The Potentials of Decentralised Wastewater Treatment Systems within Informal Settlements in relation to Organic Waste Recycling

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ABSTRACT

Household waste is a serious environmental problem in Indonesia, especially in dense urban areas; the kampungs. As only 2% of the total population is being connected to a centralized sewage system and due to a lack of efficiency and quality of currently applied decentralized wastewater treatment solutions, still 8 million tons of organic waste is annually being discharged in rivers. This study describes the current sanitation system within the kampungs in the Tamansari sub district in the city of Bandung, Indonesia, while examining the possible benefits of implementing a decentralized wastewater treatment system. The currently disposed human excreta and food waste offer major possibilities to retrieve useful nutrients for the production of biogas and natural fertilizers, when using anaerobic digestion as a treatment process, therefore applying an anaerobic digester within the treatment system's configuration of components. The anaerobic digestion should be followed up by secondary treatment of the effluent to achieve the required reduced level of pollutants to allow safe discharge in natural waters. Several case studies prove that even within a limited space due to the dense environment of the kampung, treatment system configurations with low space requirements are available and applicable.

KEYWORDS

Wastewater treatment, decentralized system, anaerobic digestion, biogas production, informal dense settlements, spatial requirements.

INTRODUCTION

Indonesia is currently facing a serious sanitation problem. From an immense population number of 242 million people, only 2% of them are connected to a centralized sewage system. Half of the total population lives in dense urban settlements called kampungs, which are affected the most by the insufficient coverage of the waste collection services. Historically, the responsibilities for sanitation improvement have been put at the individual households, resulting in insufficient wastewater treatment management (Eales, 2013, p. 5).

As most part of the annually produced waste is domestic waste, tackling the problem of this source is crucial. Nationwide, only 16.7 million tons of organic waste – mainly consisting of food waste and human excreta – is being collected by the official sanitation departments, while 169 million tons are informally handled by local individual or communities. Due to this informal waste management, a considerable amount of *ca.* 8 and 6 million tons of waste per year are being discharged in the rivers and burned (Amir, Hophmayer-Tokich, & Kurnani, 2015, p. 62).

While the kampungs are putting a high pressure on the environment, their high population densities and therefore large numbers of waste production might be offering potentials as well, as human excreta and food waste contain many useful nutrients which are interesting for recycling. Due to the application of a local decentralized wastewater treatment system containing an anaerobic digester, beneficial resources as biogas and natural fertilizers can be obtained as an output of the applied system.

This study will examine the possibilities of applying a decentralized system within a dense kampung to provide a solution for preventing the irresponsible organic waste disposal. The paper will focus on the specific case of the kampungs within the Tamansari sub district in the city of Bandung. Therefore the following research question has been formulated:

What treatment systems for organic waste are suitable to be applied within the dense spatially limited Tamansari kampung area, while being able to make optimal use of the beneficial capabilities of organic waste being converted into recycled resources?

METHOD

To understand the full scope of the problem and the opportunities which are present within the current situation of Tamansari in Bandung, this paper consists of several sections which together will be able to answer the research question. First of all, a short examination of the current centralised and decentralised systems in Bandung is described, while the exact advantages and disadvantages of both centralised and decentralised waste water treatment systems will be presented, to understand why the current system is not working, and a solution may be found in a more futuristic decentralised approach rather than a conventional centralised treatment system. The second part goes more into depth onto the gains which can be obtained from applying a decentralised system, in specific an anaerobic digestion system. In the following third section the principle of an anaerobic decentralised system will be examined in relation to the technical configuration of elements which are needed, supported by some examples of technical elements which should be implemented within the series of components to complete a fully operating decentralised wastewater treatment system. The fourth section consists of an overview of several case studies, in which the realization of decentralised systems in practice is being analysed. From these analyses, mainly the used technical elements and their technical performances are being examined. The four subsections are combined and used to answer the main question of this research. It is considered how the decentralized anaerobic water treatment systems can be implied in the informal dense settlements of Tamansari, by pointing out the benefits while taking the complicating impacts in consideration.

RESULTS

1 Centralised versus decentralised systems

1.1 Current sanitation system in Bandung

Similar to a lot of developing countries, a complete sewerage system network is a rarity in Indonesian cities. Only 2% of the inhabitants are being covered by any sewage network (Eales, 2013, p. 5). The city of Bandung is one of the only twelve cities which contain a (limited) sewage network, as it inherits a sewage network from Dutch colonial times constructed from 1916 on, to provide the newly built formal settlements in the North-East of Bandung (Bruijn, 1927, p. 103). This limited system, plus a separate system constructed in around the 1980's to cover another part over the city, only serves about 20% of the population. In addition, there is an insufficient wastewater inflow towards the central treatment plant, which results in a disappointing operational usage of 30% of its capacity (Sukarma & Pollard, 2001, p. 10).

As for many parts of the city, urban kampungs – by Schefold and Nas (2008) described as indigenous, low-class urban neighbourhoods – are not connected to the centralised sewage system, due to a difficult topography as the sewage system is working on a gravity basis, and therefore the investment costs of pumps to attach the kampungs to a centralized sewage piping system are too high.

Kampungs often lack a decent infrastructure, even though various urban kampung improvement programmes were initiated during the colonial period and latter periods between the 1960's to 80's, introducing infrastructural improvements as concrete paths, building lines and drainage (Schefold & Nas, 2008, p. 645). As a collective water management system is often lacking, many types of informal decentralised water and sanitation services are being applied, mainly pour-flush toilets connected to septic tanks, often only functioning as short-term survival tactics of individual households (Putri & Moulaert, 2017, p. 936). These informal water and sanitation services often don't lead to improved conditions of the kampung, while adjacent the lack of a collective system to recycle wastewater and protect the natural water sources will let this situation continue to exist (Putri & Moulaert, 2017, p. 937).

The described circumstances are similar in the specific case of the kampungs in the sub district of Tamansari in the city of Bandung. Tamansari has an area of about 102 hectares, with a population of 24,897 inhabitants within approximately 6,600 households. Despite the use of septic tanks, a lot of domestic wastewater is directly poured into the centrally located Cikapundung river. One factor for this direct disposal is the densification all the way up to the borders of the river, at which many houses are facing backwards towards the water. The Cikapundung river holds approximately 2.5 millions litres of domestic waste, while the organic waste production for Tamansari is considered to be about 53,000 L/day, or 1,98 L per person per day (BAPPEDA Kota Bandung, 2011).

1.2 *Centralised versus decentralised wastewater treatment systems*

To consider what kind of collective wastewater treatment system should be implied on an urban dense kampung community, one has to understand the different kind of systems. As mentioned before, Bandung is partly covered by a centralised sewage system, which can be considered as a conventional system. In contrast with that is the decentralised wastewater treatment system principal, which has gained more attention of the Indonesian state, as only recently (2009) they started to actively interfere in the lacking sanitation situation by launching a state-facilitated wastewater treatment program within the Indonesian Sanitation Development Program *Percepatan Pembangunan Sanitasi Permukiman*, focusing on a decentralised approach (Putri & Moulaert, 2017, p. 936). The focus on a decentralised approach is not rare, as a decentralised system has several advantages to be applied on a dense informal settlement compared to a centralised system.

First of all, centralised treatment systems handle way larger volumes of water compared to decentralised systems, as centralised systems focus on big urban areas while decentralised systems only cover individual or clusters of houses in small communities. Besides, decentralised systems treat the water nearby the generation point, while centralised systems treat the water in central treatment plants. The larger volume and the bigger transportation distance results in larger amounts and dimensions of sewage piping, causing higher construction and maintenance costs. Dense informal communities in developing countries with low income class inhabitants will not be able to finance such systems, while investment is not profitable for external investors (Massoud, Tarhini, & Nasr, 2009, p. 652).

Another complicating factor for the construction or attachment of a centralised system is the need of a proper zoning for a decent infrastructure, which is often lacking in informal settlements. Decentralised systems are less dependent on the available space and a formal zoning for infrastructural construction, and can be applied individually on a local needed basis (Massoud et al., 2009, p. 653).

Next to this, decentralised systems also mainly consist of simpler technologies, which besides their lower financial impact compared to the expensive pumps and pipes necessary for a centralised sewage network, are also easier to install and maintain. Although, decentralised systems require a certain strictness on a management level, as successful operation is highly dependent on communal awareness, knowledge and involvement, therefore needing a strong disciplined organizational management structure or responsible caretaker(s) (USEPA, 1997, p. iv).

As decentralised systems treat the wastewater nearby the source, it makes it possible to separate the different kinds of waste streams like grey and black water, as it merely treats effluents of domestic origin. Therefore, decentralised systems are able to reuse the nutrients from the treated effluent on a high concentrated level and in a cost-effective way. Within a centralised system domestic and industrial effluents are joined, which makes it more likely that the effluent contains more pollutants, heavy metals, etc., which makes it more difficult to retrieve and reuse the nutrients from the effluent (Robbins & Ligon, 2014, p. 2).

Moreover, the abuse of decent clean water for transport usage of human excreta through a sewage network is prevented when making use of a decentralised wastewater treatment system. Especially in regions or countries in which water is scarce, this can be an important factor (Lier, Zeeman, & Huibers, 1999, p. 522).

1.3 *Issues with currently used decentralised system techniques: septic tanks*

As described before, on site sanitation has already been largely used in Indonesia in the form of septic tanks, especially in dense kampung areas. The septic tank is the oldest anaerobic treatment system still being used. It is a watertight chamber in which black or grey wastewater is being treated, by the settling of heavy particles and anaerobic processes which reduce solids and organics (Tilley, Ulrich, & Lüthi, 2014, p. 74). Even though decentralisation has a lot of potential in developing countries, especially compared to centralised sewerage systems, the applied septic tanks are not a sufficient solution and contain many disadvantages.

First of all, considering the purely technical efficiency of the septic tank, it is only capable of moderate treatment of the polluted wastewater. Only a small amount of the pathogens, solids and organics are being reduced, making the septic tank only properly usable prior to further treatment (Tilley et al., 2014, p. 75).

Furthermore, the responsibilities of these sanitary improvements are often unclear, or put at individual households or communities, causing the development of an informal industry with inconsistent quantities and qualities of the septic tanks as a result (Sukarma & Pollard, 2001, p. 7).

Next to that, the settled sludge within septic tanks should be periodically removed by septage collection trucks (every 2-5 years) and transported to a central treatment plant. In the Tamansari kampung in Bandung, many septic tanks have not been emptied periodically as required or have never been emptied at all, due to the unclear responsibility and/or a lack of knowledge among the inhabitants.

Even when being emptied, the sludge is often not being disposed properly, nonetheless ending up in natural waters like rivers. Beside of that, not incidentally, the tanks contain leakages leading to contamination of groundwater (Baz, Otterpohl, & Wendland, 2008, p. 164).

Additionally, the efficiency of the septage collection is reduced as several waste collection trucks in Bandung have exceeded their operating life span (Amir et al., 2015, p. 62).

Septic tanks are being applied everywhere in developing countries, as partial treatment is of course being preferred over direct discharge into the environment, and the septic tanks are a cheap option. Next to that, the technology is simple and robust, resulting in a long service life. But as shown, the technology's efficiency is insufficient and often not properly managed, resulting in only partially or even unsolved environmental issues. While septic tanks are a form of on-site anaerobic treatment, which is considered best suitable for dense settlements in developing countries, the tanks do not optimally use the anaerobic digestion potential of producing energy and retrieving and reusing available nutrients from human excreta (Moussavi, Kazembeigi, & Farzadkia, 2010, p. 47).

2 Anaerobic on-site wastewater treatment system

2.1 Anaerobic digestion

Despite the lacking performance of septic tanks, the anaerobic treatment of wastewater in general is considered to be extremely suitable for on-site treatment. The type of treatment system is based on the anaerobic digestion process, which converts organic matter to inorganic end products, which can be reused. Due to the absence of oxygen, microorganisms are able to stabilize and break down biodegradable material, leading to the formation of energy-rich biogas and nutrient-rich residues (Mir, Hussain, & Verma, 2016, p. 3)

2.2 Benefits of anaerobic wastewater treatment

The main reasons for its excellent applicability are its capability to revaluate organic waste as a useful resource, its capacity to recover nutrients and carbon for fertilization use and the production of energy in the form of biogas (Angeli, Morales, LeFloch, Lakel, & Andres, 2018, p. 2). Next to these main benefits, it proved to be very valuable for decentralised treatment for several other arguments.

First of all, the biochemical functioning of anaerobic digestion proves to be highly efficient in breaking down organic materials. The conversion of organic material to gas – main percentage methane; CH4 – lowers the Chemical Oxygen Demand (COD) from the liquid phase, which can be seen as an indicator of the water pollution. The anaerobic treatment is capable of stabilising about 80 to 90% of the organic material (Foxon, 2009, p. 9).

Anaerobic digestion does not require any energy input to the process, and is therefore not dependant on any external energy sources. This makes the process quite cheap as well, making it very interesting for on-site water treatment in low income areas (Moussavi et al., 2010, p. 22).

Another impact on its relatively cheap investment, are the rather simple technologies being used and their designs; anaerobic reactors are often not complex and quite compact in their design, therefore being fairly cost-effective. Furthermore, its compact design means the overall space requirements of the system are relatively small as well, which is a relevant quality for application in dense informal settlements, like the kampungs in Indonesia.

Another beneficial characteristic of the anaerobic digestion process is its high loading capacity for input resources. Together with a certain flexible toleration for gaps between feedings of input resources and low quantities of sludge being produced, it can be considered as a flexible and easy manageable treatment technique (Moussavi et al., 2010, p. 47).

2.3 Converting organic waste into useful resources; natural fertilizer and biogas

Besides the aforementioned benefits concerning the economical, environmental and spatial fields, one might consider that the major beneficial outcomes of anaerobic digestion are its capability of converting organic waste into useful resources.

Firstly, the present nutrients in organic waste can be of high value for agriculture, using the extracted sludge as a natural fertilizer. This has several benefits, as first of all the process costs no energy or electricity to produce the natural fertilizer (Foxon, 2009, p. 4). Secondly, the production of nutrient-rich effluent as a natural fertilizer reduces the demand for mineral fertilizers. This is important, as in the past century the dependence on mineral fertilizers for food production has increased dramatically. The nutrients in these fertilizers mainly consist of phosphorus and nitrogen, which both are finite resources. Recycling nutrients reduces environmental damage and used energy caused by extraction of these finite resources (Kjerstadius, Haghighatafshar, & Davidsson, 2015, p. 1).

In this paper, the most important benefit of anaerobic on-site wastewater treatment is considered to be the capability of producing renewable energy in the form of biogas, which is able to replace the non-renewable fuels that are now still in use for several purposes as cooking, running vehicles and lighting. Biogas mainly consists of methane (50 to 70%), which acts as an energy source, whereas it furthermore consists of carbon dioxide which has no energetic value (Amir et al., 2015, p. 64). Besides biogas production, anaerobic digestion indirectly reduces the greenhouse gasses which are being produced by other treatment processes currently being in use (Foxon, 2009, p. 2).

While the shift to renewable sources is of major importance as the demand and shortage of fossil fuels is increasing, the production of biogas has another side benefit which is very relevant for Indonesia as well. Currently, the Indonesian population has been encouraged by the National Energy Policy to shift their cooking fuel from kerosene to LPG, leading to an increasing demand for LPG, annually rising by 20%. This may be seen as concerning as the domestic production capacity is not longer capable to meet the required quantities, leading to a forced increasing import of LPG from abroad. As the scarcity of LPG increases, this directly leads to a rising purchasing price, making utilization of local renewable sources economically more interesting for low-income households. The conversion of organic waste into biogas therefore cuts both ways, as it solves both the waste problem besides providing alternative energy to the households as an interesting economic stimulation (Amir et al., 2015, p. 63).

2.4 Anaerobic co-digestion

Anaerobic digestion uses organic waste as an input resource, which can be different types of waste. In the previous part of this paper, organic waste concerned human excreta, continuing on the introduction of anaerobic digestion as an interesting principle for decentralised sewage systems, while in fact this can also be food waste resulting from unprocessed raw foods and leftovers. Combining several types of waste for treatment is called anaerobic co-digestion, and is proven to have a positive effect on the anaerobic digestion process, as it is able to increase the methane production up to 67 to 294% (Mir et al., 2016, p. 2) and improves the general process stability. Meanwhile, it can be considered as economically beneficial as several waste streams are simultaneously being treated in one shared treatment facility (Estoppey, 2010, p. 16).

3 Decentralised wastewater treatment system components, configurations and techniques

3.1 Configuration of decentralised wastewater treatment system components

A decentralised treatment system does not only consist of one single technology, but uses a variety of them that work together to achieve several goals. For this, several configurations are possible, but all with the same goals of removing sewage away from humans, reduce the pollution level and safely discharge or reuse the treated effluent. Depending on the specific local needs of a site and its users, appropriate technologies are being linked to form a complete system, varying in complexity and costs (Robbins & Ligon, 2014, p. 3).

Robbins & Ligon (2014) use the comprehensive abbreviation DWMS (Decentralised Wastewater Management Systems), of which they claim it is hard to define what such a system exactly comprises, as decentralisation may differ greatly in scale (Robbins & Ligon, 2014, p. 4). For this paper, decentralised systems includes systems for individual households as well as small or relatively larger communities, as this still differs from a centralised approach in which a single system is used to serve an entire city or urban district. Despite quite big variable possibilities in scale and the technical elements used, DWMS generally consist of several sub-systems, which are applied in most cases:

- The user interface
- Pre-treatment system
- Conveyance system
- Primary treatment system
- Secondary treatment system
- (Potential) tertiary treatment system
- Final disposition, discharge or reuse.

These sub-systems will be examined and explained in the following section, each with some of the most common or best applicable technologies within a dense informal settlement like kampung Tamansari.

3.2 *Technical elements within treatment component categories*

3.2.1 User interface

The user interface is the actual toilets as a collection point of human excreta. The various options use different methods of collecting or even pre-separating the organic waste into different streams, for making the treatment process more efficient. Where in most developing countries most of the used toilets are the conventional pour-and-flush toilets which are perfectly suitable for a decentralised treatment system, there are new low-tech innovations being developed which focus on waterless toilet technologies and nutrient-capture programs (Robbins & Ligon, 2014, p. 63). For the efficiency of nutrient recovery and the anaerobic digestion process, these innovations can be very valuable, improving the concentration of valuable nutrients when excluding unnecessary extra added water.

3.2.2 Pre-treatment systems

In this stage, the materials which are harmful for the treatment are being removed from the polluted water, often happening directly at the source. Mostly, pre-treatment is only needed when high levels of pollutants within the treated water are present which are specifically desired to be filtered out – often at commercial or industrial facilities – while it should be treated at the source, to protect downstream treatment systems from damage or clogging. Pre-treatment requires regular maintaining, monitoring and cleaning, which makes a dedicated person with responsibility preferable (Tilley et al., 2014, p. 101).

For an anaerobic wastewater treatment system, a pre-treatment can be very valuable, as the removal of pollutants like sands, trash and grease reduces the amount of waste sources which are worthless for the anaerobic digestion process. A higher concentration of valuable nutrients within the effluent is beneficial if elements with limited space impact are required, as their capacity is used as efficiently as possible (Robbins & Ligon, 2014, p. 64).

The technologies used for pre-treatment are compact devices which should be able to be placed close to the source. The devices are often aimed to function at a specific location with specific filtration purposes. Examples are; grease traps which remove fats, oil and grease from food waste and trash traps functioning at for instance public markets, where the wastewater contains high levels of suspended solids which should be removed to prevent clogging and damage to further treatment elements (Robbins & Ligon, 2014, p. 66).

3.2.3 Conveyance system

This implies the transportation of wastewater from one place to another. This could be from the building to a treatment component, or between several treatment components within the whole system itself. This transport could be by human or motor powered force, as well as by constructed infrastructure, like open or closed sewers (Robbins & Ligon, 2014, p. 68).

The non-infrastructural technologies which are considered to be some sort of a conveyance system are examples like jerry cans, human-powered emptying pumps for removing sludge from pits, vaults and tanks, and motorized emptying and transport systems like the septage hauler tanks currently being used in kampung Tamansari.

Within the infrastructural technologies category we mainly consider several types of sewers, for instance ‘simplified sewers’, ‘solids-free sewers’ or ‘conventional gravity sewers’.

3.2.4 Primary treatment

After the pre-treatment, this is the first phase of the actual water treatment, in which a series of components work together to break down the contaminants by physical, chemical and biological processes. The primary treatment consists of the settling of solids and initial reduction of organic material, so the efficiency of later treatment steps if kept optimal. In an anaerobic digestion treatment system, the anaerobic digestion tank is a form of primary treatment (Robbins & Ligon, 2014, p. 76).

Biogas reactor

Different options for primary treatment are a standard biogas reactor, an Anaerobic Baffled Reactor (ABR) or an Upflow Anaerobic Sludge Blanket Reactor (UASB). A biogas reactor consists of one airtight chamber at which black water and/or food waste can be biodegraded. Gas is formed in the slurry and rises to the top of the tank, where it is collected. The tanks can be prefabricated or easily constructed out of bricks. The tanks are often applied on a household scale and directly connected to the toilets with additional inflow points for food waste, which is necessary as only black water input will not result in a significant gas production. The reactor is easy to manage, as it should only be emptied every 5 to 10 years, but regular feeding of the plant is necessary (Tilley et al., 2014, p. 134).

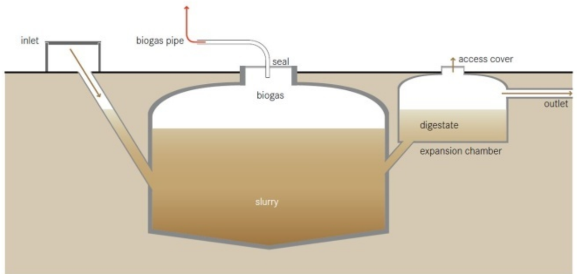

Figure 1 - biogas reactor (Tilley et al., 2014, p. 134)

Anaerobic Baffled Reactor (ABR)

The Anaerobic Baffled Reactor can be considered as an improved septic tank, with a series of baffled through which the wastewater is forced to flow. Before the actual ABR, the majority of settleable solids are removed in a sedimentation chamber, which is often integrated within the total tank itself. As the water has a longer time of contact with the active sludge, the treatment efficiency increases (Tilley et al., 2014, p. 105).

The ABR can be applied at household scale and in small as well as bigger neighbourhoods. It is very suitable for locations where land is limited, as it can be placed underground and it is compact in size. However, it should be accessible for tanks for sludge removal every 1 to 3 years. The tank requires regular monitoring, but process operation and maintenance is very limited (Tilley et al., 2014, p. 106).

Upflow Anaerobic Sludge Blanket (UASB)

An Upflow Anaerobic Sludge Blanket reactor (UASB) is a single tank in which the wastewater enters from the bottom from the tank and flows upwards, leaving the tank again. A filtering sludge blanket is suspended within the tank and treats the water due to special microorganisms which of their weight are not being washed out while the water flows up. After a certain period, larger pieces of sludge clot together, functioning as a filter for smaller particles. Meanwhile, the microorganisms produce biogas, which mixes the sludge which improves the process as well (Tilley et al., 2014, p. 122).

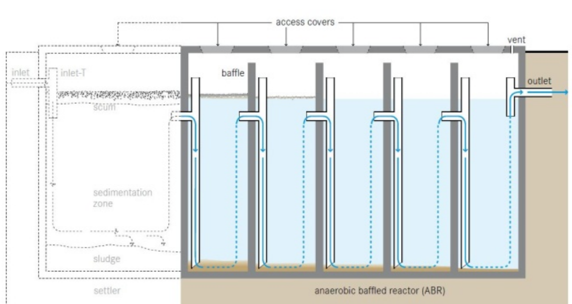

Figure 2 - Anaerobic Baffled Reactor (Tilley et al., 2014, p. 106)

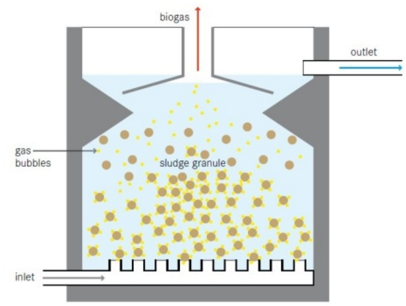

Figure 3 - Upflow Anaerobic Baffled Reactor (Tilley et al., 2014, p. 122)

Even though the technique is very promising and effective, it does require a constant water supply and electricity. The technology is rather simple to build, but for the clotted sludge to be formed it can take a lot of time, sometimes several months. The application on household level is possible, but still quite new. Last of all, the operation and management requires professional knowledge, so does the monitoring and repairing of the reactor (Tilley et al., 2014, p. 123).

3.2.5 Secondary treatment systems

As the organic matter in wastewater is only moderately being reduced in primary treatment, and the effluent still contains high levels of pollutants, therefore being insufficiently cleaned to be disposed or reused, secondary treatment is required to further reduce these pollutant levels. Secondary treatment often consists of aerobic treatment processes, in which oxygen is being used to stimulate the reduction of organic matter and pathogen levels by aerobic bacteria (Robbins & Ligon, 2014, p. 81).

Several techniques exist for secondary treatment, but most of them require a lot of land and produce uncomfortable odours, or when being more compact in size requiring high amounts of energy input. One of the few interesting options are constructed wetlands (CW), containing some additional benefits which make them optional. Constructed wetlands are lined basins filled with gravel that support plants and microbes, and can be divided in three different categories: free-water surface flow CWs, horizontal subsurface flow CWs and vertical flow CWs (Robbins & Ligon, 2014, p. 86).

Free-water surface constructed wetland

The free-water surface constructed wetland is an artificial copy of the natural occurring process within a natural wetland, marsh or swamp. It is a basin lined with an impermeable barrier covered with soil, rock and gravel and vegetation on top. Particles settle and pathogens are destroyed as the water flows through the wetland and organisms and plants absorb the nutrients. As the inlet sludge settles a surface of water remains on top of it. Most pathogens are reduced by natural decay, sedimentation and UV irradiation (Tilley et al., 2014, p. 114).

The wetlands are highly efficient in reducing and removing pollutants, while it is very flexible in its input water levels and nutrient loads. The system does require a lot of land, while it is possible to limit its size when being applied on a small communal level. In general, their maintenance is minimal and it is adding aesthetical value to the environment (Tilley et al., 2014, p. 115).

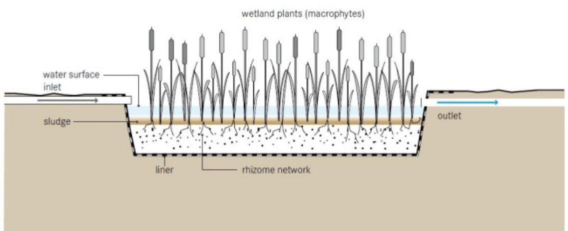

Figure 4 - Free-water surface constructed wetland (Tilley, 2014, p. 114)

Hor. subsurface flow constructed wetland

A horizontal subsurface flow constructed wetland as well is a basin filled with gravel and vegetation, while with this technology not primarily the flow of the water, but the filter material reduces pollutants. It works as a fixed surface upon bacteria can attach, and vegetation can grow. Most of the organics are broken down by anaerobic bacteria, but as the vegetation transfers oxygen to its roots, aerobic bacteria are able to process organic materials as well.

The reducing efficiency of the system is relative to the surface area of the wetland, while the maximum possible flow is determined by the sectional area. In general, about 5-10 m^2 is required for treatment per person. Pre-treatment or primary treatment is essential, as clogging is a common problem, which makes it unsuitable for untreated black water (Tilley et al., 2014, p. 117).

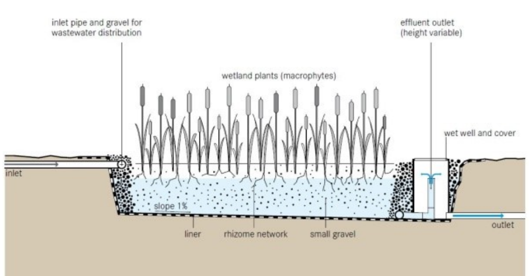

Figure 5 – Horizontal subsurface constructed wetland (Tilley, 2014, p. 117)

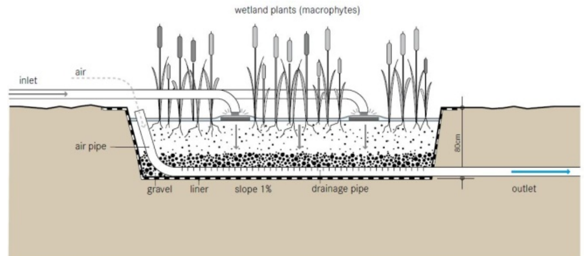

Figure 6 - Vertical subsurface constructed wetland (Tilley, 2014, p. 119)

Vertical subsurface flow constructed wetl.

This version of a constructed wetland almost looks the same as the previous examples, but differs in the way that water is being dosed onto the surface from above, while being drained at the bottom. This creates a vertical flow of the water which makes it pass through a filter. Due to a non continuous feeding of the wetland, but with interruptions, different phases of aerobic and anaerobic conditions are achieved, which stimulates the organic breakdown (Tilley et al., 2014, p. 118).

Similar to the other wetlands, the system needs pretreatment to prevent clogging. Compared to the other wetlands it requires less space, as it can be designed as shallow long systems. In general, a surface of 1 to 3 m^2 per person is required for treatment. Disadvantages of the system are the required trained people for maintenance and the constant power supply (Tilley et al., 2014, p. 119).

3.2.6 (Potential) tertiary treatment systems

In only few cases, when a high level of effluent treatment is required, primary and secondary treatment are not sufficient enough for reduction of pollution levels to be able to be disposed, or reused (mainly with agricultural uses). This tertiary treatment phase contains filtration and disinfection, for further microbial reduction (Robbins & Ligon, 2014, p. 99).

3.2.7 Final disposition, discharge or reuse

At the full end of the DWMS cycle, the treated effluent has to be discharged off-site, into ditches, sewers or directly into rivers, streams, etc, only if the pollutant reduction meets the required levels set by national or local governments. Depending on the configuration of the decentralised treatment system, treated water and other extracted resources can be reused (Robbins & Ligon, 2014, p. 101).

3.3 Concepts for system configurations with different scale regarding collection, transport and treatment processes

The exact set-up of an anaerobic decentralised wastewater treatment system at a specific site strongly depends on the existing local conditions. The collection, transport and treatment of the wastewater can be applied in various configurations, varying in scale and techniques being applied within the system. Generally speaking, there are three different organisational concepts with a decentralised system: a fully community based system, a semi community based semi privately based system and a system which is fully applied on the scale of individual households (Lier et al., 1999, p. 518). A side note should be placed that as the DWMS systems consist of several components, there can be variations in configuration which could combine elements of these three concepts.

In the fully community based concept (see figure 1), the total domestic waste is directly being collected from the individual households and transported to a central place where it is being treated. Except for the occasionally present pre-treatment which will happen at the individual household nearby the source, the primary, secondary and tertiary treatment processes will happen on a community based scale. Retrieved beneficial outcomes like fertilizers and biogas will become shared communal resources, while the treated water can be discharged (Lier et al., 1999, p. 518).

Within the second concept (see figure 2), which consists of a combination of a private and communal scale, the primary treatment phase in which the total sewage (black + grey water) will be treated at the scale of individual or small clusters of a few households. The organic matter is being conversed to biogas, which is supplied to the individual houses. The effluent retrieved from primary treatment is being transported via a conveyance system towards communal on-site secondary and tertiary treatment. The outcome of this post-treatment phase can be used for fertilisation, while the water has reached a sufficient level of reduced pollutants to be discharged in natural waters (Lier et al., 1999, p. 519).

The third concept (see figure 3) focuses on locating the treatment system completely within the household scale. As the technical elements allow a limited spatial impact, there are higher limits to the capacity of the treatment system. Sizes of the elements can be kept minimal when reducing the amount of water entering the system from the user interface (toilets). This way, concentrated slurry called 'night soil' is produced, instead of black water. Most often within these small scaled systems an accumulation (AC) system is used instead of the conventional digestion reactor, as different waste streams like human excreta and food waste are often combined. The biogas being retrieved from this reactor and the digested sludge are being used by the individual households which are directly attached to the system (Lier et al., 1999, p. 521).

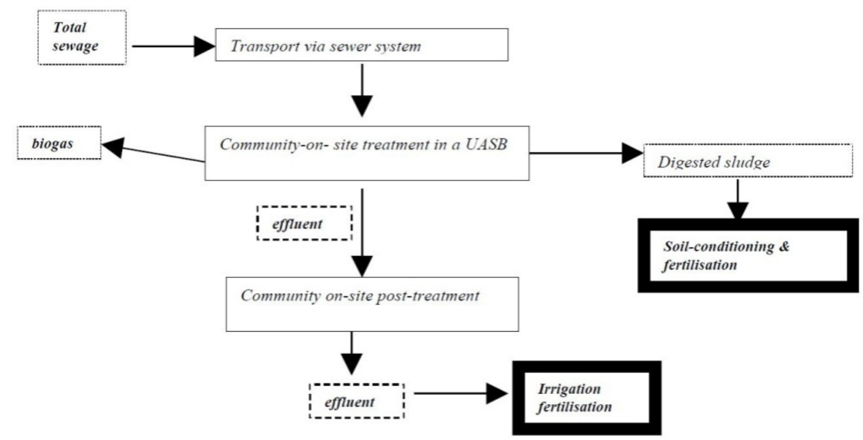

__Figure 7__ – Complete community based on-site treatment concept of domestic sewage waste (Lier et al., 1999)

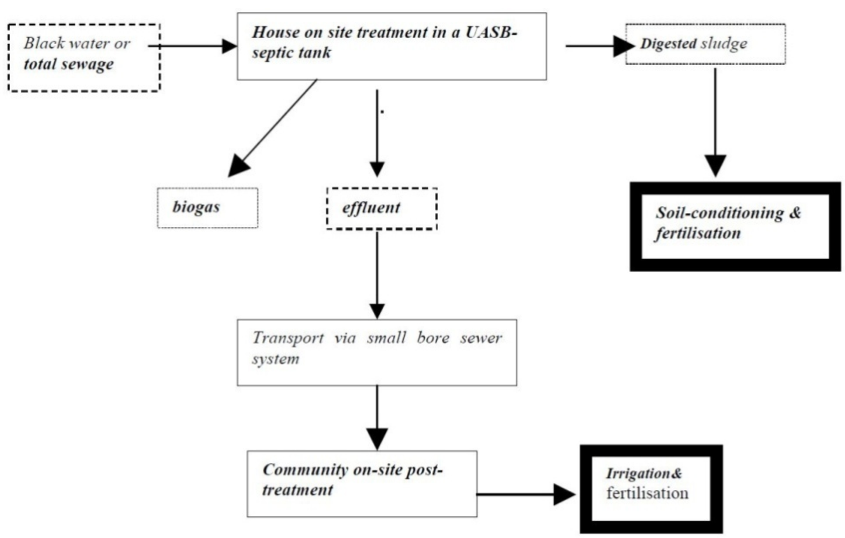

__Figure 8__ – Combined community based and household based on-site treatment concept of domestic sewage waste (Lier et al., 1999)

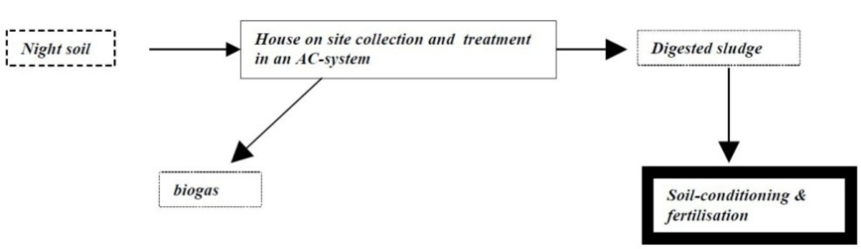

__Figure 9__ – Fully household based on-site treatment concept of domestic sewage waste (Lier et al., 1999)

4 Anaerobic digestion systems in practice

4.1 BIOTECH toilet-linked biogas plants, Kumbalanghi village, Kochi, South-India

The village of Kumbalanghi consisting of around 30,000 inhabitants is an island nearby Kochi City, in the Southwest of India. Due to several issues like a low lying terrain and a relatively high groundwater level connecting to a centralised sewage system is quite difficult, therefore a decentralised solution was being developed. The organisation BIOTECH introduced small scale toilet-linked biogas plants, which are able to digest human excreta and food waste on a household scale. Around 150 toilet linked plants and 650 kitchen waste plants have been installed within Kumbalanghi. The goal was to solve the waste dumping and water pollution problems at the source by installing a treatment plant at every single household (Estoppey, 2010, pp. 6-14).

The system's configuration is quite simple, as it only contains of one single element: the biogas plant itself. The households are directly linked to the plant, which has two inlets; one for food waste and another for human excreta. There are different sizes of digesters possible, varying from 1 to 6 m^3, but the most common digester is around 2 m^3 with limited dimensions of around 140 cm in diameter, 160 cm deep in the ground and 70 centimetre in height above the ground (Estoppey, 2010, p. 15).

One treatment plant of 2 m^3 was being used by a family consisting of 4 persons. The feedstock which went in to the digester contained of an average of 0.7kg of food waste per day, plus around 0.25kg of toilet waste per day, which makes a total of +/- 1kg of waste input. The Chemical Oxygen Demand (COD), which can be considered as an equivalent value for the pollution level of the water, was reduced with a total of 86,8% after treatment (Estoppey, 2010, p. 30).

The outputs of the system contain biogas and natural fertilizers, which had economical benefits for the local inhabitants due to the ability to replace the formerly used cooking energy and fertilizers. The plant produced an average amount of 680 L of biogas per day with an average of 61% of CH_4, which was enough for a family to cook on biogas for about 3,25 hours each day, enough for their main dishes (Estoppey, 2010, p. 32). The effluent showed a high reduction of pathogen content, but still contained a quite high concentration of contaminants which only allow a restricted agricultural use according to the WHO-guidelines. Therefore, the utilisation of the effluent as a fertilizer was only possible for vegetables which are not eaten raw. Furthermore, the COD level of the effluent is still too high to allow the effluent to be discharged, and therefore further treatment would be necessary (Estoppey, 2010, p. 45).

Figure 10 – BIOTECH toilet-linked digester, with fixation point (A) and measurements points (B) of the connected gas meter (Estoppey, 2010, p. 18).

4.2 SANIMA systems, Yogyakarta & Bali, Indonesia

In Indonesia, decentralised wastewater treatment systems are already quite commonly applied, on locations with Decentralised Wastewater Treatment Plants or Community-based Sanitation, called SANIMAS. This main principle can be classified in the following four categories: communal toilets, communal wastewater treatment, small scale industries and cattle farming. The specific systems' elements which are applied are often universally developed by an organisation called BORDA, therefore often having the same shape and size (Rochmadi, Ciptaraharja, & Setiadi, 2010, p. 1).

4.2.1 Yogyakarta, Indonesia: Communal wastewater treatment

In this case study, an informal community within the city of Yogyakarta is being examined. It contains a relatively small community with a maximum of 51 households being connected to the treatment system. The SANIMA system being applied here is the communal wastewater treatment system, in which domestic wastewater is brought from the individual households to a central communal treatment component. In this specific case, the black and grey water is being collected separately, whereas the black water of 15 households is connected to the system with an adjacent 51 households discharging their grey water onto the system (Rochmadi et al., 2010, p. 2).

The system itself consists of only a few simple elements and relations between them. The black water is directly discharged from the households into the BORDA developed biodigester as a primary treatment system; a dome shaped tank with a diameter of 3 meter. This specific biodigester is easy to construct by the local community with common available materials and easy to operate, therefore making it relatively cheap. Within the biodigester, the pollutant level is being reduced and biogas is being produced. As the effluent outcome does not comply with the regulations for being discharged, the system adds an Anaerobic Baffled Reactor – described in chapter 3 – as a secondary treatment system.

The influent of wastewater within the system in Yogyakarta had a flowrate of 1261 L/day, with a Chemical Oxygen Demand (COD) of 2361 mg/L. After primary treatment in the biodigester, followed by secondary treatment in the ABR, a final COD level of 61 mg/L was accomplished (reduction of 97,42%), sufficient to be discharged into natural waters. As an output resource, biogas was extracted from the process, with a total production of 1850L of biogas per day, with a concentration of 75% of CH_4 as valuable energy. Unfortunately, this produced biogas was not sufficient to be used by all the connected households: only 2 households were able to benefit from the system with each 4,5 hours of cooking activity per day (Rochmadi et al., 2010, p. 3).

4.2.2 Bali, Indonesia: Food (tofu) industries

Similar to the previous case study, this example as well applied the SANIMA system as a decentralised wastewater treatment system. But instead of the communal treatment system, it applied the small scale industries SANIMA system on a location containing six industrial food (tofu) services, with a production capacity of 1400 kg of soy-beans per day (Rochmadi et al., 2010, p. 3).

Just as in Yogyakarta, the system is equipped with an anaerobic digester, and an additional Anaerobic Baffled Reactor, which are all on a community based construction and management scale. The difference primarily can be found in the scale in size of the elements, as the flowrate and content of the input differs, with a relatively higher percentage of food waste due to its function. The digester is able to handle 20 m^3 of wastewater per day, whereas the ABR consists of 6 compartments with a total volume of 56 m^3 (Rochmadi et al., 2010, p. 3).

Whereas the flowrate of the influent is only 462 L/day, the COD value is relatively high (8103 mg/L), due to the high concentration of food waste. After primary treatment in the digester and secondary treatment in the ABR, the COD value reduced to 407 mg/L, a reduction of 94.97%. Even though this high reduction, the wastewater still does not meet the standards for safe discharging, therefore actually requiring additional tertiary treatment which is not applied at the moment yet. The system's processes result in a biogas production of 1620 L/day with a high CH_4 concentration of 84.5%, for which the local industry is able to achieve 24 hours of cooking activity per day (Rochmadi et al., 2010, p. 5).

Figure 11 - underground anaerobic digester serving 2 tofu industries in Bali (Rochmadi et al, 2010, p.9)

4.3 *Ecological formal neighbourhood, Flintenbreite, Hannover, Germany*

A completely different case study compared to the previous examples from developing countries is the neighbourhood of Flintenbreite in Hannover, Germany. This collective of ecological housing was constructed as a part of the global Hannover EXPO 2000 project and consists of 117 dwellings accommodating up to 380 inhabitants. This case study differs greatly from the previous examples from developing countries, as there was a possibility to develop a completely new infrastructure with a purpose to develop a completely circular ecological concept from scratch, instead of implementing technologies onto an existing environment (Angeli et al., 2018, p. 9). This case study is taken into consideration to review the possibilities of anaerobic digestion on a more formalised and bigger scale.

The system consists of a way broader collection of components compared to the low-tech systems in the previous case studies. The treatment system is a so called semi-centralised system, as all the waste streams are directly collected from the households and brought to a central "infrastructural shaft" underneath the ground in between of all the dwellings, in which everything is transported to a central technical space where the treatment systems are installed within a basement (Timmeren, 2006, p. 274).

First of all, black water is being collected separately and is being transported from each household through a vacuum sewage system towards a collective pre-treatment tank. The vacuum system reduces the amount of used water which will make a smaller bioreactor possible. Food waste will be transported via a crush tank before being added to the pre-treatment tank, from which both waste streams will be transported to the primary treatment system in the form of a Continuous Stirred Tank Reactor (CSTR) as a digester at which biogas is produced. Within this project, the biogas is not used for cooking purposes, but is transported to a Combined Heat and Power (CHP) system for usage of heat and electricity. A part of the biogas is being stored in a separate storage tank. The grey water is being collected separately as well, and is treated through a 1200 square meter reed-bed field, after which the water is used for agriculture (Anilir, Nelson, & Allen, 2008, p. 80).

Even though the system contains quite some (high-tech) steps around the anaerobic digester, these are primarily added to be able to reduce the size of the reactor, which has a capacity of 72 m^3. The total space requirement for water treatment per person is 3.8 m^2. In general, the system does not require a high level of management, as the infrastructure is takes care of the separated collection of black and grey water as well as the food waste (Angeli et al., 2018, p. 9).

The system has an inflow of 1217 m^3 black water per year (or 3334 L/day, compared to the previous examples) and 3 tons/year (8kg/day) of kitchen waste. From this inflow, a biogas production of 4700-22500 m^3 of CH_4 per year is estimated (Angeli et al., 2018, pp. 9, 10), which can be converted to a production of 12900-61600 L/day, which has to be divided over 117 households. If this production was used for cooking purposes and the biogas usage of 180L per cooking hour from the previous examples in developed countries was used (Estoppey, 2010, p. 32), this will result in a cooking capacity of 0,6-2,9 hours per day.

Figure 12 - Some of the technical components of the sanitation/energy system in the basement of the communal building (Timmeren, 2006, p. 275)

CONCLUSION

The implementation of a decentralized wastewater treatment system, as a replacement of the currently lacking septic tanks and an absent centralized system, has major potentials for the dense kampung of Tamansari. An optimally beneficial developed decentralized system should contain an anaerobic digester as a primary treatment component, to break down the organic materials while producing biogas. The anaerobic digestion process is very suitable for dense urban environments like Tamansari, due to their compact technology systems with high treatment efficiency and no energy input. The produced biogas can be of economical benefit for the kampung inhabitants, as a replacement of the current LPG as a cooking fuel which they have to buy. Similarly, natural fertilizers out of the extracted slurry can replace the chemical fertilizers which currently have to be bought, while in addition they are made of the finite resource phosphorus.

When comparing the several digestion tanks, the UBSR has a high production capacity, but needs constant energy which makes it quite unsuitable for the kampung community. Instead, both the biogas reactor as well as the ABR are suitable, showing promising results in the case studies as well. As both systems have limited required space and are able to be built partly underground, the main difference lies in the different scale to be applied in. As the ABR works well in a semi-centralized system, fewer amounts are needed while they can be spread out space efficiently. To collect the wastewater from the households and transfer it to a semi-central primary treatment component, a smart conveyance system is needed, as currently all the streams are discharged by opens sewers and pipes straight into the river. Perhaps a new affordable infrastructure can be applied for central collection, like a low-tech variation to the infrastructural shaft in Flintenbreite.

After initial treatment and the resulting beneficial production of biogas, the effluent needs further treatment to be allowed to be discharged in natural waters. For this secondary treatment, a vertical subsurface flow constructed wetland might be preferred, due to its limited size requirements, but it does need a constant energy input, which is not very suitable for Tamansari. Therefore, application of a horizontal surface or free-water surfaced constructed wetlands are most preferred, while there must be considered that free land has to be found or created for this.

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Appendix I - Overview of advantages and disadvantages of examined techniques (retrieved from (Tilley et al., 2014))

Primary treatment technology	Pros	Cons
Biogas reactor	+ Generation of renewable energy + Small land area required (most of the structure can be built underground) + No electrical energy required + Conservation of nutrients + Long service life + Low operating costs	- Requires expert design and skilled construction - Incomplete pathogen removal, the digestate might require further treatment - Limited gas production below 15 °C
Anaerobic Baffled Reactor (ABR)	+ Resistant to organic and hydraulic shock loads + No electrical energy is required + Low operating costs + Long service life + High reduction of BOD + Low sludge production; the sludge is stabilized + Moderate area requirement (can be built underground)	- Requires expert design and construction - Low reduction of pathogens and nutrients - Effluent and sludge require further treatment and/or appropriate discharge
Upflow Anaerobic Sludge Blanket Reactor (UASB)	+ High reduction of BOD + Can withstand high organic and hydraulic loading rates + Low sludge production (and, thus, infrequent desludging required) + Biogas can be used for energy (but usually first requires scrubbing)	- Treatment may be unstable with variable hydraulic and organic loads - Requires operation and maintenance by skilled personnel; difficult to maintain proper hydraulic conditions (upflow and settling rates must be balanced) - Long start-up time - A constant source of electricity is required - Not all parts and materials may be locally available - Requires expert design and construction - Effluent and sludge require further treatment and/or appropriate discharge

Secondary treatment technology	Pros	Cons
Free-water surface constructed wetland	+ Aesthetically pleasing and provides animal habitat + High reduction of BOD and solids; moderate pathogen removal + Can be built and repaired with locally available materials + No electrical energy is required + No real problems with odours if designed and maintained correctly + Low operating costs	- May facilitate mosquito breeding - Requires a large land area - Long start-up time to work at full capacity - Requires expert design and construction
Horizontal subsurface flow constructed wetland	+ High reduction of BOD, suspended solids and pathogens + Does not have the mosquito problems of the Free-Water Surface Constructed Wetl. + No electrical energy is required + Low operating costs	- Requires a large land area - Little nutrient removal - Risk of clogging, depending on pre- and primary treatment - Long start-up time to work at full capacity - Requires expert design and construction
Vertical subsurface flow constructed wetland	+ High reduction of BOD, suspended solids and pathogens + Ability to nitrify due to good oxygen transfer + Does not have the mosquito problems of the Free-Water Surface Constructed Wetland + Less clogging than in a Horizontal Subsurface Flow Constructed Wetland + Requires less space than a Free-Water Surface or Horizontal Flow Wetland + Low operating costs	- Requires expert design and construction, particularly, the dosing system - Requires more frequent maintenance than a Horizontal Subsurface Flow Constructed Wetland - A constant source of electrical energy may be required - Long start-up time to work at full capacity - Not all parts and materials may be locally available

Appendix II – Overview of case study characteristics. Wastewater input characteristics, primary treatment data, secondary treatment data and biogas production.

Case study	unit	Depensar, Indonesia	Yogyakarta, Indonesia	Kochi, South-India	Flintenbreite, Hannover, Germany
DWMS	-	**communal**	**communal**	**individual**	**semi-centr.**
Scale of system	Househ. Industr.	6 tofu industries	20 households	1 household (4 persons)	117 households
Input					
Wastewater					
Volume	L/day	462 L/day	1261 L/day	25-40 L/day	3334 L/day
COD value	mg/L	8103 mg/L	2361 mg/L	25000 mg/L	-
Food waste					
Volume	kg/day	-	-	0.7 kg/day	8 kg/day
Primary treatment					
Technique	-	Biodigester	Biodigester	Biogas plant	CSTR reactor
Volume capacity	m^3/day	20 m^3/day	6 m^3	2 m^3	72 m^3
COD value after treat.	mg/L	604 mg/L	346 mg/L	3460 mg/L	-
Secondary Treatment					
Technique	-	Anaerobic Baffled Reactor	Anaerobic Baffled Reactor	-	
Volume capacity	m^3/day	56 m^3	?	-	
COD value after treat.	mg/L	407 mg/L	61 mg/L	-	
Biogas					
Production	L/day	1620 L/day	1850 L/day	680 L/day	12900 – 61600 L/day[1 2]
CH_4 value	%	84,5%	75%	61%	-
Cooking value	hrs/day	9 hours	24 hours	3,25 hours	-
Pollution red.					
COD reduction	%	94,98 %	97,42 %	86,16 %	-

[1] Biogas production can vary due to the changing circumstances. This is an estimation, extracted from Angeli et al, (2018), p. 9-10

[2] The written number represents the produced CH_4, instead of the total biogas production, which often contains other gasses like CO_2.