Reactor (UASB)

**T.12** Activated Sludge (T.13)

**T.13** Sedimentation/Thickening Ponds (T.8)

**T.14** Unplanted Drying Beds (T.9)

**T.15** Planted Drying Beds (T.10)

**T.16** Co-Composting (T.11)

**T.17** Biogas Reactor (T.4)

**POST** Tertiary Filtration and Disinfection

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# Glossary

### A

**Acidic:** Used to describe the pH value of a material (solid or liquid) when it is less than 7.

**Aerobic:** Describes biological processes that occur in the presence of oxygen.

**Algae**: See R.15.

**Algae cultivation:** See T.22.

**Alkaline:** Used to describe the pH value of a material (solid or liquid) when it is greater than 7.

**Alkaline dehydration of urine:** See T.31.

**Ammonia sanitisation:** See T.32.

**Anaerobic:** Describes biological processes that occur in the absence of oxygen.

**Anaerobic digestion:** The degradation and stabilisation of organic compounds by microorganisms in the absence of oxygen, leading to production of biogas.

**Anal cleansing water:** See Terminology, page 11.

**Anoxic:** Describes the condition when water lacks dissolved/free oxygen.

**Ash from sludge:** See R.12.

**Aquaculture:** The controlled cultivation of aquatic plants and animals.

### B

**Bacteria:** Simple, single-celled organisms that are found everywhere on earth. They are essential for maintaining life and performing essential “services”, such as composting, aerobic degradation of waste and digesting food in our intestines. Some types, however, can be pathogenic and cause mild to severe illnesses.

**Biochar:** See R.13.

**Biochemical oxygen demand (BOD):** A measure of the amount of oxygen used by microorganisms to degrade organic matter in water over time (expressed in mg/L and normally measured over five days as BOD5). It is an indirect measure of the amount of biodegradable organic material present in water or wastewater; the higher the organic content, the more oxygen is required to degrade it (high BOD).

**Biodegradation:** Biological transformation of organic material into more basic compounds and elements (e.g., carbon dioxide and water) by bacteria, fungi and other microorganisms.

**Biogas:** See R.21.

**Biomass:** Material produced by the growth of microorganisms, plants or animals.

**Black soldier fly larvae:** See R.17.

**Black soldier fly composting:** See T.21.

**Blackwater:** See Terminology, page 11.

**BOD:** See Biochemical oxygen demand.

## C

**Capital cost:** Funds spent for the acquisition of a fixed asset, such as sanitation infrastructure.

**Carbonisation:** See T.27.

**Centralized treatment:** Refers to the treatment of wastewater (or any of its constituent fractions) at a large-scale centralized location that is designed to handle a comparatively large volume of wastewater (or any of its constituent fractions), typically that of a city district or an entire city.

**Chemical oxygen demand (COD)**: A measure of the amount of oxygen required for chemical oxidation of organic material in water by a strong chemical oxidant (expressed in mg/L). COD is always equal to or higher than the BOD, since it is the oxygen required for complete oxidation. It is an indirect measure of the amount of organic material present in water or wastewater; the higher the organic content, the more oxygen is required to chemically oxidise it (high COD).

**Compost:** See R.11.

**Composting:** The process by which biodegradable components are biologically decomposed by microorganisms (mainly bacteria and fungi) under controlled aerobic conditions.

**Concentrated urine:** See R.2.

## D

**Decentralised treatment:** Refers to the treatment of wastewater (or any of its constituent fractions) at a small-scale decentralised location (usually where sewer networks are not available), that is designed to handle a comparatively small amount of wastewater, typically that of one to several households up to that of an entire neighbourhood.

**Denitrification:** The process by which nitrate is biologically converted to nitrogen gas in the absence of oxygen.

**Desludging:** The process of removing the accumulated sludge from a storage or treatment facility.

**Detention time:** See Hydraulic retention time (HRT).

**Dewatered sludge:** See R.10.

**Dewatering:** The process of reducing the water content of a sludge or slurry. Dewatered sludge may still have a significant moisture content, but it is typically dry enough to be conveyed as a solid (e.g., shovelled).

**Digestate:** The solid and/or liquid material remaining after undergoing anaerobic digestion.

**Disinfection:** The elimination of (pathogenic) microorganisms by inactivation (using chemical agents, radiation or heat) or by physical separation processes (e.g., membranes).

**Dried faeces:** See R.8.

**Dry cleansing materials:** See Terminology, page 11.

**Dry urine:** See R.6.

## E

***E. coli:*** *Escherichia coli,* a bacterium inhabiting the intestines of humans and warm-blooded animals. It is used as an indicator of faecal contamination of water, but pathogenic strains also exist.

**Effluent:** The general name for the liquid that leaves a system or process (e.g., treated wastewater).

**Eutrophication:** The enrichment of water, both fresh and saline, by nutrients (especially the compounds of nitrogen and phosphorus) that accelerate the growth of algae and higher forms of plant life and lead to the depletion of oxygen.

**Evaporation:** The phase change from liquid to gas that takes place below the boiling temperature and normally occurs on the surface of a liquid.

**Evapotranspiration:** The combined loss of water from a surface by evaporation and plant transpiration.

**Excreta:** See Terminology, page 11.

## F

**Faecal sludge:** See Terminology, page 12.

**Faeces:** See Terminology, page 10.

**Fertiliser:** A chemical or natural substance rich in plant nutrients (such as nitrogen, phosphorus, potassium and sulphur) that can be applied in agriculture to improve the soil nutrient composition and increase yields of grown crops.

**Filter:** See T.30.

**Filtrate:** The liquid that has passed through a filter.

**Filtration:** A mechanical separation process using a porous medium (e.g., cloth, paper, sand bed or mixed medium bed) that captures particulate material and permits the liquid or gaseous fraction to pass through. The size of the pores of the medium determines what is captured and what passes through.

**Fish pond:** See R.20.

**Flotation:** The process whereby lighter fractions of a wastewater, including oil, grease, soaps, etc., rise to the surface, and thereby can be separated.

**Flocculation:** The process by which the size of particles increases as a result of particle collision. Particles form aggregates or flocs from finely divided particles and from chemically destabilised particles and can then be removed by settling or filtration.

**Flushwater:** See Terminology, page 11.

## G

**Greywater:** See Terminology, page 11.

**Groundwater:** Water that is located beneath the earth's surface. See X.3.

**Groundwater table:** The level below the earth's surface to which the soil is saturated with water. It corresponds to the level where water is found when a hole is dug or drilled. A groundwater table is not static and varies by season, year and groundwater usage (synonym: Water table).

## H

**Helminth:** A parasitic worm, i.e., one that lives in or on its host, causing damage. Some examples that infect humans are roundworms (e.g., *Ascaris* spp., whipworm and hookworm), tapeworms and flukes. The infective eggs of helminths can be found in excreta, wastewater and sludge. They are very resistant to inactivation and may remain viable in faeces and sludge for several years.

**Humus:** The stable remnant of decomposed organic material. It improves soil structure and increases water retention, but has no nutritive value.

**Hydraulic retention time (HRT):** The average amount of time that liquid and soluble compounds stay in a reactor or tank. (synonym: Detention time)

## I

**Improved sanitation:** Facilities that ensure hygienic separation of human excreta from human contact.

**Incineration:** See T.26.

**Industrial input:** A product that can be used as a raw material in an industrial production process, e.g., as an additive to fertiliser production or other product.

**Influent:** The general name for the liquid that enters into a system or process (e.g., wastewater).

**Irrigation water:** See R.19.

## L

**Larvae:** See R.17.

**Lime:** The common name for calcium oxide (quicklime, CaO) or calcium hydroxide (slaked or hydrated lime, $Ca(OH)_2$). It is a white, caustic and alkaline powder produced by heating limestone. Slaked lime is less caustic than quicklime and is widely used in water/wastewater treatment and construction (for mortars and plasters). It can also be used for on-site treatment of faecal sludge. See S.17.

**Lime sanitisation:** See T.33.

**Liquid fertiliser:** Concentrated liquid solutions that act as a fertiliser. See Fertiliser.

**$Log_{10}$ reduction:** Organism removal efficiencies. 1 $log_{10}$ unit = 90%, 2 $log_{10}$ units = 99%, 3 $log_{10}$ units = 99.9%, and so on.

## M

**Macrophyte:** An aquatic plant, i.e., a plant that grows in or near water and is either emergent, submergent or floating.

**Membranes:** See T.29.

**Methane:** A colourless, odourless, flammable, gaseous hydrocarbon with the chemical formula $CH_4$. Methane is present in natural gas and is the main component (50 to 75%) of biogas that is formed by the anaerobic decomposition of organic matter.

**Microbial fuel cell:** See T.23.

**Microorganism:** Any cellular or non-cellular microbiological entity capable of replication or of transferring genetic material (e.g., bacteria, viruses, protozoa, algae or fungi).

**Micropollutant:** Pollutant that is present in extremely low concentrations (e.g., trace organic compounds).

## N

**Nano-filter:** A membrane filter with a pore size ranging from 1 to 10 nm (10 to 9 m).

**Nitrification and Distillation of Urine:** See T.24.

**Nutrient:** Any substance that is used for growth. Nitrogen (N), phosphorus (P) and potassium (K) are the nutrients required in large amounts, and N and P are also primarily responsible for the eutrophication of water bodies.

**Nutrient-enriched filter material:** See R.14.

**Nutrient solutions:** See R.5.

## O

**Off-site sanitation:** A sanitation system in which excreta and wastewater are collected and conveyed away from the plot where they are generated. An offsite sanitation system relies on a sewer technology (see C.3 and C.4) for conveyance.

**On-site sanitation:** A sanitation system in which excreta and wastewater are collected and stored or treated on the plot where they are generated.

**Open defaecation:** Practice of defaecating outside in the open environment.

**Operation and maintenance (O&M):** Routine or periodic tasks required to keep a process or system functioning according to performance requirements and to prevent delays, repairs or downtime.

**Organics:** See Terminology, page 12.

## P

**Parasite:** An organism that lives on or in another organism and damages its host.

**Pathogen:** Disease-causing microorganism, an infectious agent, including common food- and waterborne pathogens belongs to the organism groups bacteria, viruses, protozoa and helminths (parasitic worms).

**Personal protective equipment (PPE):** Protective clothing including boots, masks, gloves, apron, etc., or other garments or equipment designed to protect the wearer’s body from injury or infection from sanitation products.

**pH:** The measure of acidity or alkalinity of a substance. A pH value below 7 indicates that it is acidic, and a pH value above 7 indicates that it is basic (alkaline).

**Pharmaceutical residues:** The remains of pharmaceuticals that have not been fully metabolised by the human body. Pharmaceutical residues are primarily excreted through urine.

**Pit humus:** Term used to describe the nutrient-rich, hygienically improved, humic material that is generated in on-site pit latrines. The main difference between pit humus and compost is that the degradation processes in pit humus are passive and are not subjected to a controlled oxygen supply, and the carbon-to-nitrogen ratio, humidity and temperature may be less favourable. Therefore, the rate of pathogen reduction is generally lower and the quality of the product, including its nutrient and organic matter content, can vary considerably. Pit humus can look very similar to compost and have good soil conditioning properties, although pathogens can still be present. See R.9.

**Precipitation:** The process by which materials (e.g., solids, particles and organic matter) that are suspended in a liquid (e.g., wastewater) are allowed to settle out at the bottom of a reactor or a storage tank, usually by the addition of precipitation chemicals that clump the material into larger aggregates that allow for increased settling rates. Gravitational forces acting on the suspended material naturally drive precipitation.

**Primary treatment:** The first major stage in wastewater treatment that removes solids and organic matter, mostly by the process of sedimentation or flotation.

**Protozoa:** A diverse group of unicellular eukaryotic organisms, including amoeba, ciliates, and flagellates. Some can be pathogenic and cause mild to severe illnesses. Common waterborne protozoan pathogens include *Cryptosporidium* spp., *Giardia hominis* and *Entamoeba histolytica.*

**Pseudo-stabilisation:** When microbiological activity is hampered not by the degradation of organic material but by adverse conditions such as low water content, high ammonia concentrations, etc. Pseudo-stable material may continue to be degraded if the adverse conditions are changed, e.g., if dry material is rewetted.

## R

**Reject water:** See Terminology, page 12.

**Reverse osmosis:** A membrane filtration process that uses high pressure and a semi-permeable membrane to remove ions, unwanted molecules, pathogens and larger particles from water Reverse osmosis membranes have pore sizes that are less than 1 nm.

## S

**Sanitation:** The means of safely collecting and hygienically disposing of excreta and liquid wastes for the protection of public health and the preservation of the quality of public water bodies and, more generally, of the environment.

**Sanitisation:** Reduction of disease-causing microorganisms/pathogens (not necessarily all) to a degree that is considered safe for humans, animals and the environment.

**Sanitation system:** A sanitation system is a multi-step process in which sanitation inputs such as human excreta and wastewater are managed from the point of generation to the point of reuse or disposal. It is a context-specific series of technologies and services for the management of these sanitation products, i.e., for their collection, containment, transport, treatment, transformation, use or disposal.

**Sanitised blackwater:** See R.3.

**Secondary treatment:** Follows primary treatment to achieve the removal of biodegradable organic matter and suspended solids. Nutrient removal (e.g., nitrogen) and disinfection can be included in the definition of secondary treatment or tertiary treatment, depending on the configuration.

**Septage:** A historical term to define sludge removed from septic tanks.

**Septic:** Describes the conditions under which putrefaction and anaerobic digestion take place.

**Sewage:** Waste matter that is transported through the sewer.

**Sludge:** See Terminology, page 12.

**Solar drying:** See T.28.

**Solid fertiliser:** Solid chemical or organic material that acts as a fertiliser. See Fertiliser.

**Soil conditioner:** A product that enhances the water- and/or nutrient-retaining properties of soil.

**Stabilisation:** The degradation of organic matter with the goal of reducing readily biodegradable compounds to lessen environmental impacts (e.g., oxygen depletion or nutrient leaching).

**Stored urine:** See R.1.

**Stormwater:** See Terminology, page 12.

**Struvite:** See R.7.

**Struvite precipitation:** See T.25.

**Surface water:** A natural or human-made water body that appears on the surface, such as a stream, river, lake, pond or reservoir.

## T

**Tertiary treatment:** Follows secondary treatment to achieve enhanced removal of pollutants. Nutrient removal (e.g., phosphorus) and disinfection can be included in the definition of secondary treatment or tertiary treatment, depending on the configuration.

**Toilet:** User interface for urination and defaecation.

**Total solids (TS):** The residue that remains after filtering a water or sludge sample through a glass fibre filter with a pore size in the range of 1 to 2 µm and drying the resulting solids at 105°C (expressed in mg/L). It is the sum of total dissolved solids (TDS) and total suspended solids (TSS).

## U

**Urea:** The organic molecule $(NH_2)_2CO$ that is excreted in urine and that contains the nutrient nitrogen. Over time, urea breaks down into carbon dioxide and ammonium, which is readily used by organisms in soil. It can also be used for on-site faecal sludge treatment. See. T.32.

**Urine:** See Terminology, page 10.

## V

**Vector:** An organism (most commonly an insect) that transmits a disease to a host. For example, flies are vectors, as they can carry and transmit pathogens from faeces to humans.

**Vermicomposting:** See T.20.

**Virus:** An infectious agent consisting of a nucleic acid (DNA or RNA) and a protein coat. Viruses can only replicate in the cells of a living host. Viruses can be rather persistent in the environment, and due to their small size, can be water transported through soil profiles and filters. Common food- and waterborne viruses include, e.g., calicivirus and hepatitis A virus.

## W

**Wastewater:** See Terminology, page 11.

**Water table:** See Groundwater table.

**Worms:** See R.18.

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This publication has been developed to raise awareness of the possibilities for resource recovery from sanitation and provide guidance on treatment processes to achieve safe reuse. It is intended to support decision making and is a complement to, not a substitute for, sound professional judgement. The authors do not guarantee functionality, and accept no legal liability of whatever nature arising from or connected to the contents of this publication.

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The aim of this document is to provide an overview of the possibilities for resource recovery from sanitation and provide guidance on treatment processes to achieve safe products for reuse. The focus of this document is on resource recovery from the organic wastes managed in sanitation systems and to a lesser extent on the recovery of water that is often mixed with these wastes. Resource recovery sanitation systems are defined as systems that safely recycle excreta and organic waste while minimising the use of non-renewable resources such as water and chemicals. Safe recycling means that waste flows are managed so that physical, microbial and chemical risks are minimised. Thus, the recycled product should not pose any significant health threat or environmental impact when correctly used.

The specific objectives of this document are:

1. To expose the user to a broad range of recovered sanitation products and innovative treatment technologies.
2. To help the user to design functional solutions for resource recovery by illustrating the linkages between sanitation inputs, treatment technology and the recoverable products.
3. To provide an overview of basic information regarding design aspects, operational requirements, and health, safety and social considerations related to resource recovery technologies and products.
4. Describe and fairly present technology-specific advantages and disadvantages.

Cover illustration by Annika Nordin, SLU (Uppsala, Sweden)