Training Material on Biogas Sanitation

Ecosan Training Course

“Capacity Building for Ecological Sanitation in India”

Compiled by Ecosan Services Foundation (ESF)
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1 INTRODUCTION

1.1 Biogas definition

Biogas originates from bacteria in the process of bio-degradation of organic material under anaerobic (without air) conditions. The natural generation of biogas is an important part of the biogeochemical carbon cycle. Methanogens (methane producing bacteria) are the last link in a chain of micro-organisms which degrade organic material and return the decomposition products to the environment. In this process biogas is generated, a source of renewable energy [1].

1.2 Composition and properties of biogas

Biogas is a mixture of gases that is composed chiefly of:

- **methane** (CH_4): 40 - 70 vol.%
- **carbon dioxide** (CO_2): 30 - 60 vol.%
- **other gases**: 1 - 5 vol.%

including

- hydrogen (H_2): 0 - 1 vol.%
- hydrogen sulfide (H_2S): 0 - 3 vol.%

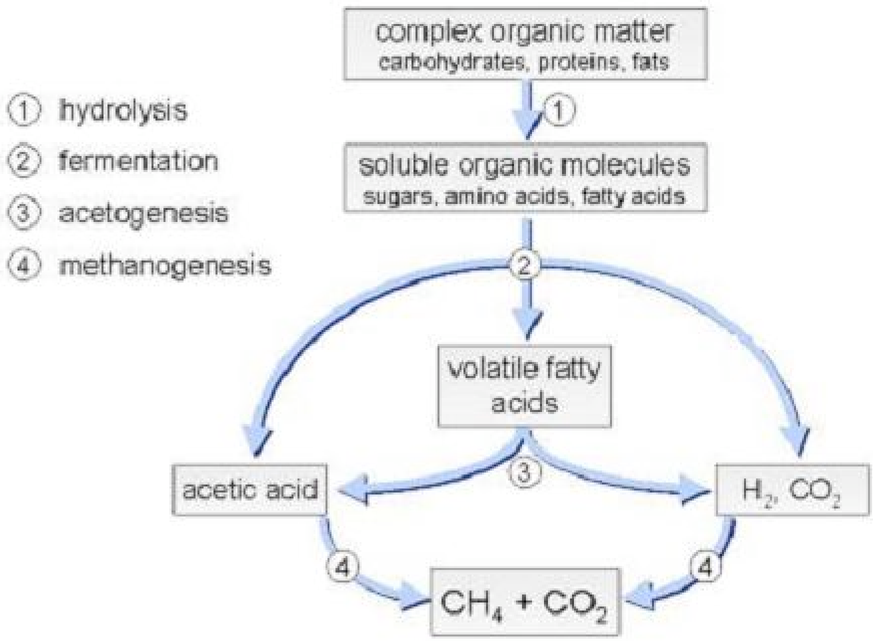
Like those of any pure gas, the characteristic properties of biogas are pressure and temperature-dependent. They are also affected by the moisture content. The factors of main interest are:

- change in volume as a function of temperature and pressure,
- change in calorific value as a function of temperature, pressure and water-vapor content, and
- change in water-vapor content as a function of temperature and pressure.

Biogas is used as an ecologically friendly and future oriented technology in many countries. The calorific value of biogas is about 6 kWh/m^3 - this corresponds to about half a litre of diesel oil. The net calorific value depends on the efficiency of the burners or appliances. Methane is the valuable component under the aspect of using biogas as a fuel [1].

1.3 How is it produced (the three steps of biogas production)

The general model for degradation of organic material under anaerobic conditions operates principally with three main groups of bacteria: fermenting, acetogenic and methanogenic bacteria, which degrade organic mater in four stages viz., hydrolysis, fermentation, acidification and methane formation (see figure 1).



(source: [2])

figure 1: Anaerobic digestion pathway

1.3.1 Hydrolysis and fermentation

In the first step (hydrolisis), the organic matter is enzymolyzed externally by extracellular enzymes (cellulase, amylase, protease and lipase) of microorganisms. Bacteria decompose the long chains of the complex carbohydrates, proteins and lipids into shorter parts. For example, polysaccharides are converted into monosaccharides. Proteins are split into peptides and amino acids [1].

1.3.2 Acidification

Acid-producing bacteria, involved in the second step, convert the intermediates of fermenting bacteria into acetic acid (CH_3COOH), hydrogen (H_2) and carbon dioxide (CO_2).

These bacteria are facultatively anaerobic and can grow under acid conditions. To produce acetic acid, they need oxygen and carbon. For this, they use the oxygen solved in the solution or bound oxygen. Hereby, the acid-producing bacteria create an anaerobic condition, which is essential for the methane producing microorganisms. Moreover, they reduce the compounds with a low molecular weight into alcohols, organic acids, amino acids, carbon dioxide, hydrogen sulphide and traces of methane. From a chemical standpoint, this process is partially endergonic (i.e. only possible with energy input), since bacteria alone are not capable of sustaining that type of reaction [1].

1.3.3 Methane formation

Methane-producing bacteria, involved in the third step, decompose compounds with a low molecular weight. For example, they utilize hydrogen, carbon dioxide and acetic acid to form methane and carbon dioxide. Under natural conditions, methane producing microorganisms occur to the extent that anaerobic conditions are provided, e.g. under water (for exemple in marine sediments), in ruminant stomaches and in marshes. They are obligatory anaerobic and very sensitive to environmental changes [1].

1.3.4 Symbiosis of bacteria

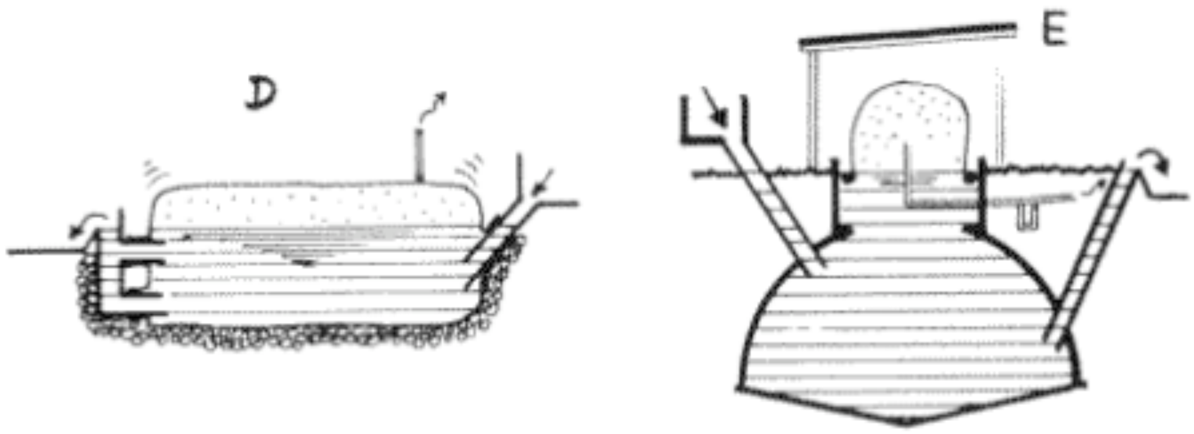
Methane- and acid-producing bacteria act in a symbiotical way. On the one hand, acidproducing bacteria create an atmosphere with ideal parameters for methane-producing bacteria (anaerobic conditions, compounds with a low molecular weight). On the other hand, methane-producing microorganisms use the intermediates of the acid-producing bacteria. Without consuming them, toxic conditions for the acid-producing microorganisms would develop.

In practical fermentation processes the metabolic actions of various bacteria all act in concert. No single bacterium is able to produce fermentation products alone [1].

1.4 Description of smale scale biogas plants

1.4.1 Balloon digester

The balloon plant (figure 2, left hand side) consists of a digester bag (e.g. PVC) in the upper part of which the gas is stored. The inlet and outlet are attached directly to the plastic skin of the balloon. The gas pressure is achieved through the elasticity of the balloon and by added weights placed on the balloon. A variation of the balloon plant is the channel-type digester, which is usually covered with plastic sheeting and a sunshade



(source: [1])

figure 2: Conceptual sketches of balloon-type digesters

(figure 2, right hand side). Balloon plants can be recommended wherever the balloon skin is not likely to be damaged and where the temperature is even and high [1].

Pros and cons of balloon digesters are summarized in table 1.

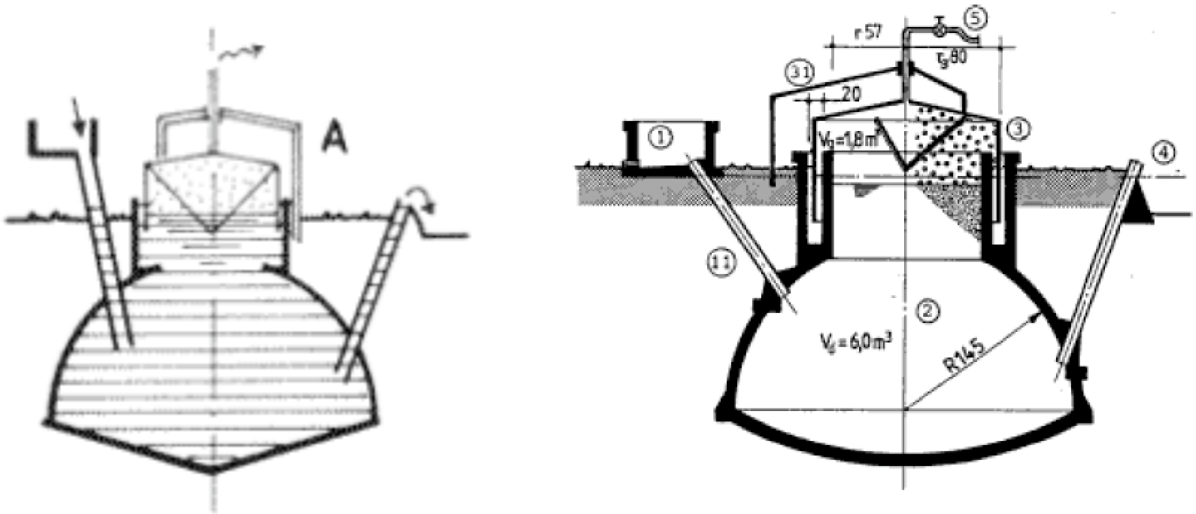
table 1: Pros and cons of balloon digesters

Pros:	**Cons:**
• low cost;	• relatively short life (about five years);
• ease of transportation;	• susceptibility to damage;
• low construction sophistication;	• little creation of local employment;
• high digester temperatures;	• limited self-help potential;
• uncomplicated cleaning, emptying and maintenance;	• little knowledge for repairing by local craftsmen [3]

(source: [1])

1.4.2 Floating-drum digester

Floating-drum plants consist of an underground digester and a moving gasholder. The gasholder floats either directly on the fermentation slurry (figure 3, left hand side) or in a water jacket of its own (figure 3, right hand side). The gas is collected in the gas drum, which rises or moves down, according to the amount of gas stored. The gas drum is prevented from tilting by a guiding frame [1]. Water-jacket digesters are universally applicable and especially easy to maintain. The drum won't stick, even if the substrate has a high solids content. Floating-drums made of glass-fibre reinforced plastic and high-density polyethylene have been used successfully, but the construction cost is higher than for its steel counterpart. Floating-drums made of wire-mesh-reinforced concrete are liable to hairline cracking and are intrinsically porous. They require a gastight, elastic internal coating. PVC drums are unsuitable because they are not resistant to UV radiation [3].



(source: [1])

figure 3: Conceptual sketches of floating-drum type digesters

Pros and cons of floating-drum type digesters are summarized in table 2.

table 2: Pros and cons of floating-drum type digesters

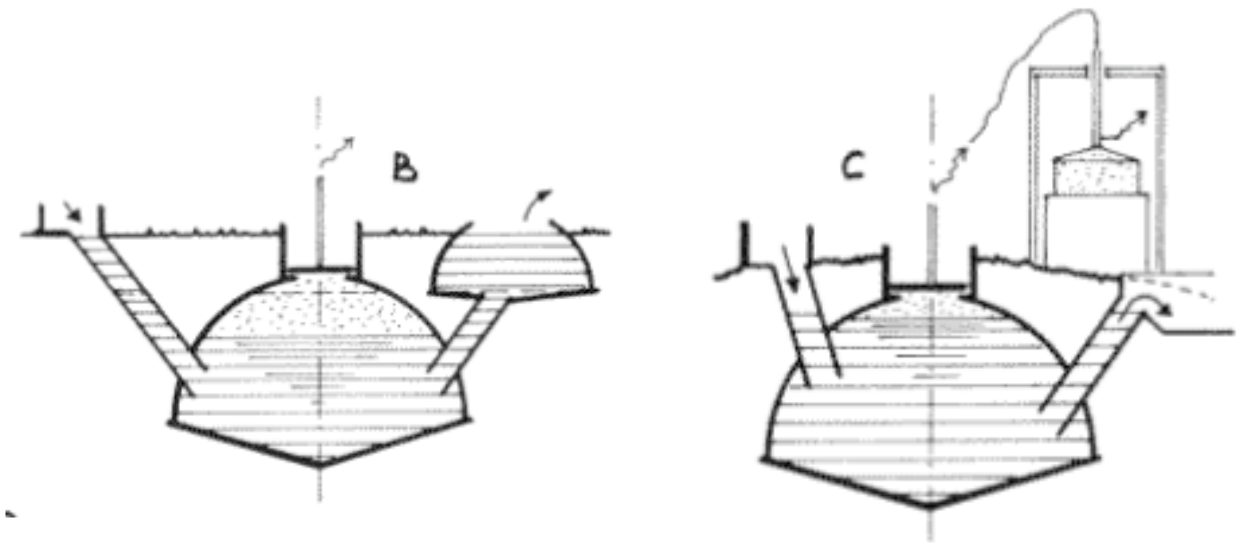
Pros:	**Cons:**
• simple, easily understood operation;	• high material costs of the steel drum;
• they volume of stored gas is directly visible;	• susceptibility of steel parts to corrosion (because of this, floating drum plants have a shorter life span than fixed-dome plants);
• the gas pressure is constant (determined by the weight of the gas holder);	• regular maintenance costs for the painting of the drum

• construction is relatively easy;	• if fibrous substrates are used, the gasholder shows a tendency to get "stuck" in the resultant floating scum [3];
• construction mistakes do not lead to major problems in operation and gas yield;	

(source: [1])

1.4.3 Fixed-dome digester

The fixed-dome plant consists of a digester with a fixed, non-movable gas holder, which sits on top of the digester. When gas production starts, the slurry is displaced into the compensation tank. Gas pressure increases with the volume of gas stored and the height difference between the slurry level in the digester and the slurry level in the compensation tank [1].



(source: [1])

figure 4: Conceptual sketches of fixed-dome type digesters

Pros and cons of fixed-dome type digesters are summarized in table 3.

table 3: Pros and cons of fixed-dome type digesters

Pros:	Cons:
• relatively low construction costs;	• frequent problems with the gas-tightness of the brickwork gas holder (a small crack in the upper brickwork can cause heavy losses of biogas);
• absence of moving parts and rusting steel parts;	• gas pressure fluctuates substantially depending on the volume of the stored gas;
• long life span if well constructed;	• even though the underground construction buffers temperature extremes, digester temperatures are generally low;
• underground construction saves space and protects the digester from temperature changes;	
• construction provides opportunities for skilled local employment;	

(source: [1])

2 BIOGAS SANITATION CONCEPTS

2.1 Domestic wastewater quantification and characterisation

Domestic wastewater contains organic and inorganic matter in suspended, colloidal and dissolved forms. The concentration in the wastewater depends on the original concentration in the water supply, and the uses to which the water has been put. The climate, and the wealth and habits of the people have a marked effect on the wastewater characteristics [4].

Raw domestic wastewater characteristics are shown in table 4.

table 4: Domestic wastewater characteristics (excerpt)

item	Range in values contgributed in wastes [4]
Biochemical oxygen demand, 5 days, 20 °C (BOD_5)	45 - 54
Chemical oxygen demand	1.6 - 1.9 x BOD_5
Total organic carbon	0.6 - 1.0 x BOD_5
Total solids	170 - 220
Suspended solids	70 - 145
Grit (inorganic, 0.2 mm and above)	5 - 15
Grease	10 - 30
Total nitrogen N	6 - 12
Organic nitrogen	~ 0.4 x total N
Free ammonia	~ 0.6 x total N
Nitrite	-
Nitrate	0.0 - 0.5 x total N
Total phosphorus, P	0.6 - 4.5
Organic phosphorus	~ 0.3 x total P
Inorganic (ortho- and polyphosphates)	~ 0.7 x total P
Potassium (as potassium oxide K_2O)	2.0 - 6.0

The per capita daily water usage ranges from 180 to 300 litres im most sewered communities [4] though water consumption may be much higher. The values of biological oxygen demand (BOD) generally average 54 grams per person per day where the sewage collection system is separate from the storm collection system and is reasonably efficient [4].

According to the Central Public Health and Environmental Engineering Organisation (CPHEEO) water supply demand for Indian cities provided with piped water supply with sewerage amounts to 135 litres per capita per day. Break up of water demand is shown in table 5. At least 80 - 85 % of the water supplied returns as wastewater [4].

table 5: Break up of water requirements for domestic purposes according to CPHEEO „Manual on Water Supply and Treatment“

description	quantity of water [5] [l/cap/d]
bathing	55
washing of clothes	20
flushing of WC	30
washing of house	10
washing of utensils	10
cooking	5
drinking	5
total	**135**

2.2 Objectives of reuse-oriented wastewater management

The very basic objective of wastewater management is to protect public health and the environment in a socio-culturally and economically sustainable manner. Wastewater management systems should also account for the willingness and ability of users to operate their own system (user-friendliness). The basic objectives of a household or community wastewater management system can be summarised as follows (adopted from [12]):

- **Protection of public health:** A wastewater management system should create an effective physical barrier between contaminated blackwater and user, as well as avoid odour emissions and stagnant water leading to breeding sites for mosquitoes.
- **Protection of the environment:** A wastewater management system should prevent eutrophication and pollution of sensitive aquatic systems (surface water, groundwater, drinking water reservoirs) as well as terrestrial systems (irrigated soil).
- **Socio-culturally and economically acceptable:** wastewater management systems have to be adapted to the socio-cultural and economic settings of the household or neighbourhood. If waste reuse is culturally not anchored for example, blackwater management systems aiming at irrigation are likely to fail.
- **Simple and user-friendly:** Household or neighbourhood wastewater management systems should be manageable by the user, technically simple and robust and possibly not rely on external fuel, power supply or chemicals.
- **Compliance with national and international regulations and standards:** Qualitative and quantitative effluent standards have to maintain or even enhance the quality of receiving waters, to ensure soil fertility and protect public health.

2.3 Physical appearance of biogas sanitation concepts

In this training material the following biogas sanitation concept will be discussed:

- on-site pre-treatment of domestic wastewater in a biogas settler and advanced treatment of the effluent in a vertical flow constructed wetland (VFCW)

2.3.1 On-site pre-treatment of domestic wastewater in biogas settlers

Biogas settlers (sometimes also refered to as “Biodigester Septic Tanks” or “UASB Septic Tanks”) have been introduced as cost-effective pre-treatment or treatment step for domestic wastewater or blackwater in countries such as Jaimaca [6], South Africa [7], China [8] and India [9] by various organisations.

Biogas settler are designed to:

- facilitate solid-liquid separation;
- provide a high sludge retention time, that facilitates almost complete degradation of organics;
- enable production and collection of biogas for direct use (e.g. lighting, cooking, etc.).

Depending upon the hydraulic retention time (HRT) a biogas settler may be considered a pre-treatment or treatment unit. Biogas settlers that are designed for pre-treatment of domestic wastewater (combined greywater and blackwater) provide a HRT of 24 hours or less [10]; subsequent treatment of the effluent in an anaerobic baffle reactor and constructed wetland system may be required. With an increased HRT (8 to 10 days and ca. 15 days with and without urine-separation, respectively) anaerobic treatment of the liquid phase happens and advanced treatment of the effluent may be done in a constructed wetland system only [8].

Pros and cons of on-site treatment of wastewater in biogas settlers are summarized in table 6.

table 6: Pros and cons of on-site treatment of wastewater in biogas settlers

Pros:	**Cons:**
• no handling of raw (unprocessed) wastewater;	• external energy required for lifting of pre-treated wastewater to VFCW surface;
• biogas may be used as a substitute to LPG in cooking;	

2.4 Key factors for the successful implementation of biogas sanitation concepts

For the successful and sustainable implementation of blackwater management schemes it’s crucial to:

- create awareness amongst future users (sanitation related problems in general and value of wastewater in particular);
- participatory planning and decision making;

- training of users on how to operate and maintain the wastewater system;
- training of caretakers and operators;

3 SIZING OF BIOGAS SANITATION SCHEMES

3.1 On-site pre-treatment of domestic wastewater in biogas settler

Anaerobic on-site treatment of wastewater requires pre-treatment of wastewater in a biogas settler for solid-liquid separation up-stream a VFCW and an optional tank for the collection of the VFCW effluent. The required facilities are summarized below:

- primary treatment of raw wastewater in a biogas settler,
- secondary treatment of (pre-treated) wastewater in a VFCW and
- optional tank for collection of treated wastewater, direct application without storage, infiltration or discharge to receiving water bodies.

3.1.1 Calculation of wastewater production

Daily wastewater production is calculated using equation (1):

$$Q_D = N \bullet Q_S \qquad \text{equation (1)}$$

where:

Q_D .... daily wastewater production [l/d]

N .... number of people contributing to wastewater production [p/d]

Q_S .... specific wastewater production [l/p/d]

BOD_5- and COD concentration of raw wastewater are calculated as follows:

$$C_{BOD-RAW} = \frac{L_{BOD} \bullet 1{,}000}{Q_S} \qquad \text{equation (2)}$$

$$C_{COD-RAW} = 2 \bullet C_{BOD-RAW} \qquad \text{equation (3)}$$

where:

$C_{BOD\text{-}RAW}$....... BOD_5 concentration of raw wastewater [mg/l]

L_{BOD} .... specific BOD_5 load [g/p/d]

1,000........... conversion factor

Q_S .... specific wastewater production [l/p/d]

$C_{COD\text{-}RAW}$ ...... COD concentration of raw wastewater [mg/l]

2.................. conversion factor

3.1.2 Sizing of biogas settler

While calculating the net volume of the biogas settler for pre-treatment of raw wastewater, four distinct volumes viz., the sludge accumulation volume, the volume for recommended hydraulic detention time, the volume for the scum layer and the volume for gas storage, have to be considered.

$$V_{BS} = V_{SL} + V_D + V_{SC} + V_G \qquad \text{equation (4)}$$

where:

V_{BS} .... net volume of biogas settler [m^3]

V_{SL} .... sludge accumulation volume [m^3]

V_D................. volume for recommended hydraulic detention time [m^3]

V_{SC} .... volume for scum layer [m^3]

V_G .... volume for gas storage [m^3]

The required sludge accumulation volume is calculated by multiplying the specific sludge production rate, “removed” BOD_5, daily wastewater production and desludging frequency.

$$C_{BOD-EBS} = C_{BOD-RAW} \bullet \left(1 - BOD_{REM-BS}\right) \qquad \text{equation (5)}$$

$$V_{SL} = \frac{V_{SSV} \bullet \left(C_{BOD-RAW} - C_{BOD-EBS}\right) \bullet Q_D \bullet 30 \bullet P_{DS}}{1{,}000 \bullet 1{,}000} \qquad \text{equation (6)}$$

where:

$C_{BOD-EBS}$ .... BOD_5 concentration of biogas settler effluent [mg/l]

$C_{BOD-RAW}$....... BOD_5 concentration of raw wastewater [mg/l]

BOD_{REM-BS}.... BOD "removal" in biogas settler [%]

V_{SL} .... sludge accumulation volume [m^3]

V_{SSV} .... specific sludge production [l/g BOD_{REM}]

Q_D .... daily wastewater production [l/d]

30................. days per month

P_{DS} .... desludging frequency [month]

1,000........... conversion factor

Hydraulic detention volume is calculated using equation (7):

$$V_D = \frac{Q_D \bullet T_D}{1{,}000} \qquad \text{equation (7)}$$

where:

V_D................. volume for recommended hydraulic detention time [m^3]

Q_D .... daily wastewater production [l/d]

T_D................. detention time [d]

1,000........... conversion factor

At 24 hours HRT, 15 – 20 % of the liquid volume can be taken for estimating the volume to be provided for the scum layer:

$$V_{SC} = PC \bullet V_D \qquad \text{equation (8)}$$

where:

V_{SC} .... volume for scum accumulation [m^3]

PC .... percentage of recommended hydraulic detention volume [%]

V_D .... volume for recommended hydraulic detention time [m^3]

The required gas storage volume is calculated by multiplying the specific gas production rate, “removed” COD and daily wastewater production. Provide additional gas storage capacity for period of non-use of gas of 20% of liquid storage capacity (at 24 hours HRT).

$$C_{COD-EBS} = C_{COD-RAW} \bullet \left(1 - COD_{REM-BS}\right) \qquad \text{equation (9)}$$

$$V_G = \frac{V_{SL} \bullet \left(C_{COD-RAW} - C_{COD-EBS}\right) \bullet Q_D}{1{,}000 \bullet 1{,}000} + \frac{PC \bullet V_D}{1{,}000} \qquad \text{equation (10)}$$

where:

$C_{COD-EBS}$ .... COD concentration of biogas settler effluent [mg/l]

$C_{COD-RAW}$ ...... COD concentration of raw wastewater [mg/l]

COD_{REM-BS} ... COD “removal” in biogas settler [%]

V_{GS} .... volume for gas storage [m^3]

V_{SL} .... specific gas production [l/g COD_{REM}]

Q_D .... daily wastewater production [l/d]

1,000 .... conversion factor

PC .... percentage of recommended hydraulic detention volume [%]

V_D .... volume for recommended hydraulic detention time [m^3]

The volume of a half round biogas settler is determined by using equation (11), which can be rearranged and used to calculate the halfmeter (radius). Both forms of the equation are shown below.

$$V_{BS} = \frac{2 \bullet R_{BS}^3 \bullet \pi}{3}$$ equation (11)

$$R_{BS} = \sqrt[3]{\frac{3 \bullet V_{BS}}{2 \bullet \pi}}$$ equation (11)

where:

V_{BS} .... volume of biogas settler [m^3]

R_{BS} .... halfmeter (radius) of biogas settler [m]

The net volume of the compensation tank equals the gas storage capacity. A common design for the compensation tank is to provide a hemisphere with the overflow at height H above the base (or zero line). The net volume of the compensation tank is calculated by subtracting the volume of the free space above the overflow (R_{EC} – H) from the volume of the hemisphere:

$$V_{CT} = \frac{2 \bullet \left(R_{CT} - 0.02\right)^3 \bullet \pi}{3} - \left[\left(R_{CT} - H\right)^2 \bullet \pi \bullet \left(R_{CT} - \frac{R_{CT} - H}{3}\right)\right]$$ equation (12)

where:

V_{CT} .... net volume of compensation tank [m^3]

R_{CT} .... halfmeter (radius) of compensation tank [m]

0.02.............. thickness of plaster [m]

H .... hight of overflow above the base of compensation tank [m]

Maximum gas pressure occurs at a level P below the overflow level of the compensation tank, which is also the lowest slurry level. For calculation of level P equation (13) is applied to the total volume - equation (14) - of the free space above maximum slurry level (lowest gas pressure) and the net volume of the compensation tank.

$$P^2 \bullet \pi \bullet \left(R_{BS} - \frac{P}{3} \right) = V_{F+V_{CT}} \qquad \text{equation (13)}$$

$$V_{F+V_{CT}} = H^2 \bullet \pi \bullet \left(R_{BS} - \frac{H}{3} \right) + V_{CT} \qquad \text{equation (14)}$$

where:

P .... vertical distance of lowest slurry level and overflow level [m]

R_{BS} .... halfmeter (radius) of biogas settler [m]

V_F .... volume of the free space above maximum slurry level [m^3]

V_{CT} .... net volume of compensation tank [m^3]

H .... hight of overflow above the base of displacement chamber [m]

3.1.3 Sizing of siphon tank or pump sump

Application of pre-treated blackwater to the VFCW has to be done intermittently. The volume of each batch is calculated using equation (15):

$$Q_B = \frac{Q_D}{N_B} \qquad \text{equation (15)}$$

where:

Q_B .... batch volume [l]

Q_D .... daily wastewater production [l/d]

N_B .... number of batches per day

3.1.4 Sizing of VFCW

The surface area of the VFCW is determined by comparing the impact of hydraulic and organic loading criteria, and adopting the larger of the two surface areas.

$$A_{HYD} = \frac{Q_D}{HSL} \qquad \text{equation (16)}$$

$$A_{BOD} = \frac{C_{BOD-EBS} \bullet Q_D}{OSL_{VFCW-MAX} \bullet 1,000}$$ equation (17)

$$A = MAX\left[A_{HYD}; A_{BOD}\right]$$ equation (18)

where:

A_{HYD} .... surface area of VFCW [m^2]

Q_D .... daily wastewater production [l/d]

HSL.............. hydraulic surface load [$l/m^2/d$]

A_{BOD} .... surface area of VFCW [m^2]

$C_{BOD-EST}$ .... BOD_5 concentration of biogas settler effluent [mg/l]

$OSL_{VFCW-MAX}$ maximum organic surface load of VFCW [g $BOD_5/m^2/d$]

1,000........... conversion factor

A .... larger of the two surface areas [m^2]

BOD concentration of the final effluent is estimated based upon average BOD "removal" values from literature:

$$C_{BOD-EVFCW} = C_{BOD-EBS} \bullet \left(1 - BOD_{REM-VFCW}\right)$$ equation (19)

where:

$C_{BOD-EVFCW}$ ... BOD_5 concentration of VFCW effluent [mg/l]

$C_{BOD-EBS}$ .... BOD_5 concentration of biogas settler effluent [mg/l]

$BOD_{REM-VFCW}$ BOD "removal" in VFCW [%]

3.1.5 Sizing of collection tank

Net storage capacity of the collection tank is calculated taking daily wastewater production and desired storage time into account:

$$V_{CT} = \frac{Q_D \bullet T}{1,000}$$ equation (20)

where:

V_{CT} .... net volume of collection tank [m^3]

Q_D .... daily wastewater production [l/d]

T .... desired storage time [d]

1,000 .... conversion factor

4 SAMPLE DESIGN PROBLEM

Please note that design parameters (e.g. specific wastewater production, specific BOD load, etc.) have been choosen solely to exemplify designing of a biogas sanitation system presented as sample design problem in this training material and must not be applied for designing of real-life wastewater management systems without verification.

For proper designing of real-life projects, measuring of wastewater production and BOD load of the raw wastewater is recommended. If measuring of e.g. wastewater production and/or BOD load of the raw wastewater is not possible (e.g. designing of biogas sanitation system for an up-coming project, etc.) design parameters have to be set in all conscience.

4.1 On-site treatment of wastewater

Calculate the required volume for a biogas settler and surface area for a VFCW where wastewater is from a housing society.

4.1.1 Calculation of wastewater production

For calculation of daily wastewater production assume that 88 people are living in the society and that specific wastewater production is 135 litres per person per day. Specific BOD load per person per day is set with 54 grams [4].

Designing of the wastewater management sheme shall be based upon the following assumptions:

- number of users (N): 88
- specific wastewater prod. (Q_S): 135 l/p/d

- specific BOD load (L_{BOD}): 54 g BOD_5/p/d

$$Q_D = 88 \bullet 135 \approx 12{,}000 \; l/d \qquad \text{equation (1)}$$

$$C_{BOD-RAW} = \frac{54 \bullet 1{,}000}{135} = 400 \; mg/l \qquad \text{equation (2)}$$

$$C_{COD-RAW} = 2 \bullet 400 = 800 \; mg/l \qquad \text{equation (3)}$$

Daily wastewater production arises to ca. 12,000 litres (12.0 m^3). BOD and COD level of the raw wastewater are ca. 400 mg/l and 800 mg/l, respectively.

4.1.2 Sizing of biogas settler

A common design rule is for biogas settlers to provide a minimum hydraulic detention time of at least 1 day (24 hours) at maximum depth of sludge and scum layer.

Sizigning of the biogas settler and estimation of BOD_5 concentration of the effluent shall be based upon the following assumptions:

- BOD_5 raw wastewater ($C_{BOD-RAW}$): 400 mg BOD_5/l
- BOD_5 removal (BOD_{REM}) 36 %
- specific sludge volume (V_{SSV}): 0.0037 l/g BOD_{REM}
- daily wastewater prod. (Q_D): 12,000 l/d
- desludging frequency (T_D): every 18 months
- hydraulic detention time (HRT): 1 day (24 hours)
- COD removal (COD_{REM}): 34 %
- Specific biogas production (V_{SL}): 0.35 l/g COD_{REM}
- additional gas storage capacity: 20 % of V_D

$$C_{BOD-EBS} = 400 \bullet (1 - 0.36) = 256 \; mg \; BOD_5/l \qquad \text{equation (5)}$$

$$V_{SL} = \frac{0.0037 \bullet (400 - 256) \bullet 12{,}000 \bullet 30 \bullet 18}{1{,}000 \bullet 1{,}000} \approx 3.5 \; m^3 \qquad \text{equation (6)}$$

$$V_D = \frac{12{,}000 \bullet 1}{1{,}000} = 12{,}0 \; m^3 \qquad \text{equation (7)}$$

$$V_{SC} = 0.20 \bullet 12.0 = 2.4 \; m^3 \qquad \text{equation (8)}$$

$$C_{COD-EBS} = 800 \bullet (1-0.34) = 528 \; mg \; COD / l$$ equation (9)

$$V_G = \frac{0.35 \bullet (800-528) \bullet 12{,}000}{1{,}000 \bullet 1{,}000} + \frac{0.2 \bullet 12{,}000}{1{,}000} \approx 3.5 \; m^3$$ equation (10)

$$V_{BS} = 3.5 + 12.0 + 2.4 + 3.5 = 21.4 \; m^3$$ equation (4)

$$R_{BS} = \sqrt[3]{\frac{3 \bullet 21.4}{2 \bullet \pi}} \approx 2.17 \; m$$ equation (11)

$$V_{CT} = \frac{2 \bullet (R_{CT} - 0.02)^3 \bullet \pi}{3} - \left[(R_{CT} - 0.45)^2 \bullet \pi \bullet \left(R_{CT} - \frac{R_{CT} - 0.45}{3} \right) \right]$$ equation (12)

$$3.6 = \frac{2 \bullet (1.70 - 0.02)^3 \bullet \pi}{3} - \left[(1.70 - 0.45)^2 \bullet \pi \bullet \left(1.70 - \frac{1.70 - 0.45}{3} \right) \right]$$ equation (12)

$$P^2 \bullet \pi \bullet \left(R_{BS} - \frac{P}{3} \right) = 0.45^2 \bullet \pi \bullet \left(2.20 - \frac{0.45}{3} \right) + 3.6$$ equation (13)

$$P^2 \bullet \pi \bullet \left(2.20 - \frac{P}{3} \right) = 4.9$$ equation (13)

$$0.91^2 \bullet \pi \bullet \left(2.20 - \frac{0.91}{3} \right) = 4.9$$ equation (13)

ad equation (12): by trial and error (for $V_G = 3.5$ m^3), R_{CT} lies between 1.6 and 1.7 meter, adopt 1.7 meter for a volume of 3.6 m^3.

ad equation (13) by trial and error (for $V_F + V_{CT} = 3.5$ m^3), P is 0.91 meter.

4.1.3 Sizing of siphon tank or pump sump

Intermittent feeding of pre-treated wastewater shall be done in 3 to 4 batches per day.

Sizigning of the siphon tank or pump sump for intermittent feeding of pre-treated wastewater to the VFCW shall be based upon the following assumptions:

- daily blackwater prod. (QD): 12,000 l/d
- number of batches per day (NB): 3

$$Q_B = \frac{12{,}000}{3} = 4.0 \; m^3 / batch$$ equation (15)

Construction details and other important information

- All civil works have to comply with local as well as national standards and regulations.
- The siphon tank or pump sump must be watertight.
- A manhole has to be provided in the cover slab for maintenance.
- The manhole or the whole cover slab must be raised above the surrounding ground level to prevent surface run-off water from entering the tank.
- If possible, the siphon tank or pump sump is to be provided a fail-safe overflow that diverts water to low lying areas or a sewer in case of break-down of the pump or power cut.

4.1.4 Sizing of VFCW

Maximum organic surface load ($OSL_{VFCW-MAX}$) for VFCWs is given as follows:

- organic surface load: 20 to 40 [11] and up to 60g [12] BOD_5/m²/day

Common hydraulic surface loads (HSL) for HFCWs are given as follows:

- hydraulic surface load: 50 to 130 [11] and up to 200 l/m²/day

Sizigning of the vertical flow constructed wetland shall be based upon the following assumptions:

- daily wastewater prod. (QD): 12,000 l/d
- hydraulic surface load (HSL): 200 l/m^2/d
- BOD_5 settler eff. ($C_{BOD-EBS}$): 256 mg BOD_5/l
- max. OSL ($OSL_{VFCW-MAX}$): 20 mg BOD_5/m^2/d

$$A_{HYD} = \frac{12,000}{200} = 60.0\ m^2 \qquad \text{equation (16)}$$

$$A_{BOD} = \frac{256 \bullet 12,000}{30 \bullet 1,000} \approx 100.0\ m^2 \qquad \text{equation (17)}$$

$$A = MAX\left[60.0;100.0\right] = 100.0\ m^2 \qquad \text{equation (18)}$$

$$C_{BOD-EVFCW} = 256 \bullet (1-0.75) \approx 65\ mg\ BOD_5\ /\ l \qquad \text{equation (19)}$$

__Construction details and other important information__

- The location of the VFCW is to be selected in such a manner that it's safe from flooding.
- VFCW should be designed in such a way that they are integrated into landscape as much as possible.
- Surface water must be diverted away from the VFCW.
- If the existing soil has a permeability coefficient < 10^{-8} m/s, no artificial sealing layer is necessary for sewage treatment applications. In this case a density test (after Procter) has to be performed. Constructed wetland systems in soil with higher permeability require sealing of the bottom and sides so that untreated or partly treated wastewater cannot infiltrate to the groundwater. This can be achieved by: [11]
    - Using concrete or plastic tank.
    - Providing plastic liner, UV resistant, if exposed to the sun, thickness ≥ 1 mm, root resistant, preferably from polyethylene or equivalent material. The liner has to be protected against damages caused by rocks of the existing soil and by sharp edged gravel of the drainage layer. Geotextiles may be used for prevention of such damages.
    - Providing clay sealing with a verified thickness of ≥ 30 cm. It has to be compacted properly.
    - Improvement of existing soil by admixture of bentonite or very fine clay (two layers of 20 cm each, mixed and compacted separately).

  After finishing the sealing a leakage test should be carried out by filling the bed with water. If the loss is less than 2 mm overnight, the sealing is to be considered as satisfactory.
- Washed river sand and gravel are the preferred filter media;
    - top layer: 10 cm fine gravel (Ø 8/16 mm),
    - main layer: 60 to 80 cm coarse sand (Ø 1/4 mm),
    - intermediate layer: 10 cm fine gravel (Ø 4/8 mm),
    - drainage layer: 20 cm coarse gravel (Ø 16/32 mm).
- A freeboard of at least 25 cm (distance from bed surface to the upper edge of the lateral sealing) is to be provided.
- PVC pipes (Ø 50 to 75 mm) with drilled holes are acceptable for inlet and outlet manifolds. The distribution system has to be designed and constructed in such a way that they distribute the incoming wastewater uniformly over the surface of the VFCW

without leading to the formation of erosion furrows on the bed surface. After each application the pipes of the inflow construction should run empty. This prevents bacterial growth and resulting clogging problems.

- PVC pipes (Ø 100 mm) with drilled holes are acceptable for outlet manifolds.
- The construction of in- and outflow devices must allow for cleaning with mechanical or high pressure flushing tools.
- Local plant species should be used on the bed. The preferred species include: cattail, sedge, rush, soft stem bulrush, and reeds. Decorative, flowering plants can be used around the edges of the bed.
- The VFCW should be protected from unauthorized access, but be accessible for maintenance. There should be free access to all operational points, like manholes, pumping stations, maintenance locations and sampling points. The access has to be constructed in a way, that crossing of the VFCW is avoided.

4.1.5 Sizing of collection tank

Net storage capacity of the collection tank should be at least one-days wastewater production.

Sizing of the collection tank shall be based upon the following assumptions:

- daily blackwater prod. (QD): 12,000 l/d
- storage time (T): 1 d

$$V_{CT} = \frac{12{,}000}{1{,}000} = 12{,}0\ m^3 \qquad \text{equation (20)}$$

Construction details and other important information

- All civil works have to comply with local as well as national standards and regulations.
- The collection tank must be watertight.
- A manhole has to be provided in the cover slab for maintenance.
- The manhole or the whole cover slab must be raised above the surrounding ground level to prevent surface run-off water from entering the tank.
- If possible, the collection tank is to be provided a fail-safe overflow that diverts water to low lying areas or a sewer in case of break-down of the pump or power cut.

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6 SKETCHES, TECHNICAL DRAWINGS

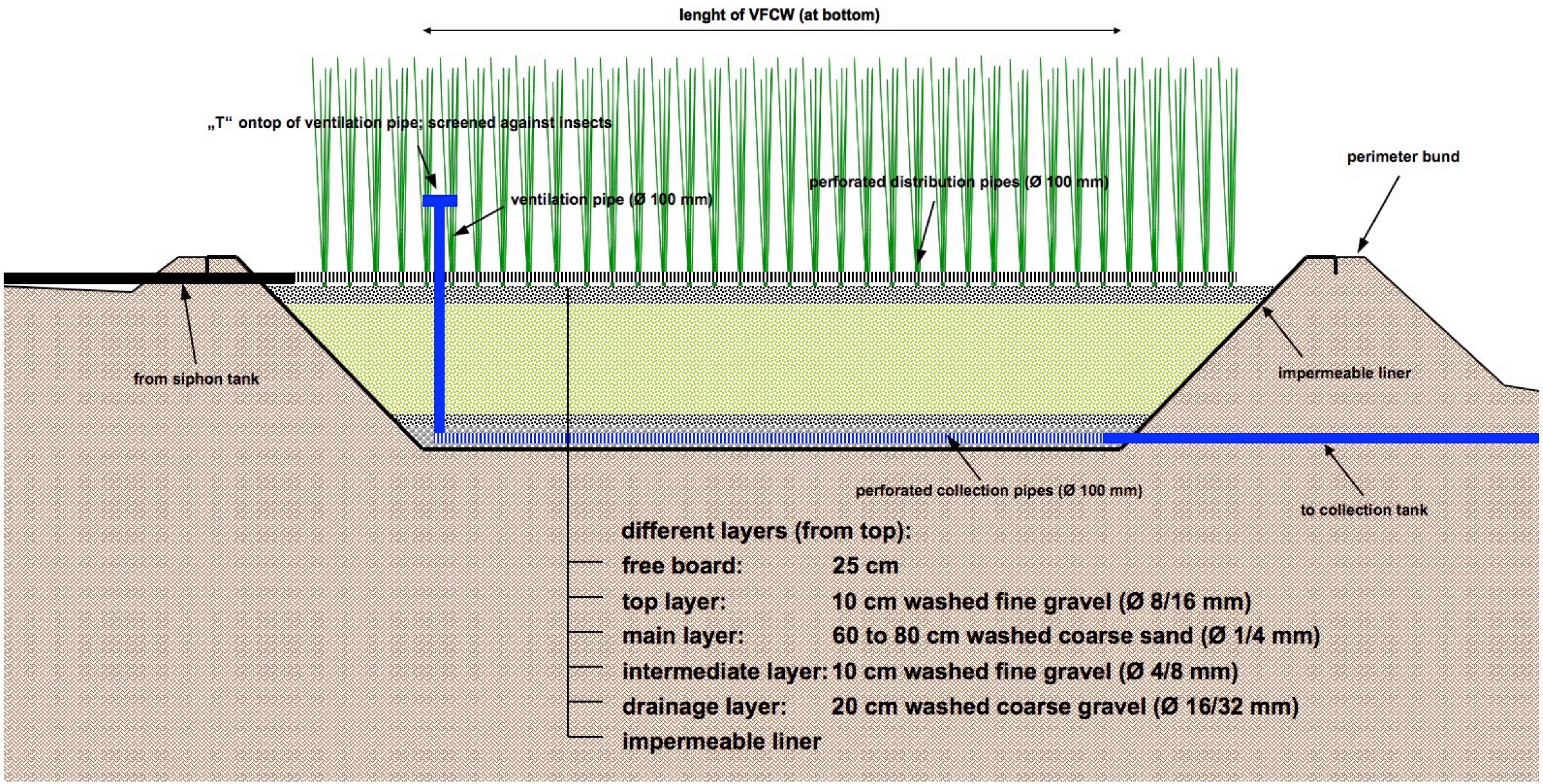

figure 5: Conceptual sketch VFCW (longitudinal section)

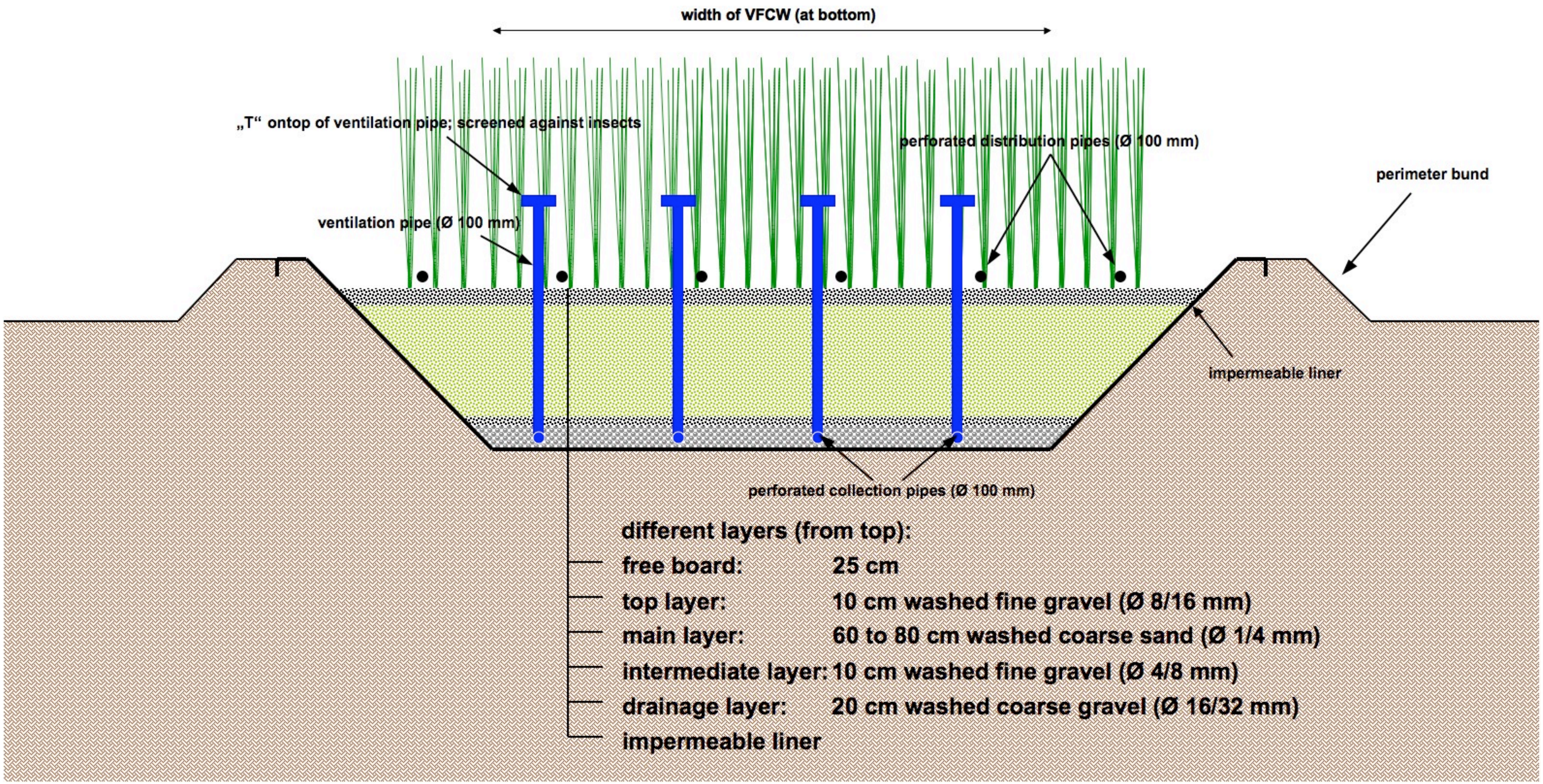

figure 6: Conceptual sketch VFCW (cross section)