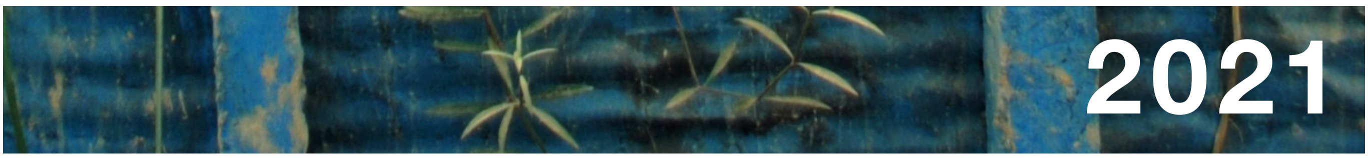
METHODOLOGIES & APPLICATION
FROM DOCUMENTED EXPERIENCE

Nº7

Comprehensive Overview on Bio-Solids Post-Treatments



2021

Comprehensive Overview
on Bio-Solids Post-Treatment

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in cooperation with Bangladesh Agricultural University
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Abbreviations & Acronyms

ABR	Anaerobic Baffled Reactor
ADEME	Agence de l’Environnement et de la Maîtrise de l’Energie (French Environment and Energy Management Agency)
BDT	Bangladesh Taka
BOD5	Biochemical Oxygen Demand measured during 5 days at 20°C
°C	Degree Celsius
Ca	Calcium
CaO	Calcium Oxide
$Ca(OH)_2$	Calcium Hydroxide
CO	Carbon Monoxide
COD	Chemical Oxygen Demand
CST	Capillary Suction Time
d	day(s)
DM	Dry Matter
DPHE	Department of Health and Engineering
EAWAG	Swiss Federal Institute of Aquatic Science and Technology
e.g.	for example (from Latin: *exempli gratia*)
$FeCl_3$	Ferric Chloride
FS	Faecal Sludge
g	gram
h	hour(s)
HCl	Hydrogen Chloride
HTC	Hydrothermal Carbonization
H_2O	Water
i.e.	in other words (from Latin: *id est*)
K	Potassium
kg	Kilogram
kW	Kilo Watt
l	liter(s)
LR	Liming Rate
m^2	square meter
m^3	cubic meter
mg	milligram
Mg	Magnesium
ml	milliliter
mm	milimeter
MWh	Mega Watt hour
N	Nitrogen
NO	Nitrogen Oxides
P	Phosphorus
P.E.	People-equivalent
pH	measure of the acidity or alkalinity of a solution
SS	Settleable Solids
SOx	Sulfur Oxides
t	ton(s)
TNK	Total Nitrogen Kjeldahl
TP	Total Phosphorus
TS	Total Solids
WHO	World Health Organization
*****	Multiplication sign
<	Less-than sign
>	Greater-than sign
≥	Greater-or-Equal-than sign

Preface

This publication is the result of the technical assistance provided by UPM Umwelt-Projekt-Management GmbH (UPM) and its partners, the Centre for Sustainable and Ecological Sanitation (CSES) of the University of Science & Technology Beijing (USTB), and the Bureau of Socioeconomic Research and Training (BSERT) of the Bangladesh University of Agriculture (BAU) to the United Nations High Commissioner for Refugees (UNHCR), the Department of Public Health Engineering (DPHE) and the local WASH sector in Cox's Bazar, Bangladesh, in cooperation with the Bill & Melinda Gates Foundation.

The goal of this technical assistance assignment was to provide support to the emergency WASH sector and local sanitation administration, regarding faecal sludge management, with focus on value recovery in emergency settings, in order to sustainably improve the living conditions of displaced populations and their host communities.

The present manual "Comprehensive Overview on DEWATS Effluent Post-Treatments" was elaborated in the context of a series of training workshops organised by UPM and its partners in Cox's Bazar based on a Training Needs Assessment implemented in early 2019 among the local WASH community.

The content of this manual was presented as part of the Training session "DEWATS – Decentralized Wastewater Treatment Plant Systems, also applicable for treatment of faecal sludge" organized in Cox's Bazar in January 2020. The objectives of the training was to support trainees to gain understanding of the selection criteria for a decentralised wastewater treatment plant system chain, their limits and required adaptations to treat sludges and their appropriateness in the Rohingya Refugee camps context.

Definitions

Faecal sludge Is a mixture of human excreta, water and solid wastes (e.g. toilet paper or other anal cleansing materials, menstrual hygiene materials, etc.) that are disposed of in pits, tanks or vaults of onsite sanitation systems. When it is removed from septic tanks, it is called septage. Historically, it has been called night soil.

Dry toilets, designed to be easily emptied without the addition of water, do not generate faecal sludge but generate instead dried feces —in the case of urine- diverting dry toilets, or compost —in the case of composting toilets.

Sludge is an unavoidable by-product of wastewater treatment. Aerobic treatment of wastewater produces up to 20 times more sludge than an anaerobic treatment. Pollutants, chemicals and pathogens accumulate in sludge and must be treated to avoid pollution of soil or water.

In summary, from a health and environmental point of view, sludge is more dangerous than wastewater, and its treatment should not be neglected. In many countries, unfortunately, faecal sludge is still often discarded without any treatment.

Types of sludge from wastewater

Different types of sludge require specific treatments.

TABLE 1: Different types of sludge.

Types of sludge	Physical-chemical properties
Primary Sludge (Settling) = inorganic particles + some dense organic and colloidal particles.	Mineral and organic content Hydrophilic - hydrophobic.
Secondary Sludge = biological sludge resulting from anaerobic or aerobic treatment): high organic concentration, low relative density made up by flocculent particles, and low concentrations of inorganic solids.	
Physico-chemical sludge (flocculation coagulation treatments).	
Mixed sludge.	
Lagoon sludge or Industrial sludge.	

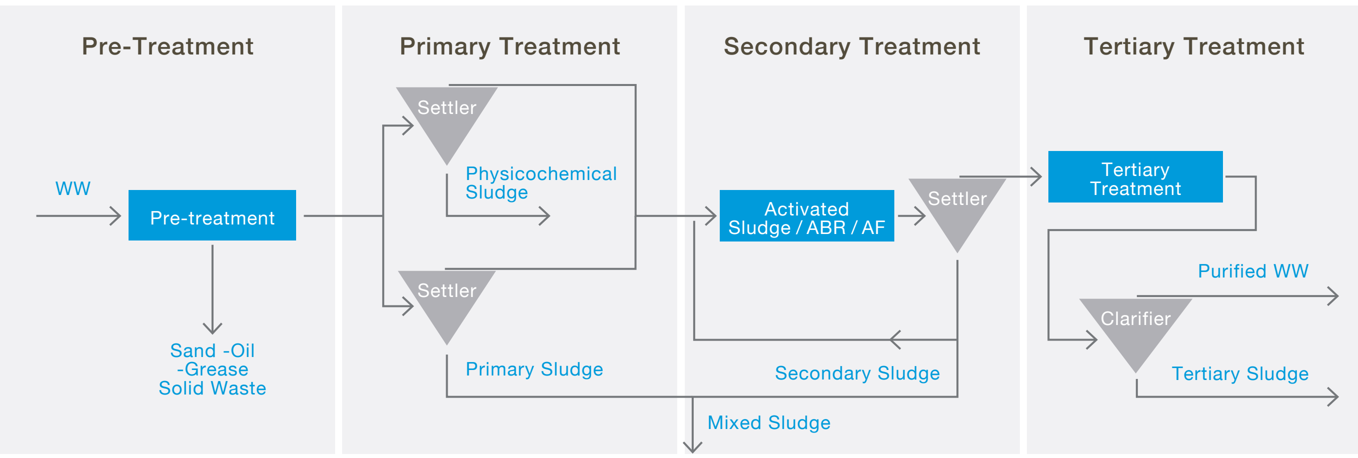


FIGURE 1: Sources of sewage sludge.

Fresh sludge issued from domestic wastewater generated with flush toilets or anal cleansing water is composed of 95–99% of water, fermentable organic matter and dissolved or insoluble mineral matter. Sludge can be characterized by the folllowing physico-chemical and biological parameters:

TABLE 2: Biological and physical-chemical parameters of sludge.

Biological parameters	Physical-chemical properties
Organic Matter (% of Total Solids (TS))	Dry Matter (DM), TS and dryness in g/l and g/kg:
Settled Solids (SS), volatile fraction, COD, BOD5, Total Phosphorus (TP), Total Nitrogen Kjeldahl (TNK).	• DM [g/l] is the main parameter to define the sludge; it is easy to measure by drying at 105°C in oven or under Infra-Reds. • Dryness [% or g/kg] is the mass fraction of total sludge mass.
Composition of organic matter and minerals.	• According to their dryness or dry matter, sludges are considered as liquid, pasty, solid or dry: – Liquid sludge: 3% < Dryness <10%. – Pasty Sludge: 10% < Dry matter <25%. – Solid sludge: Dryness > 20%. – Dry sludge: Dryness > 95%.
Greases, fibers, pathogens.	pH, temperature, conductivity.
	Heat value: potential thermal energy for incineration.

Physical characteristics are:

- → Suitability for conveying and storage.
- → State: liquid, pasty, solid, dry.
- → Density ρ.
- → Viscosity μ.
- → Ability to stick.
- → Ability to heat treatments.
- → Capacity to retain constant heat at constant pressure.
- → Thermal conductivity λ.

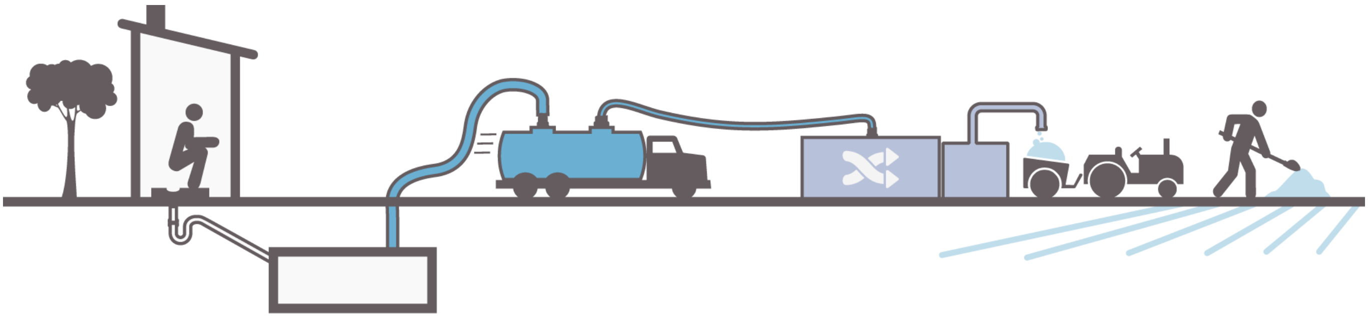
Viscosity:

- → Increasing the moisture content of the sludge from 75 to 90% will reduce the head and power of the pump by a factor 100 but will triplicate the amount of water in the sludge and, consequently, the time for pit emptying.
- → Fresh human feces exhibit temperature-dependent behavior, where there is a linear relationship between viscosity and temperature. Lower viscosities are shown at higher temperatures, over a temperature range of 10°C to 50°C.
- → Operational temperatures and ambient temperature can influence the viscosity of feces within the proposed process.

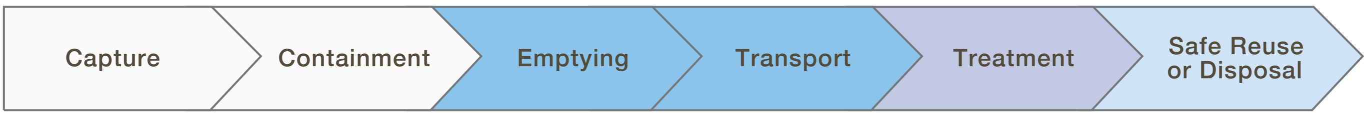
Sludge production and service chain

Treatment of wastewater produces high amounts of sludge: for 1 kg BOD5 treated, 0.7 to 1 kg dry sewage sludge is produced. For example, in Bangladesh, 1 People -Equivalent (P.E.) produces 15 kg of dry sewage sludge per year, if connected with flush toilet to WWTPs. One million people produce 22,000 t of dry sludge per year (* 0.060 kg dry sludge / P.E. * d * 365 d / year).

Sludge quantities can be reduced by anaerobic treatment, hence, reducing the sludge generated in the aerobic systems. The next figure illustrates the service chain from faecal sludge production to its reuse or disposal.



Ideally, all human waste produced ends up safely at the end of the chain:



In reality, much of the human waste disappears somewhere along the chain:

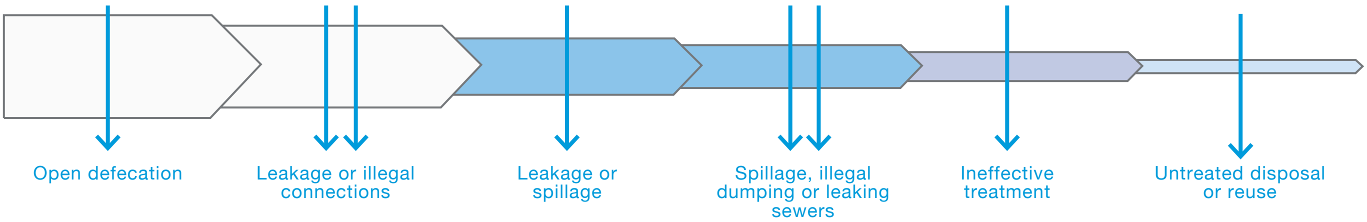


FIGURE 2: **Fecal sludge handling within the sanitation service chain.**

Sludge treatment

Three treatment concepts can be applied:

1. Reduction of the water content: dewatering, dehydration, thermal drying to reduce the quantity of sludge to be stored and spread, or improve their physical characteristics
2. Stabilization of the organic matter by reducing its fermentability, to reduce bad odors
3. Hygienization (if necessary) by destroying pathogenic microorganisms.

SLUDGE TREATMENT

Reduction of water content

Sludge dewatering includes different physical process:

a. Thickening (dryness: 1–10%).
b. Gravitational static thickening.
c. Dynamic thickening on drip table (or drum).
d. Dynamic thickening by centrifugation.
e. Dynamic thickening by floatation.

Sludge dehydration techniques (dryness: 15-40%) are as follows:

a. Centrifuge (20–25%).
b. Belt filter (20%).
c. Filter press or trays (30–35%).
d. Drying bed (35–40 / 90%).
e. Thermal Drying (dryness up to 95%).

The different physical treatments can be successive, as illustrated Figure 3:

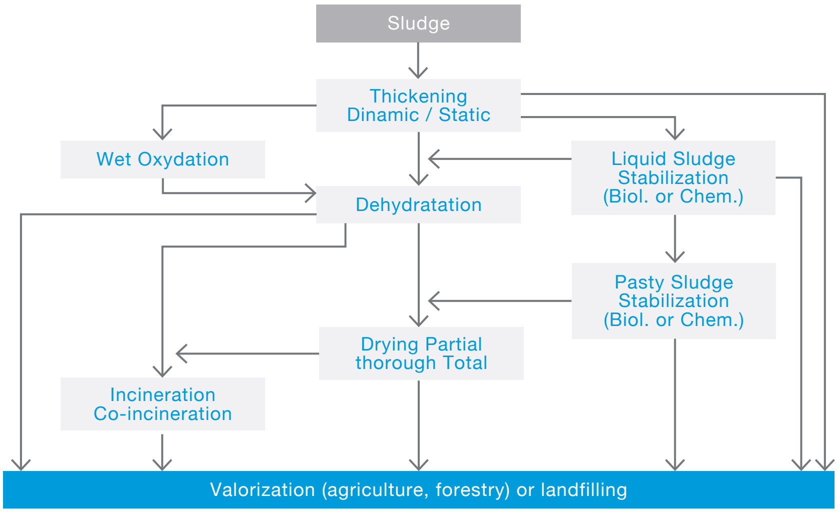


FIGURE 3: Different physical treatments.

Dynamic Thickening on Drip Table

Drip Table can be a pre-treatment of sludge before a filter press.
It filters the sludge by gravity on a filter cloth.

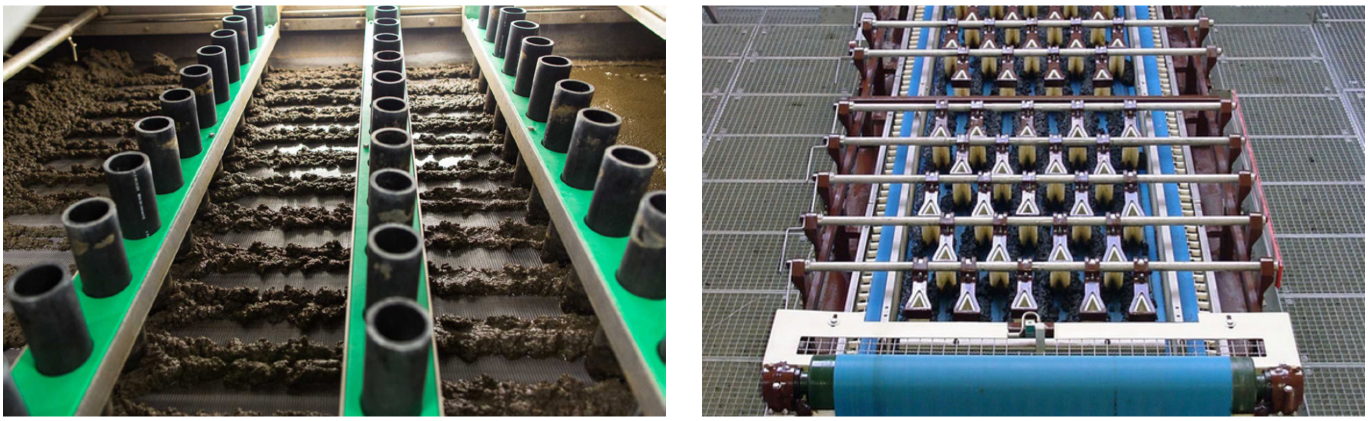


FIGURE 4: Sludge is flocculated and thickened (right) after pre-conditioning by cationic polymer (4 to 8 kg / t DM). [1]

[1] Source: Royal Haskoning DHV, The Netherlands.

Gravity Settler

The gravity settler is a robust technology. It is efficient for the removal of suspended solids by sedimentation and retains the lighter constituents by floating. The reduction of SS can be of up to 50–70%. The system reduces BOD5 concentrations by 20 to 40%.

Gravity settlers can be built in a variety of forms and from a variety of material: concrete, steel, fiberglass, PVC or plastic, and they are available as prefabricated units (See Figure 5).

The efficiency of a settler depends on wastewater characteristics, retention time and sludge withdrawal rate. The typical hydraulic retention time is 2.5 hours. The Capillary Suction Time (CST) can explain the sedimentation rate. A lower CST means a faster dewatering rate. The efficiency of a settler with large and open surface can be reduced due to wind-induced circulation, thermal convection and density currents caused by temperature differentials and, in hot climates, thermal stratification. These phenomena can lead to short-circuiting.

It needs relatively low capital and operating costs. But, the sludge, the effluent and the scum, which must be frequently removed, would require further treatment. Hydraulic and structural design are sophisticated.

To enhance the performance of settlers, inclined plates (lamellae) and tubes can be installed to increase the settling area. The lamellae allow the particles to agglomerate and, according to Stokes' Law, to settle better (See Figure 6).

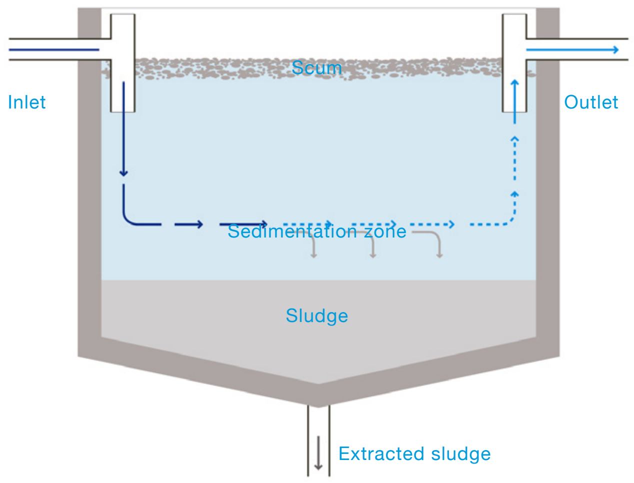
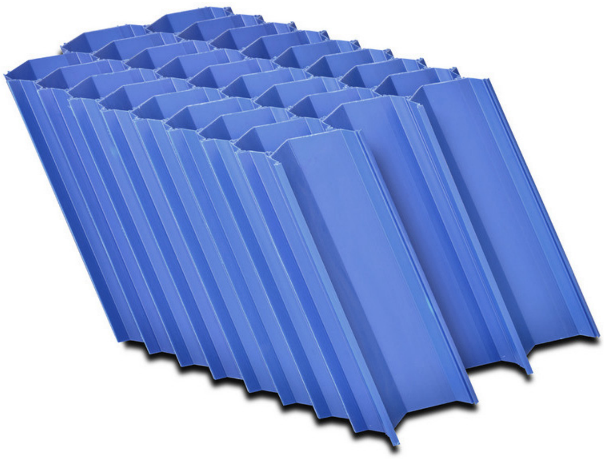


FIGURE 5: Cross-sectional view on a Gravity Settler (left) and one model constructed by Ashton Green & Company (right). [2]



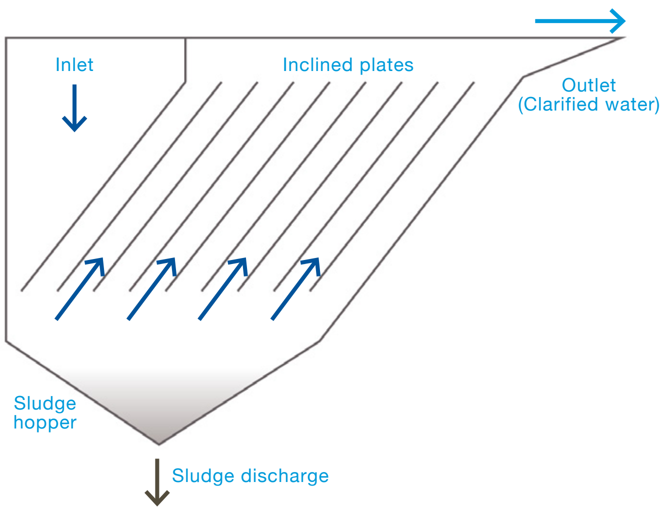


FIGURE 6: Lamellae in a gravity settler.

[2] Source: EAWAG (top); Ashton Green & Company, India (center).

Chemical coagulants can be also used. In Figure 7, faecal sludge from lined pit latrines (left) and from septic tanks (right) are conditioned at a dosage of 1 ml/g TS chitosan (chitin from shells of shrimps and other crustaceans treated with an alkaline substance such as sodium hydroxide). The faecal sludge from septic tanks showed a formation of flocs and an increased solid-liquid separation. In contrast, no flocs are formed by the faecal sludge from lined pit latrines.

The settling velocity v (m/s) is calculated according to the the Stokes' Law:

$$v = \frac{2}{9} \frac{(\rho_p - \rho_f)}{\mu} g R^2$$

where

- → g is the gravitational field strength (m/s^2)
- → R is the radius of the spherical particle (m)
- → ρ_p is the mass density of the particles (kg/m^3)
- → ρ_f is the mass density of the fluid (kg/m^3)
- → μ is the dynamic viscosity (kg/(m*s))

FIGURE 7: Fecal sludge from lined pit latrines (left) and from septic tanks (right).

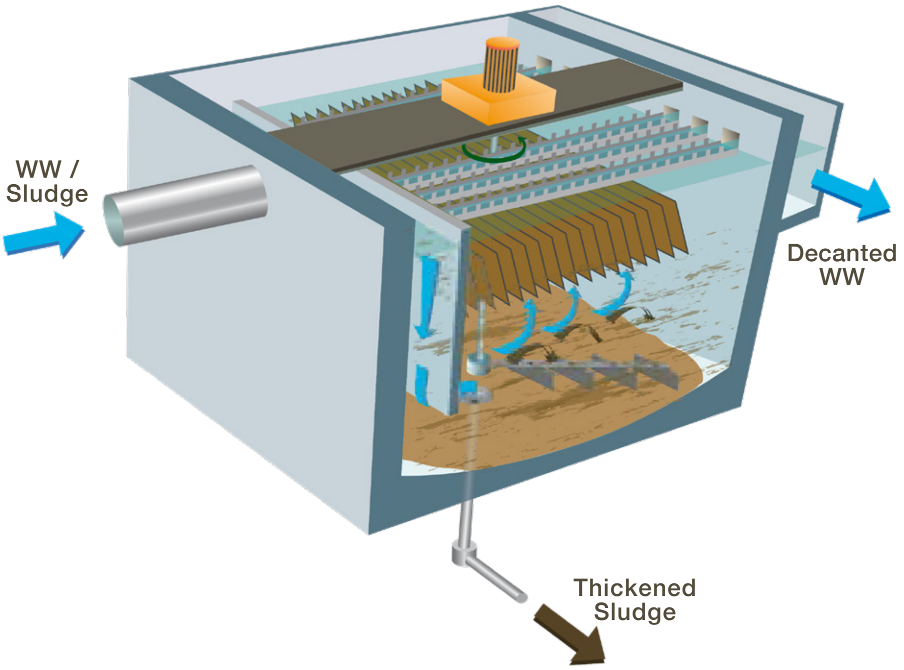


FIGURE 8: Decanter. [3]

[3] Source: Veolia Water, France.

Floatation

Floatation systems need dissolved air and power, for air compression. Power consumption is high. The system is compact (low footprint referring to land use). Upstream conditioning is made with cationic polymer 1 to 2 g/m³ (See Figure 9).

The technological process is described as follows: Injecting compressed air into the sludge receiving tank causes the accumulation of sludge particles on the surface. This sludge is scraped on the surface and collected (See Figure 10).

FIGURE 9: Floater with lamella decanter. [4]

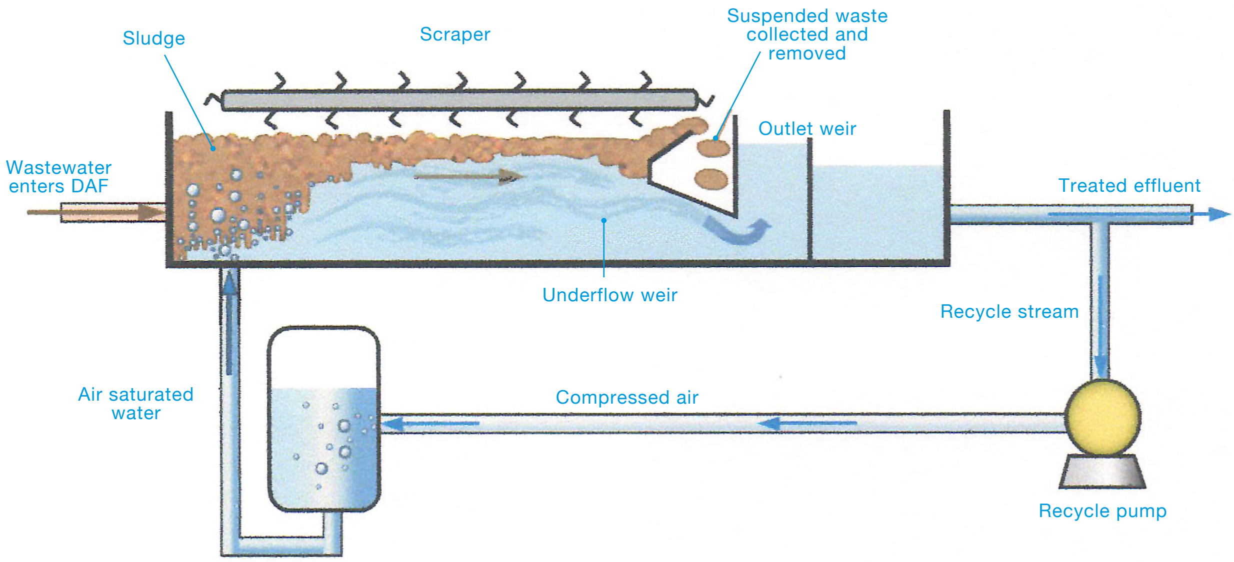


FIGURE 10: Floatation and basic filtration. [5]

[4] [5] Source: Siltbuster Process Solutions Ltd., United Kingdom.

Membrane (micro-) Filtration (Geotubes)

The Geotubes process is the process related to the filtration through membranes with tiny pores. These membranes separate water and concentrated sludge and achieve up to 15–25% dryness. Once filled up, the Geotubes are opened and the sludge is either sent to another destination for further treatment or transported to a landfill site. This technology could be suitable for installations for 1,000 to 2,000 P.E. It reduces the sludge volume by, at least, by 5 times.

FIGURE 11: Geotubes for sludge thickening.

Membrane (micro-) Filtration with STRIZbox technology[6]

The system is based on an active filtration under pressure. No coagulant is used. The dewatering is rapid and effective. The STRIZbox are vertical columns with top feedings and flow of dehydrated press cake at the lower end of the column. Modular construction allows to increase the flows, according to the needs of the customer. The system can work 24h/d.

The tubes in the columns are made of porous membranes. The working principle is as follows: (1) a column is fed with sludge; (2) Air pressure of max. 6 bars inflates the tubes; (3) filtration happens through micro-pores; (4) press cake is released automatically after the tubes are deflating.

FIGURE 12: STRIZbox. [7]

FIGURE 13: Press cake after tube compression. [8]

FIGURE 14: Working principle of the porous tubes: filled with sludge (left), air pressured filtration (center) and final press cake (right). [9]

[6] STRIZbox is a technology by Idee & Prodotti SRL.
[7] [8] [9] Source: Idee & Prodotti SRL, Italia.

Membrane (micro-) Filtration: Dry-box[10]

The system functions – like the STRIZbox, also as active filtration under pressure. The dewatering system works fast; it is operated in a rolling container. Installation on site and transport on trucks are convenient.

Active filtration is the transition from static to dynamic filtration.
The Dry- box needs 2 bar air pressure and 0.5 kW power.

The filter cloth, visible on the container walls, is disposable. One batch capacity is about 20 m^3. 10 to 11 tons of dehydrated material can be stored.

Detailed descriptions are available online as videos. [11]

FIGURE 15: Dry-box outside view (left) and transported by truck (right). [12]

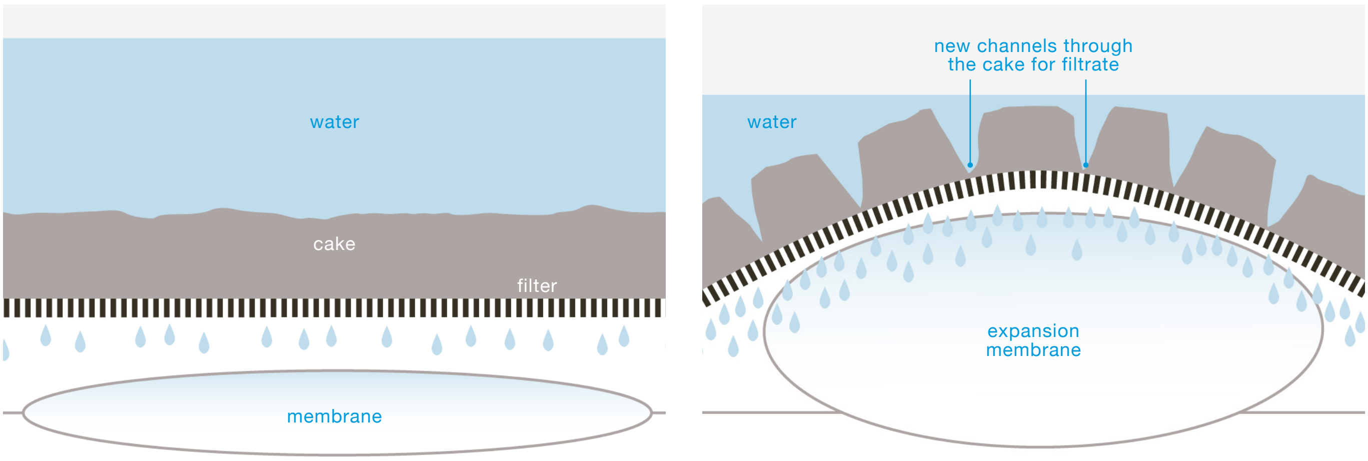


FIGURE 16: Principle of active filtration. [13]

[10] Dry-box is a technology by Idee & Prodotti SRL.
[11] Visit: https://www.youtube.com/watch?v=P2KWQEB5q4o & https://www.youtube.com/watch?v=ObhSO3xeLCw
[12] [13] Source: Idee & Prodotti SRL, Italia.

FIGURE 17: Drilling mud (top right) from Milan underground wastewater (top left) obtained without conditioning after 8h of active filtration; disposable filter cloth (center). [14]

FIGURE 18: Dry-box with roof and forced ventilation wings in polycarbonate (right). [15]

[14] [15] Source: Idee & Prodotti SRL, Italia.

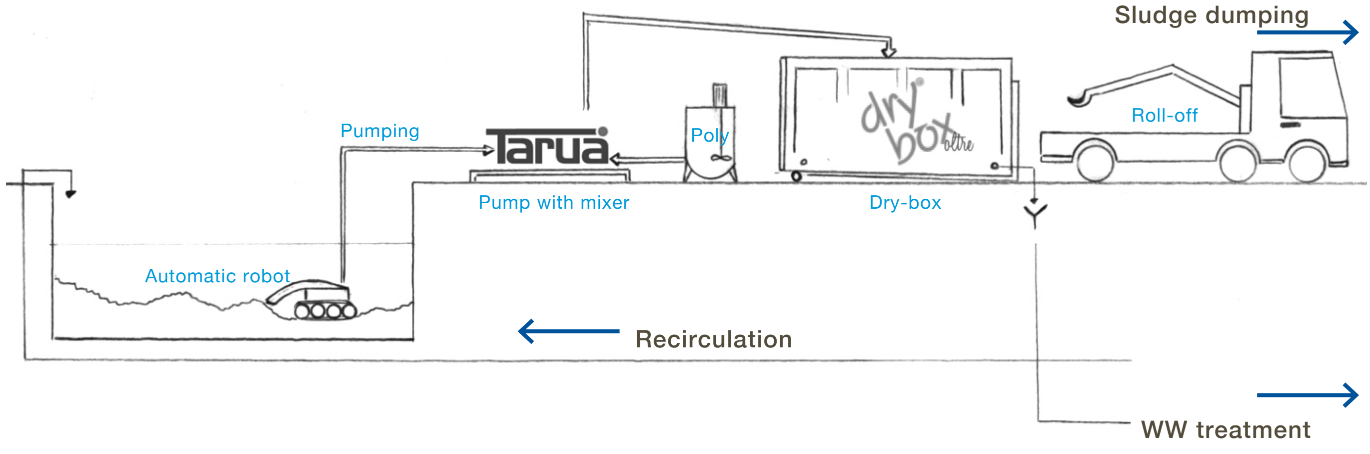


FIGURE 19: Collection of Dewatered fecal sludge by Dry-box (top) and Dry-box combined with special pump (bottom). [16]

[16] Source: Idee & Prodotti SRL, Italia.

Sludge Liming

The following description is an extract from “WASH sector`: Desludging Guideline v1 Cox’s Bazar, Bangladesh”, May 26th 2019:

> *Three types of lime exist:*
> *1. Quicklime CaO (or MgO) is produced by calcination of limestone, seashells (calcium carbonate) or dolomite (magnesium carbonate) in oven at > 900°C. The reactions are as follow:*
> $CaCO_3 \rightarrow CaO + CO_2$ *and* $MgCO_3 \rightarrow MgO + CO_2$*.*
> *2. Hydrated lime has the chemical formula* $Ca(OH)_2$*.*
> *3. Lime “milk” consists of* $Ca(OH)_2$ *saturated in water.*

Caution: CaO application could be hazardous: Quicklime CaO + water hydrated lime; At high temperature (up to 300°C), CaO found in hydrated lime can cause severe irritation when inhaled or when it comes in contact with moist skin or eyes. Inhalation may cause coughing, sneezing, labored breathing. It may then evolve into burns with perforation of the nasal septum, abdominal pain, nausea and vomiting.

Therefore, only hydrated Lime with a density of 0.5 kg/l is recommended for application on faecal sludge in the camps. Composition of a 90% + hydrated lime is described in the following table.

TABLE 3: Composition of a 90% + hydrated lime.

Chemical Entity	Proportion (%)
Water	0.1–2.5
Calcium Hydroxide	90–95
Magnesium Hydroxide	0.5–1.0
Crystalline Silica (Quartz)	< 1
Silicon Dioxide	0.5–2
Aluminium Dioxide	0–2
Iron Oxide	0–0.4
Rem.= 1 kg CaO + water $\rightarrow$ 1.85 kg $Ca(OH)_2$	

Effects of liming

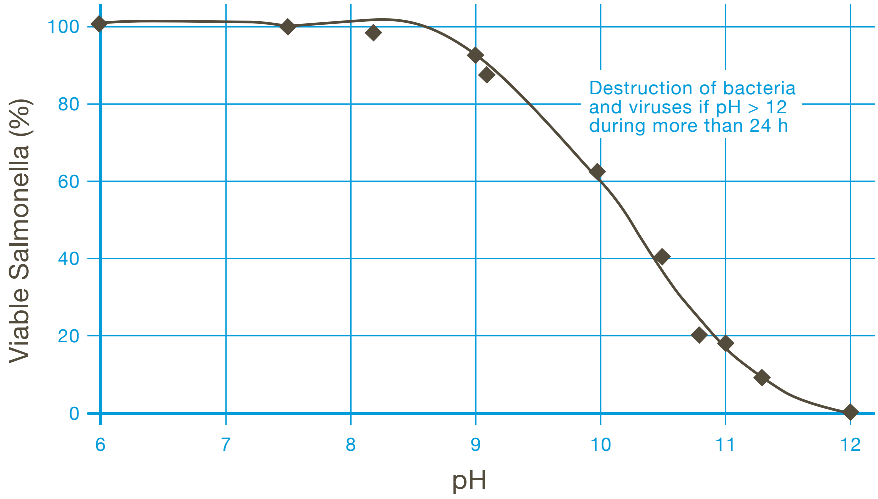
1. Liming contributes to sludge dewatering by increasing the dryness.
2. Liming increases the sludge quality (reduction of odors, increased agronomic value with pH regulation).
3. Highly dosed liming can keep the sludge at pH > 12 over several months.
4. Stabilization and blocking of fermentations.
5. Hygienization, destruction of pathogens.
6. Dehydration of $CaO + H_2O \rightarrow Ca(OH)_2$.
7. Drying agent.
8. Improved cohesion and heaping.

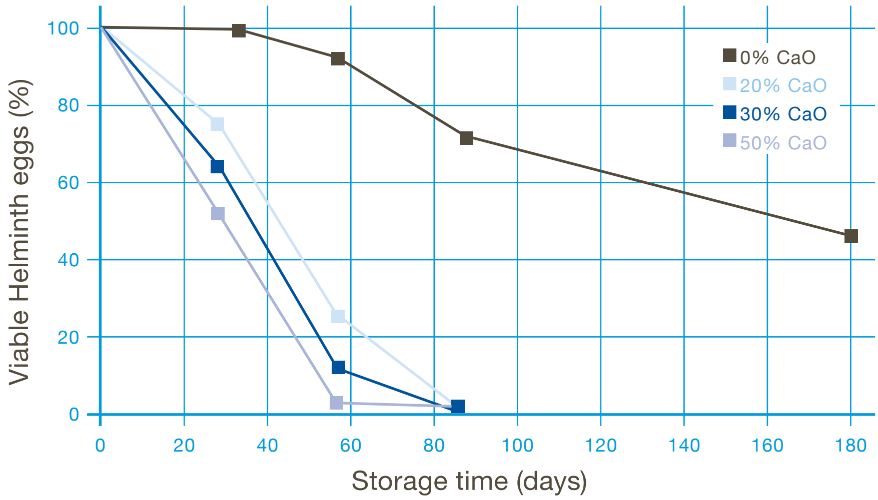
Dewatering and reduction of pathogens

After treatment with hydrated lime, the presence of bacteria and viruses decrease, up to 0 at pH 12.

FIGURE 20: Impact of hydrated lime on bacteria and viruses (top).[17]

FIGURE 21: Treatment by CaO accelerates the reduction of viable eggs in the sludge (center).[18]





Sludge quality

Liming impacts also the quality of the treated faecal sludge: it reduces odors, prepares the sludge to serve as fertilizer and soil amendment in agriculture, and especially improves the pH value of soils acidified by intensive agriculture.

The liming rate (LR) is expressed in % kg quicklime (CaO)/kg DM sludge. A LR higher than 30% leaves slight odor of faecal sludge for some months.

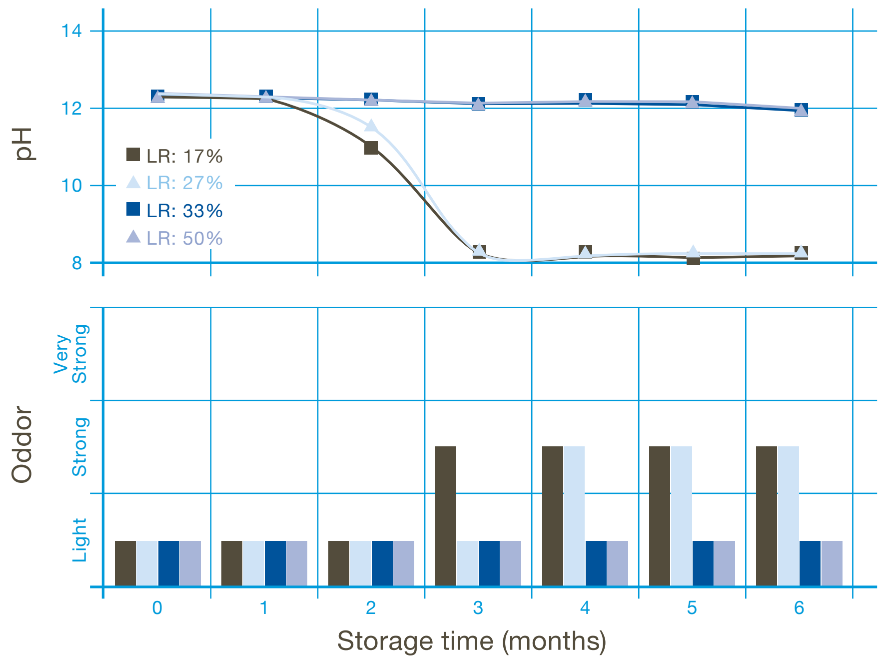


FIGURE 22: Liming rate higher than 30% results in odor reduction.[19]

[17] [19] Source: Lhoist R&D.
[18] Source: IRH Nancy (Gaspard et al.).

Applications

Treatment of fresh sludge can be achieved by so called Lime Milk. The goal is to disinfect the sludge before spreading it on fields, or further post- treatment.

Liming sludge before dewatering is recommended in order to optimize the sludge conditioning and dewatering. Other purposes are organic conditioning before belt filter, centrifuge, filter press; mineral conditioning (with $FeCl_3$) before filter press; and reduction of the amount of sludge to facilitate its handling and adapt it to the next treatment.

Liming of dewatered sludge acts on cohesion and dryness for holding the sludge in piles; stabilization and hygienization; inerting heavy metals; and adding value Ca and Mg.

FIGURE 23: Sludge treatment in tanks. [20]

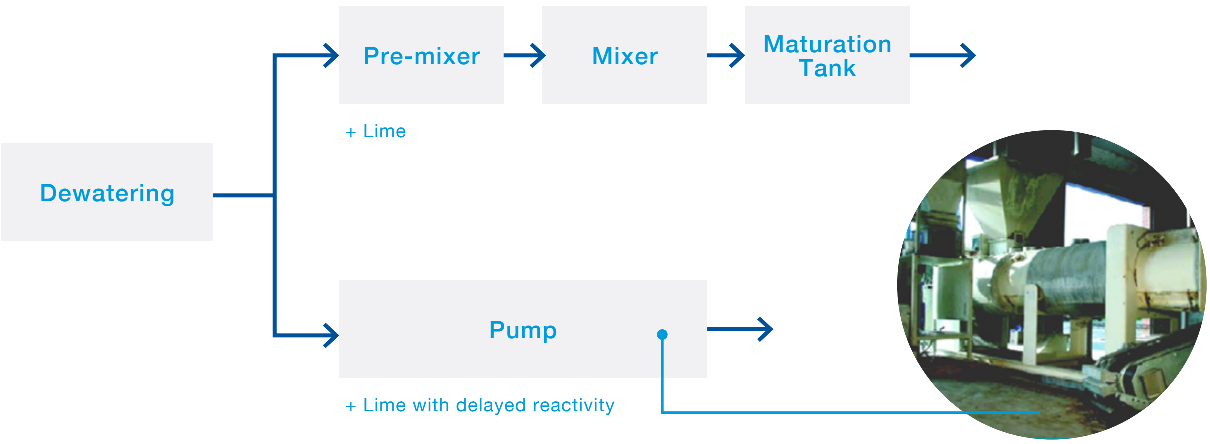


FIGURE 24: Example of techniques of liming on the dewatered sludge. [21]

[20] [21] Source: Lhoist R&D.

Drying Beds

The drying bed consists of different layers, build up from bottom to top:

→ Watertight membrane;

→ Drainage system to collect the leachates;

→ Min. 15 – 20 cm gravel layer composed of pebbles (3 – 25 mm);

→ Min. 10 – 20 cm sand layer (0.3 – 1 mm).

A drying bed is operated in 4 steps for a total treatment cycle of about 10 weeks:

1. Spreading of liquid sludge (30 to 50 cm).
2. Collection of leachate in the drains (some days).
3. Drying up the sludge to 10 to 90% Dry Matter, depending on sludge quality and local climate.
4. Emptying of the sludge

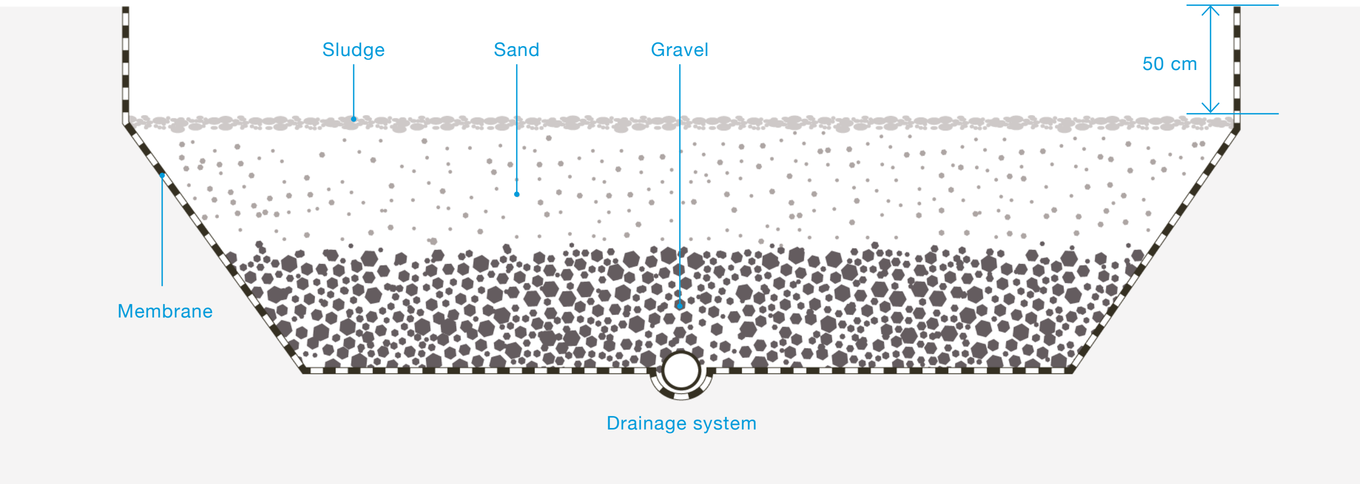
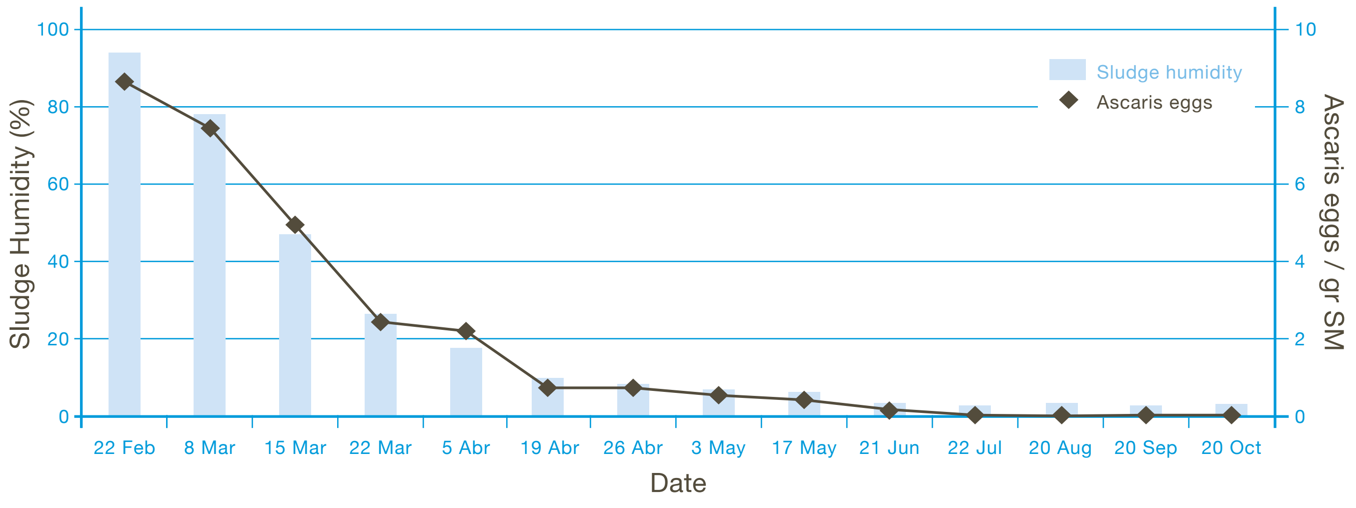


FIGURE 25 : Cross-sectional view on a multi-layer drying bed. [22]



[22] [23] Source: Xanthoulis, 1996.

FIGURE 26: Reduction of Ascaris eggs during sludge drying. [23]

Soilisation

Soilisation process happens in planted sand-gravel filters fed alternately with sludge. The drying process consists of a initial short-term gravity dewatering step, followed by evaporation and evapo-transpiration during medium and long-term periods. The drying is optimized by the plants. The best option is to use reeds. The system is low cost but needs big areas. It can accept all types of sludge, except oily sludge. The beds are fed by batches. An 8-bed system is recommended to alternate the loads on the beds, respecting the rest periods, and avoiding clogging.

The life cycle of a Planted Reed Bed starts with a period of 2 years during which the sludge load is lower than the dimensioned load. When the plants are completely developed, production takes up for about 6 years. Drainage is ongoing. Extraction of dewatered sludge is followed by loading new sludge.

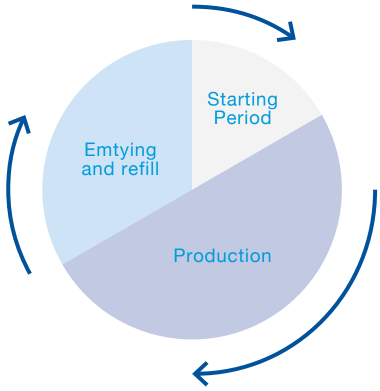
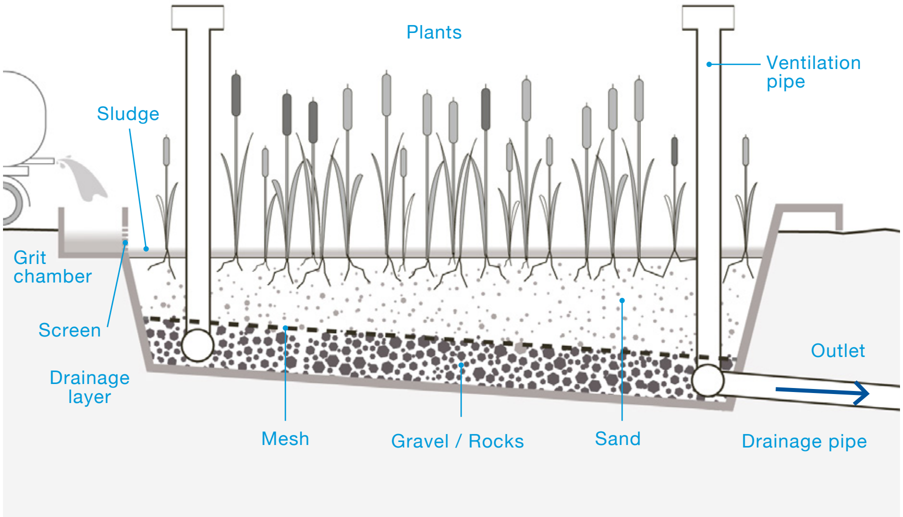


FIGURE 27: Life cycle of a Planted Reed Bed.

FIGURE 28: Cross-sectional view on a Planted Reed Bed for soilisation of sludge (right). [24]

FIGURE 29: Working principles of Planted Reed Beds: (A) Loading of planted reed bed after sludge has been removed. In the background, an empty bed and beds with fully grown plants; (B) Effect of plants on the surface of a planted reed bed for sludge dewatering and mineralization. [25]



[24] Source: EAWAG.
[25] Source: Hans Brix, 2004-2005.

Belt filter

In a belt filter, sludge dewatering is achieved between 2 filter cloths. The obtained dryness is between 16 and 22%. Sludge is pre-conditioned with cationic polymer (6kg / t DM).

Service life of the cloth's ranges from 1 to 2 years. During the process, the cloths are continuously cleaned with clear water. Working pressure is 7–8 bar. Belt filters are often combined with drip tables.

FIGURE 30: Belt filter. [26]

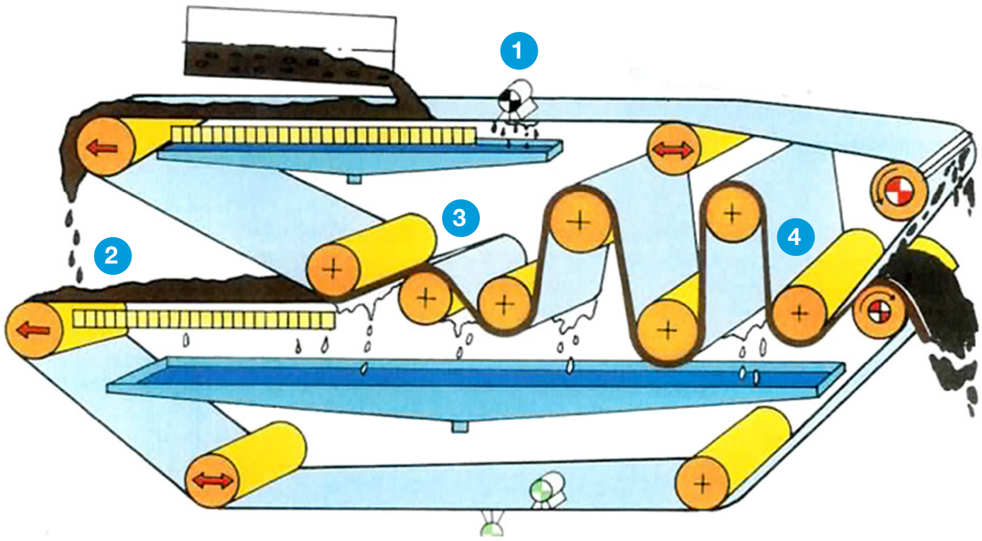


FIGURE 31: Workflow of a belt filter: (1) pre-conditioning with polymers (2–3 g/l) and flocculation in tank; (2) gravity draining area; (3) low pressure zone for compaction; (4) high pressure area (shear). [27]

[26] Source: ADEME, France.
[27] Source: Soluciones Medioambientales S.L, Spain.

Centrifuge

Centrifuge system produces pasty sludge (dryness between 16–25%). The sludge is pre-conditioned with cationic polymer (at 5–8 kg / t DM). The decantation is achieved under acceleration 2,000–3,000 g in a very short retention time of just a few tens of seconds. The footprint is small, but the technology is sophisticated and challenging, and needs precision maintenance.

The centrifuge bowl is cylindrical-conical. The sludge is pressed on the walls by a coaxial screw conveyor. The deposits are scraped from the walls. The differential speed between bowl and conveyor can be adapted according to the type of sludge, desired dryness, and other parameters.

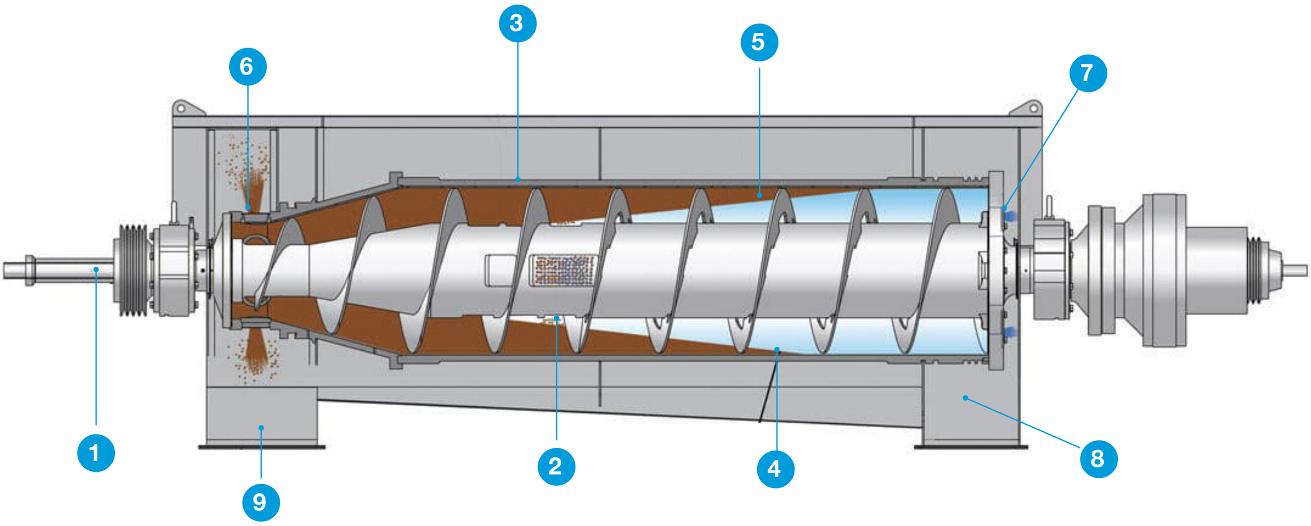


FIGURE 32: Centrifuge system installed (above) and technical design (below): (1) product feeding pie; (2) product feed chamber; (3) bowl; (4) scroll; (5) separation chamber; (6) solids discharge bushing; (7) liquids discharge bushing; (8) liquids discharge chute; (9) solids discharge chute. [28]

[28] Source: HAUS Santrifüj Teknolojileri, Turkey.

Press or tray filters

The system produces compact sludge as cake with 30–40% dryness.

Operating principles of press or tray filters are characterized by discontinuous operation and therefore batch feeding of the sludge. If the treated sludge should serve for agricultural purposes, pre-conditioning with Ferric chloride and lime is required in order to achieve stabilization and very high dryness. If the dried sludge should be used as fuel for incineration, coagulation and polymer are needed.

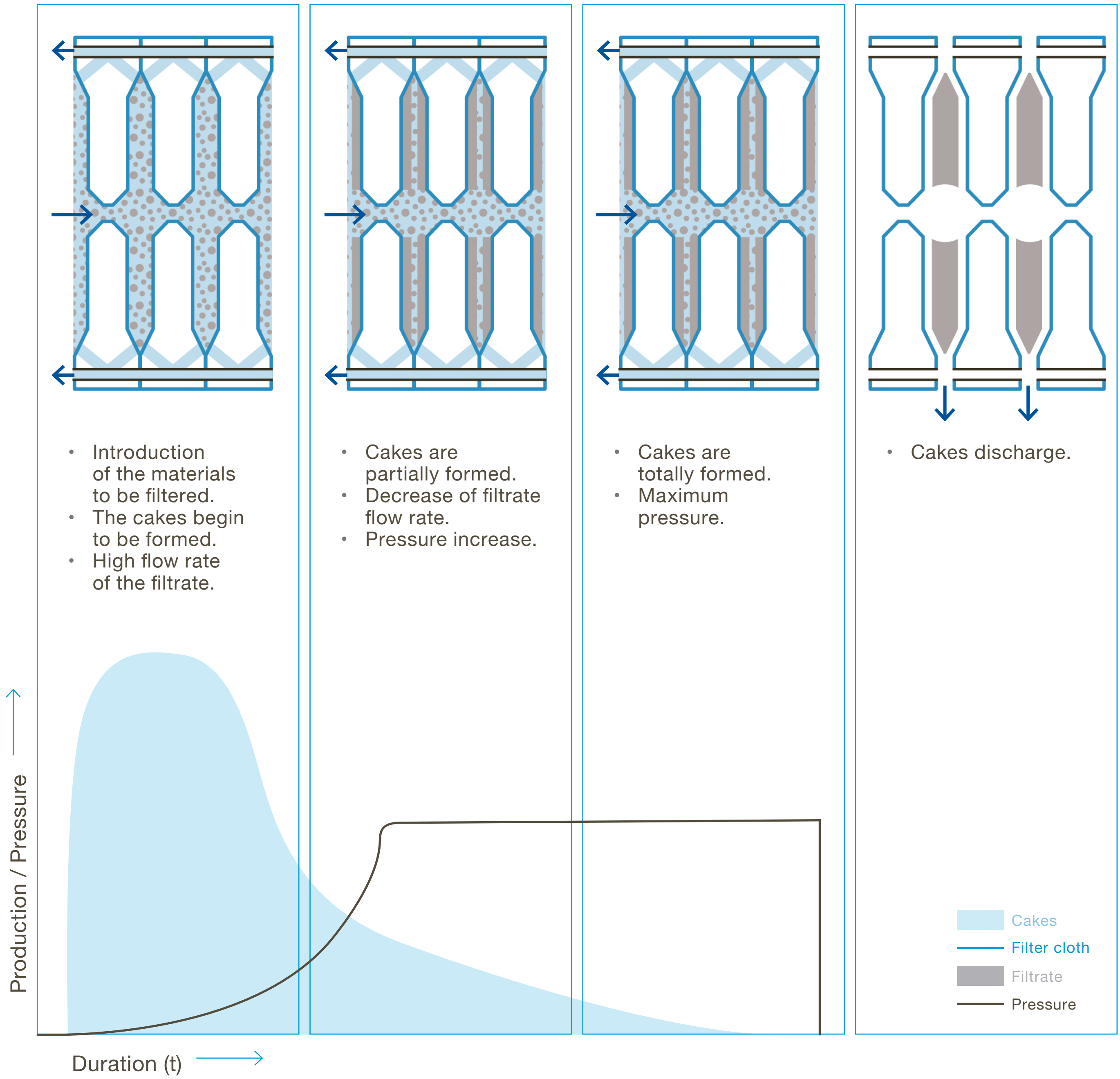


FIGURE 33: **Production of press filter cakes in four steps.** [29]

[29] Source: Faure Equipments, France.

FIGURE 34: Press filter (top), detail of the side of a press filter (center), and cakes produced by press filters (bottom). [30]

[30] Source: Faure Equipments, France (top).

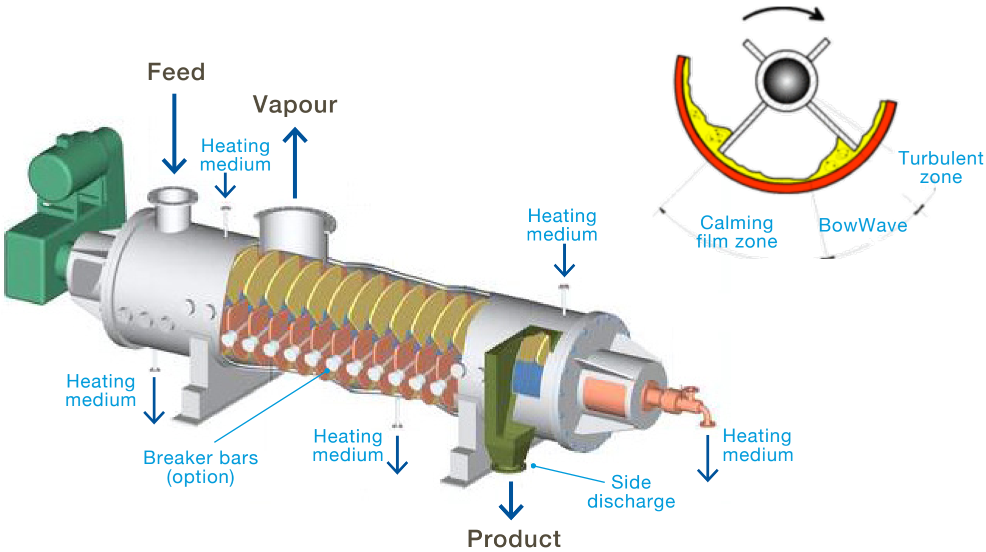
Thermal drying

Thermal drying is efficient for hygienization, stabilization, easy handling and mass reduction of sludge.

During the process of thermal drying, free and bound water evaporates.
Pre-dewatering is recommended to save energy and related cost.
In case of partial drying, the sludge will be sent to incinerators.
The objective is to reach 65 to 90% dryness, in particular if agricultural application is intended.

There are 2 types of drying, defined according to heat supply:
(1) direct drying by mixed flow via air or a mixture of air and combustion fumes brought in contact with sludge; (2) indirect drying by separate flow, bringing the sludge in contact with the heated wall.

FIGURE 35: Technical installation for thermal drying of sludge.



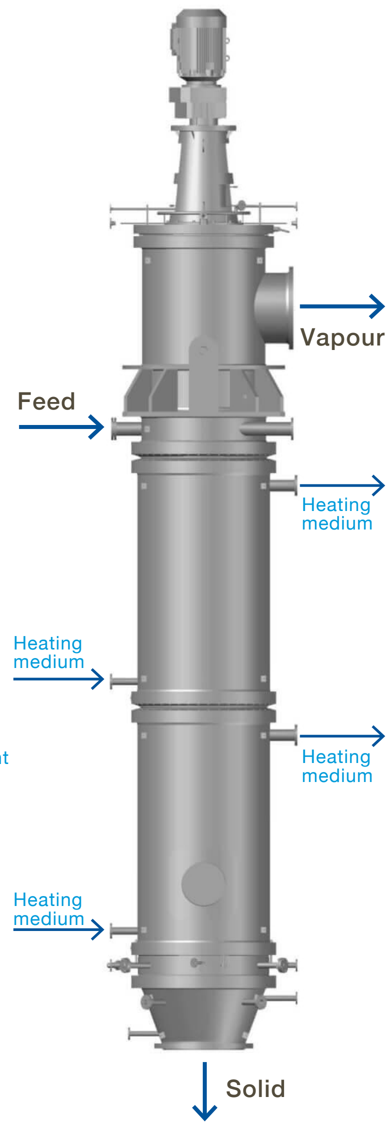


FIGURE 36: Thin film dryer (horizontal and vertical). [31]

[31] Source: Buss-SMS-Canzler GmbH, Germany.

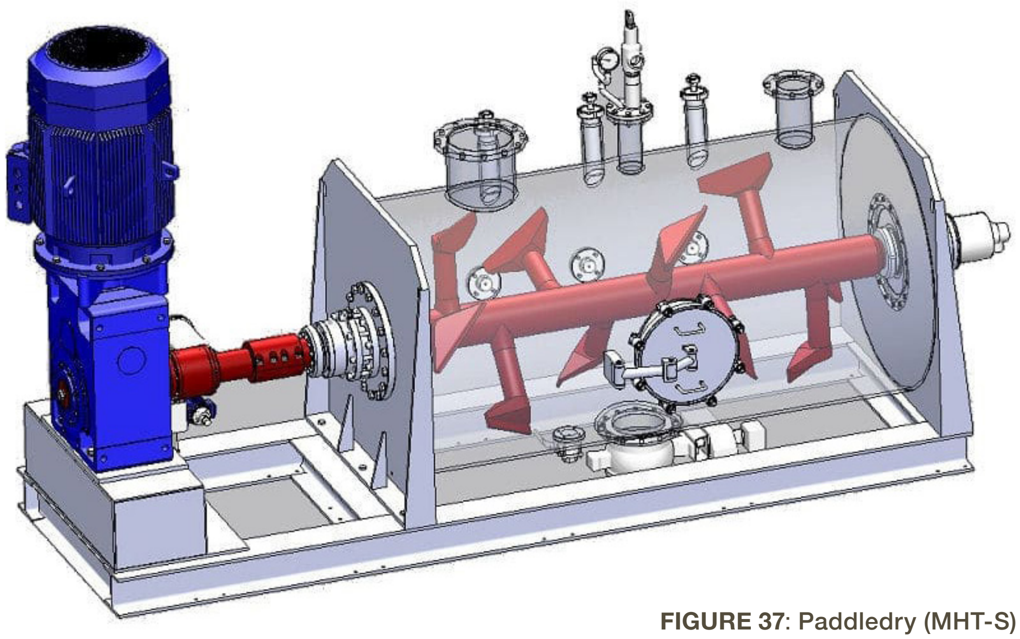


FIGURE 37: Paddledry (MHT-S) horizontal vacuum paddle dryer.[32]

Vacuum Dryer

Vacuum dryer, as described in the figure hereunder, is also used in chemical, pharmaceutical and food industries.

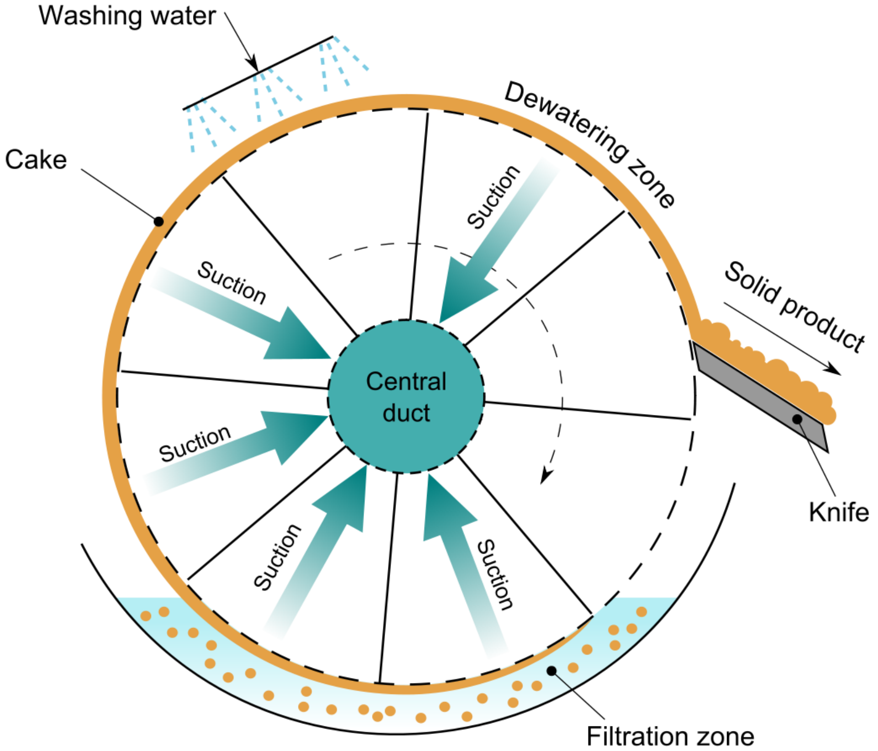


FIGURE 38: Working principles of a vacuum Dryer.

[32] Source: Bachiller, Spain.

Example: Sludge Treatment Plant in Lakshmipur, Bangladesh (2014)[33]

Population in Lakshmipur, Bangladesh, reached 122,572 people in the year 2014. Transportation of septic tank water and sludge is organized by vacutug. Households pay BDT 1,000 for desludging a volume of 2m^3. The sludge is conveyed to a sludge drying bed. Treated water would be discharged in agricultural land, sewer or water bodies. Co-composting of the solid digested portion would produce fertilizer for agricultural use.

For the sludge treatment, two conventional sludge drying beds are installed. They consist of impermeable beds of gravel, sand and planted vegetation on a total area of 780 m^2. Two sludge drying beds are alternately used, each bed consisted of 144 m^2 area. The designed service life is 5–7 years.

Desludging started in March 2013 for 900 septic tanks, representing a total volume of 4,500 m^3, servicing 20% of the population. The cost is equivalent to 25,000 BDT/month. The desludging frequency is 3–5 septic tanks per week: 2 separate days for loading, with 2–3 days for rest and aeration. Three people work for operation and revenue collection. They all are Paurashava employees.

FIGURE 39: Lakshmipur, Bangladesh: transport of raw fecal sludge (above) to sludge drying bed (below). [34]

[33] Source: FSM Convention, Bangladesh, 2016.
[34] Source: DPHE, Bangladesh (above); WaterAid, 2019 (below).

Operation is difficult during heavy rain and flooding times. Manual labor is required to remove dried sludge from the beds. Low cost disinfectant would be needed for coliform reduction, and attention has to be given to safe operation and maintenance. Land acquisition is difficult due to limited space and cost issues.

FIGURE 40: View on sludge drying beds in Lakshmipur, Bangladesh. [35]

SLUDGE TREATMENT

Comparison of different technologies for sludge thickening and drying

The following table displays the different factors that could influence the decision for or against installation of a specific technology for sludge thickening and drying.

TABLE 4: Comparison of technologies for sludge thickening and drying.

Technology	Capex	Opex	Footprint	Polymer	Odors	Feeds
Gravity Thickening	Low	Very low	Large	None	Not contained	Continuous
Gravity Belt Thickening	Moderate	Low	Moderate	High	Not contained	Continuous
Membrane Filtration	High	Moderate	Small	None	Not contained	Continuous
Air Floatation	Low	Low	Large	Moderate	Not contained	Continuous
Belt Filter Press	Moderate	Low	Small	High	Not contained	Continuous
Centrifuge	High	Moderate	Very small	Moderate	Contained	Continuous
Filter Press	Moderate	High	Small	High	Not contained	Batch
Drying Beds	Very low	Very low	Very large	Limited to none	Not contained	Batch
Geotubes	Low	Low	Large	None	Contained	Batch

[35] Source: DPHE, Bangladesh.

Co-composting & Vermi-composting

Co-composting, as composting system, mixes different organic material and fecal sludge in piles. The piled feedstocks are arranged in long heaps called windrows. The natural decomposition of the organic matter in the heaps by bacteria, fungi, and other micro-organisms produces heat. In good conditions of moisture, Carbon-Nitrogen (C/N) ratio, and aeration, this process results in thermophilic conditions (>60°C) which eliminate the pathogens. Well controlled and after some weeks, the compost is a safe and stable product and can be used as fertilizer.

Vermi-composting uses worms (Eisenia Fetida, Eudrilus Eugeniae, Perionyx Excavatus, Eisenia Andrei) to accelerate the digestion of the mixture of sludge and organic waste.

Composting needs humidity (between 30–75%), aeration, shredded organic material and temperature control. The balanced C/N ratio (from 15 to 30) is relevant in aerobic and anaerobic digestions. Human excreta has a C/N ratio of 8/1; without the addition of other material, it is not very suitable for composting. Organic waste from households should be added if the composting process is hampered due to the lack of carbon.

FIGURE 41: Co-composting improves the C/N ratio, combining faecal sludge (left) with organic waste (right). [36]

[36] Source: Waste Concern, Bangladesh (Co-composting).

FIGURE 42: Vermi-composting accelerates the transformation of faecal sludge and organic waste to fertilizer and soil- conditioner. *Eisenia Fetida* (in the figure) is one of the worms used in vermi- composting.

Long term storage

WHO recommendations refer to the storage of dry excreta and fecal sludge before their re-use at household and municipal levels.

TABLE 5: WHO recommendations for treatment through storage of dry excreta and fecal sludge.

Treatment	Criteria	Comment
Storage; ambient temperature 2–20°C	1.5–2 years	Will eliminate bacterial pathogens; regrowth of *E. coli* and *Salmonella* may need to be considered if rewetted; will reduce viruses and parasitic protozoa below risk levels. Some soil-borne ova may persist in low numbers.
Storage; ambient temperature > 20–35°C	> 1 year	Substantial to total inactivation of viruses, bacteria and protozoa; inactivation of schistosome eggs (<1 month); inactivation of nematode (roundworm) eggs, e.g. hookworm (*Ancylostoma / Necator*) and whipworm (*Trichuris*); survival of a certain percentage (10–30%) of *Ascaris* eggs (≥ 24 months), whereas a more or less complete inactivation of *Ascaris* eggs will occur within 1 year.
Alkaline treatment	pH > 9 during > 6 months	If temperature > 35°C and moisture <25%, lower pH and/or wetter material will prolong the time for absolute elimination.

[a] No addition of new material

Pyrolysis

Dried sludge can be treated, with or without other organic matter, in a pyrolysis reactor. Bio-charcoal (>90% solid content), also called biochar, is produced under an oxygen-poor environment in the reactor. 50% of the carbon are converted in charcoal and 50% are converted in syngas and bio-oils (rich in energy and that can be valorized). Figure 43 illustrates the pyrolysis process.

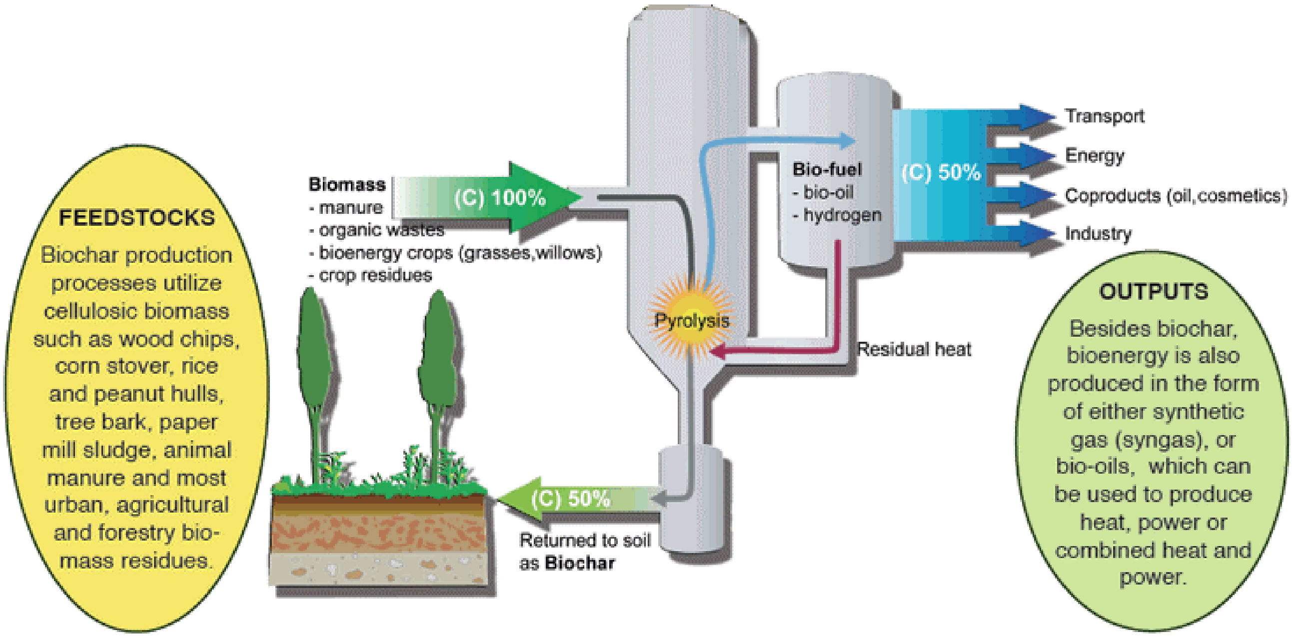
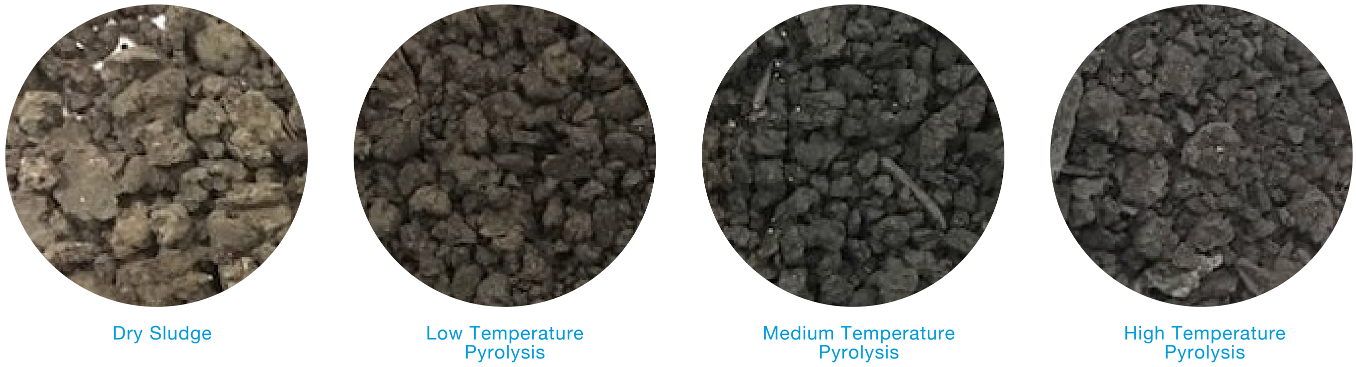


FIGURE 43: Flowchart of Biochar production. [37]

FIGURE 44: Pyrolysis uses biogenic residues as input (left) to obtain valuable liquids, fuel gas, and binding biochar as outputs (right). [38]

[37] Source: International Biochar Initiative, 2019.
[38] Source: International Biochar Initiative, 2019 (left); Oregon Department of Forestry, 2014 (right).

FIGURE 45: Pyrolysis at different temperature generates different qualities of biochar. [39]



Adding an appropriate amount of sorted solid waste to the more liquid stream FS, treatment processes will increase the carbon content of biochar-ash, the bioenergy amount produced and in general the biochar output. For reference, lignocellulosic biomasses have the highest fixed carbon content; while cow manure's carbon content ranges between the ones of wastewater sludge and septic tank sludge. In addition, pyrolysis could reduce enormously the sewage volume.

While carbonized biosolids contain valuable nutrients such as phosphorus, sludge contains relatively low levels of carbon as compared to other feedstocks used for biochar production. Given the low carbon content, carbonized biosolids may, or may not, be considered as biochar depending on the standards used for classifying biochar.

Some factors influencing the quality of biochar:

1. Biochar from pit latrine faecal waste has higher yields, ash, Ca, Fe, surface area, porosity and cadmium sorption capacity and lower fixed C, than those from sewage sludge.
2. Increasing pyrolysis temperature increases surface area and porosity, and decreases biochar yield, volatile matter and Cd sorption capacity.
3. Surface functional groups on biochar differ between the fecal wastes and among pyrolysis temperatures.
4. Ash, pH and P content are the most important parameters governing Cd sorption on biochar from fecal waste.

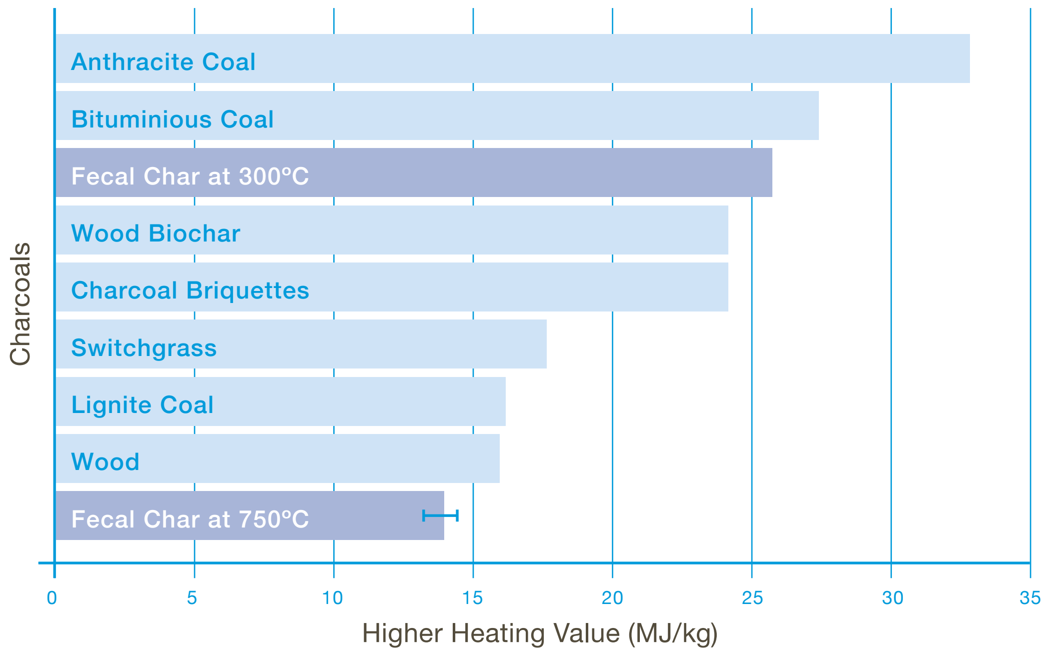


FIGURE 46: Heat Value Comparison of fecal sludge based chars and other charcoals. [40]

[39] Source: International Biochar Initiative, 2019.
[40] Source: B.J. Ward, 2013.

Advantages of biochar production:

- Generation of Biochar-ash.
- P & K recovered in biochar-ash.
- Volume reduction.
- Co-processing of organic waste is possible; syngas or oil as fuel —depending on the pyrolysis temperature.
- Excess Heat recovery.
- Removal or kill of pathogens.
- If properly designed, pyrolysis provides more advantages compared to incineration and gasification.

Disadvantages of biochar production:

- N gets completely lost.
- Pre-drying of combustible dry matter content (70–85%) is required.
- A complex infrastructure and operational skills are needed.

How does it works?

The dried sludge (60–83% DM) is stored in a silo. The silo discharges doses of the sludge on a conveyor belt at the entry to pyrolysis reactor (rotary kiln). The entry consists of a chute and an auger to feed into the reactor.

The rotary kiln is a pipe and is indirectly heated with hot flue gas. The biomass in the pivot tube, under exclusion of air, is heated until all the volatile components are converted into vapour (650°C and above). The gas is then captured and burned in an adjacent combustion chamber.

The flue gas generated is then used for heating the spin tube for the pre-warming of air and is also available for other purposes, i.e. for the belt dryer.

[41] Source: PYREG GmbH, Germany.

FIGURE 47: Sludge pyrolysis unit. [41]

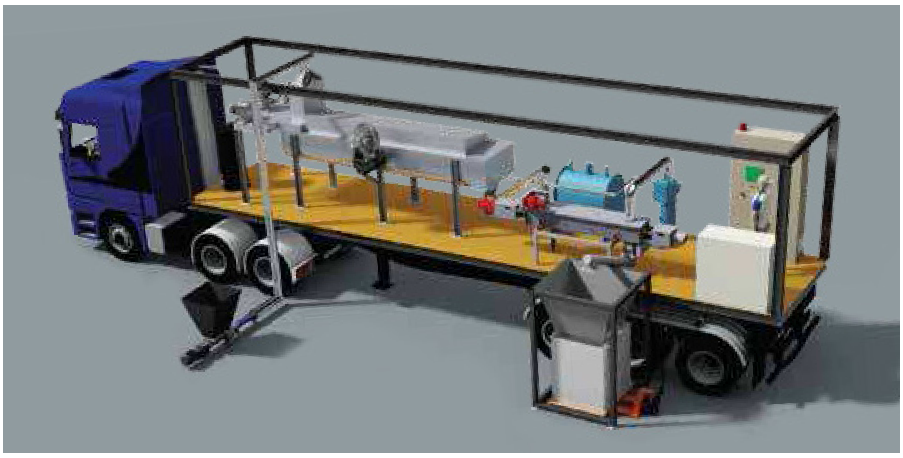
The following list presents 51 potential biochar uses. This list is not exhaustive.

1. Silage agent.
2. Feed additive / supplement.
3. Litter additive.
4. Slurry treatment.
5. Manure composting.
6. Water treatment in fish farming.
7. Carbon fertilizer.
8. Compost.
9. Substitute for peat in potting soil.
10. Plant protection.
11. Compensatory fertilizer for trace elements.
12. Insulation.
13. Air decontamination.
14. Decontamination of earth foundations.
15. Humidity regulation.
16. Paint with protection against electromagnetic radiation.
17. Soil additive for soil remediation.
18. Soil substrates.
19. Barrier preventing pesticides into surface water.
20. Treating pond and lake water.
21. Biomass additive.
22. Biogas slurry treatment.
23. Active carbon filter.
24. Pre-rinsing additive.
25. Soil substrate for organic plant beds.
26. Composting toilets.
27. Micro-filters.
28. Macro-filters in developing countries.
29. Controlling emissions.
30. Room air filters.
31. Carbon fibers.
32. Plastics.
33. Semiconductors.
34. Batteries.
35. Metal reduction.
36. Soaps.
37. Skin-cream.
38. Therapeutic bath additives.
39. Food colorants.
40. Industrial paints.
41. Pellets.
42. Substitute for lignite.
43. Detoxification.
44. Carrier for active pharmaceutical ingredients.
45. Fabric additive for functional underwear.
46. Thermal insulation for functional clothing.
47. Deodorant for shoe soles.
48. Filling for mattresses.
49. Filling for pillows.
50. Shield against electromagnetic radiation.
51. Bio-Asphalt.

Mobile Sludge Pyrolysis

A mobile pyrolysis machine can be used for treating municipal, domestic, industrial and agricultural waste and sewage sludge. Mounted on a single metal frame, it comprises a drying reactor, a pyrolysis reactor, a reactor for cooling solid pyrolysis products, and a reactor for cooling and condensing a hydrocarbon vapour-gas mixture.

FIGURE 48: Mobile sludge pyrolysis systems. [42]



Advantages of mobile pyrolysis:

- → Include the recovery of P & K in biochar-ash.
- → Volume reduction.
- → Elimination of pathogens.
- → The entire system could be transported on a lorry chassis or a trailer, and even small mobile units are possible to use.

Disadvantages of mobile pyrolysis:

- → Refer mainly to the complete loss of N.
- → Operational skills are needed.

[43] Source: Energy Farmers Australia Pty Ltd., Australia (top); Pyrosludge® by Biogreen, France (below).

Hydrothermal Carbonization (HTC)

Hydrothermal Carbonization (HTC) is a combination of sludge drying, phosphorous recovery and ultra-dewatering of sludge. It can even work with wet sludge as feedstock. HTC can refine organic waste into bio-coal for use in existing power plants to produce bio-energy. HTC bio-coal is a high quality biofuel, which can be used for co-firing power plants or for the production of syngas and second-generation biomass-to-liquid biofuels. HTC technology, based on the principles of hydrothermal carbonization, utilizes green waste from municipalities (grass, leaves, etc.) to produce dry and solid bio-coal, which has similar characteristics to dry brown coal. HTC technology is extremely energy efficient, scalable and allows the use of a wide variety and mix of organic materials.

FIGURE 49: Hydrothermal carbonization system in China. [44]

Further advantages of HTC:

→ The production of bio-coal.

→ The recovery of P & K.

→ Volume reduction and elimination of pathogens.

→ Excess Heat recovery leads to a positive energy balance.

Disadvantages of HTC:

→ Complete loss of N.

→ Complex infrastructure and operational skills are needed.

[44] Source: TerraNova Energy GmbH, 2017.

Hydrothermal Liquefaction (HTL)

Hydrothermal Liquefaction (HTL) has achieved to convert sewage or wet biomass into bio-crude oil.

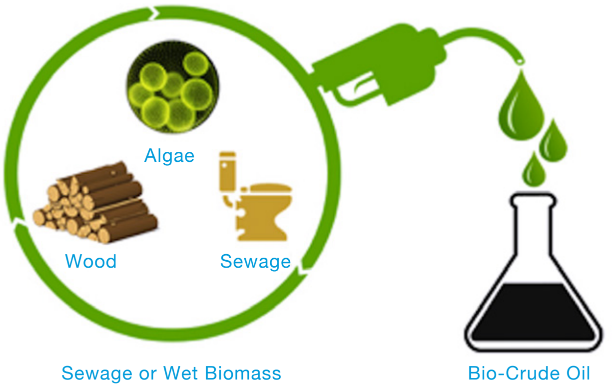


FIGURE 50: **Hydrothermal Liquefaction converts wet biomass into bio-crude oil.** [45]

Advantages of HTL:

→ The potential use of wet sludge as feedstock.

→ Volume reduction.

→ Oil as fuel.

→ Ash as P & K fertilizer

→ On-site solution to be installed in wastewater treatment plants.

→ And finally, it kills pathogens.

Disadvantages of HTL are the same as for HTC:

→ N is completely lost.

→ Complex infrastructure and operational skills are needed.

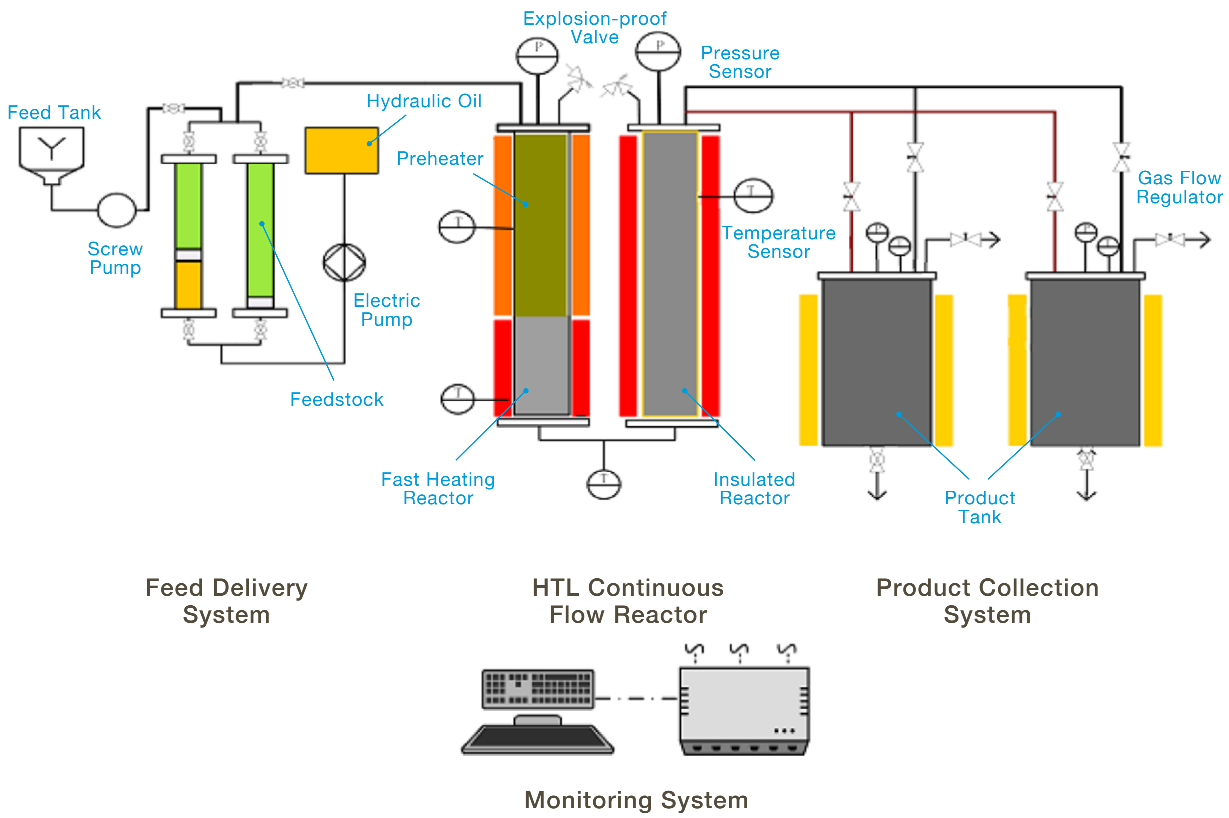


FIGURE 51: **HTL continuous flow reactor.** [46]

[45] [46] Source: China Agricultural University, 2019.

Biogas Plants

→ Refer to the publication **Comprehensive Overview of Biogas for Sanitation Options – Training of Trainers**, from the serie “Methodologies & Application from Documented Experience”, **MADE by UPM Nº2**.

Omni-Processing

Janicki Omni-Processor combines drying and combustion with the recovery of energy, ash (P, K) and water. The overall technology approach is based on evaporation: Janicki Omni-Processor is fed with sludge delivered from other drying systems and applies thermal drying with vapour recovery.

The technology was developed after having evaluated already existing technologies, such as passive drainage or drying, as well as mechanical dewatering and thickening. The first is characterized by low treatment efficiency and large space requirement. The second does not fully remove moisture content and counts with high operational costs due to polymer requirements.

The first Janicki Omni-Processor (OP) pilot unit, model S100, was manufactured in 2013 and has been operating in Dakar, Senegal since May of 2015. It produces 10,800 litres of drinking water per day. When operating in full capacity, the OP consumes 7 metric tons of dry matter per day, equivalent to 450 m^3 of raw sludge. It provides, at the same time, a net power of 125kW of electricity, with an annual output of 1,000 MWh of electricity, for 8,000 operating hours per year. The S200 doubled the capacity of the S100 and was operating in Sedro-Woolley, WA. It was shipped to West Africa in 2020. Many other additional and similar technologies are also under development in India and China at this time to address sanitation concerns from the larger scale community approach all the way down to the household level.

FIGURE 52: Janicki Omni Processor S100 in Dakar, Senegal. [47]

[47] Source: Sedron Technologies (formerly Janicki Bioenergy).

Different methods were tested before the final system was approved, such as utilization of process heat to accelerate evaporation; material recirculation to avoid the sticky phase; single pass and multi-stage evaporation; and maximizing heat transfer coefficient wherever possible.

Challenges encountered when applying this technology are related to (1) handling of sludge of very different consistency either sticky or dry and dusty; (2) odor control of vapour; (3) reducing % TS required for energy balance; (4) reducing capital cost; (5) scaling on surfaces.

FIGURE 53: Pre-drying screw.

Advantages of Janicki Omni Processor:

- → Phosphorus and Potassium partly recovered in ash.
- → Volume reduction of sludge.
- → Distilled Water.
- → Electricity.
- → Co-processing of organic waste possible.
- → Elimination of pathogens.
- → Heavy metals are bound to a low extent only into the ashes.
- → Emissions as CO, NOx, SOx, and HCl, are controlled by Temperature, Time, Turbulences. Lime may be added to the flue gas.

Disadvantages of Janicki Omni Processor:

- → N completely lost.
- → Pre-drying of combustible dry matter content required.
- → Complex infrastructure needed.
- → Operational skills needed.
- → Flue gas filter needed.

How does it works?

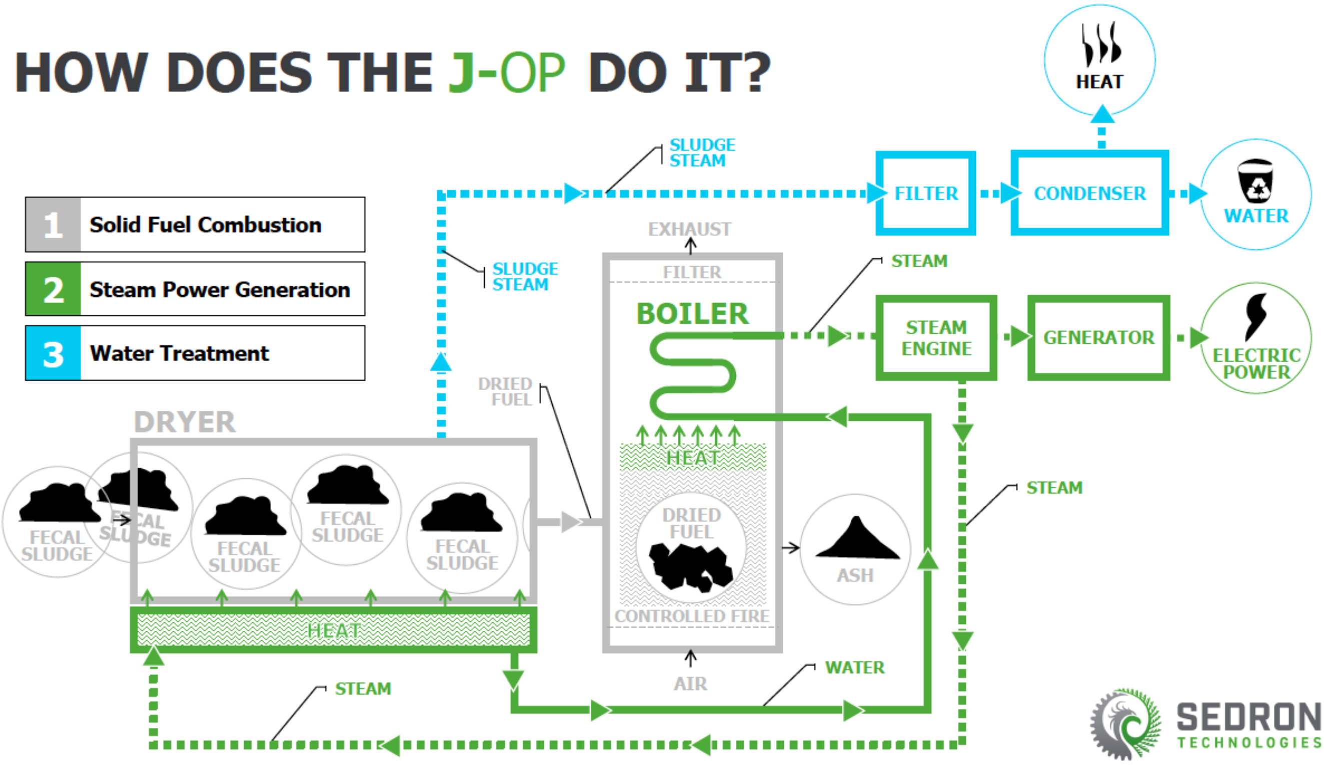


FIGURE 54: How the Omni Processor works. [48]

FIGURE 55: Omni Processor in China. [49]

[48] Source: Sedron Technologies (formerly Janicki Bioenergy).
[49] Source: CRRC, China.

Contributors

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Bangladesh Agricultural University was established as the only university of its kind in Bangladesh in 1961. It started functioning with the College of Animal Husbandry and Veterinary Science at Mymensingh as its nucleus. The university has six faculties and 43 departments covering all aspects of agricultural education and research. BAU was the second highest budgeted public university in Bangladesh for the year 2013–2014. It is ranked number four from 166 universities of Bangladesh according to the webometrics university ranking 2020.

The Bureau of Socio-Economic Research and Training at BAU was established in 1977 at the BAU Faculty of Agricultural Economics & Rural Sociology to promote research, training and extension activities of the faculty staff. The Bureau conducts nationally and internationally funded research projects, while also provides research consultancy and advisement for Government and Non-Government Organisations. The Bureau publishes twice yearly *The Bangladesh Journal of Agricultural Economics*, in addition to reports and monographs based on the research projects completed by the faculty members.

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USTB was founded in 1952 following the amalgamation of the best departments in related fields of five eminent universities as a result of a nationwide reorganization of the higher education system. Over half a century of remarkable growth, it has developed into one of the most influential key national universities sponsored by the Chinese Ministry of Education. USTB is renowned for its study of metallurgy and materials science. Its main focus is on engineering while it also maintains a balanced programme of science, management, humanities, economics and law.

The Center for Sustainable Environmental Sanitation CSES integrated in the School of Environmental Engineering at the University of Science and Technology Beijing was created in 2007 with the objective to build capacity among young professionals in the interrelated sectors of sustainable environmental sanitation, food security, bioenergy and climate protection.

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Activities: Project Planning and Development; Carbon Trading; Support to access to Climate & Development Finance; Technical Support; Feasibility Studies; Research and Studies; Capacity Building & Training; Monitoring; Tendering support; Due Diligence; Technical Design; etc.

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