Design and development of decentralized water and wastewater technologies: a combination of safe wastewater disposal and fertilizer production

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ABSTRACT

Modern wastewater treatment plants are often inappropriate for communities in developing countries. Such communities lack the funding, resources and skilled labour required to implement, operate, and maintain these plants. This research was conducted to investigate and establish an appropriate wastewater treatment system for the district of Gunung Kidul, Indonesia. Due to its lack of water during the dry season, this district is considered one of the poorest areas in the nation. First, wastewater was stored in septic tank units for a retention time of 26 days. Anaerobic conditions occurred, resulting in an 80% reduction of initial COD. The retained sludge was well stabilized with great potential, if dewatered, for reuse as fertilizer. Consequently, supernatant was separated for experiments consisting of lab scale aerobic sand filtering unit. Through filtration, further removals of COD (about 30%) and pathogens were achieved. Rich in nitrogen, the resulting effluent could be used for irrigation and soil conditioning. With faecal sludge and also a mixture of septic sludge and food waste, the hydrolysis stage of anaerobic digestion was examined. This paper discusses the laboratory findings in Karlsruhe and the design and implementation of a treatment system in Glompong, Indonesia.

Key words | anaerobic digestion, COD, fertilizer, nitrification, sand filtration, septic sludge

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INTRODUCTION

In the province of Yogyakarta in Java, the district of Gunung Kidul is considered one of the poorest areas in Indonesia. Here, water shortages greatly affect the population, especially during the dry season, which lasts from April to October (Lux & Unger 2005). Due to the karstic underground, rainfall rapidly seeps into the ground without sufficient surface storage (Uhlig 1980; Haryono & Day 2004). In May 2006, a devastating earthquake destroyed 200,000 buildings in the province of Yogyakarta and Central Java. In the village of Glompong, many houses and the school building collapsed. In cooperation with Cap Anamur (Germany), the company supporting the reconstruction of the school building, the University of Karlsruhe (Germany) has developed and installed new sanitary and water supply facilities.

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In the district of Gunung Kidul, wastewater is either discharged directly into the ground or into poorly functioning septic tanks. Especially during the rainy season, the groundwater is contaminated with high concentrations of nitrogen, phosphorus, and pathogens due to inadequate sanitation practice (Eberhardt 2006).

An alternative to disposing untreated wastewater is to reuse the wastewater and its nutrients for agriculture. This paper discusses the possibilities of wastewater treatment and reuse, particularly with the septic sludge and septic tank overflow. Proposed treatment methodology focuses on anaerobic digestion and aerobic sand filtration. Considering the economical and technical circumstances of the region, low cost solutions with low technical requirements were chosen for water and wastewater treatment. To improve the poor soil quality, the treated wastewater and solid residuals can be reused as irrigation water, soil conditioner, and fertilizer.

Involving the local people in construction work and educating future users is crucial to the success of installing a sustainable wastewater treatment system. The first step was to integrate the school staff, pupils, and residents of the surrounding areas in the planning and implementation process. Increased awareness and participation of the people ensures an understanding and acceptance of wastewater treatment applications.

METHODOLOGY

The project was divided into three phases over a 6 month period:

- Determine the appropriate solution
- Laboratory experiments
- Planning and implementation of water and wastewater treatment facilities

First, to determine an appropriate solution, available technologies were examined and a survey questionnaire was conducted. The questionnaire inquired about the technical, social, and economic aspects of the people, such as their water demand, sanitary habits, and income. At the same time, laboratory experiments were carried out, anaerobic and aerobic treatment of wastewater.

Wastewater of septic tank or 3-chamber pit latrines in Karlsruhe was used in laboratory experiments in Karlsruhe for anaerobic treatment. This kind of wastewater is comparable to the wastewater of Indonesian septic tanks, as it consists only of human waste, (black- and greywater), excluding any rainwater or industrial sewage which could inhibit the activity of biomass in the reactors. The BOD-load of the Indonesian wastewater is given by 27 g/(E ∗ d) up to 70 g/(E ∗ d) (BMBF 2005), which comply quite well with German values given by a BOD-loading of 60 g/(E ∗ d) (DIN 4261 2002). The results of these experiments were essential for the planning and implementation of water and wastewater treatment facilities. Of equal importance was considering the cultural and social attitudes of the region. Therefore the local people and local experts were greatly involved in both the design and construction process.

Anaerobic treatment of septic sludge- hydrolysis stage

Background information

Anaerobic digestion, specifically methane fermentation, is both an effective and simple method for stabilizing sludge. Optimizing process efficiency for increased biogas production, however, is complex because it relies heavily on microbial activity. Different bacterial groups are responsible for different anaerobic processes. Commonly, the major phases of fermentation are identified with three bacterial groups. First, hydrolytic bacteria convert organic matter to volatile fatty acids while producing hydrogen gas (H_2) and carbon dioxide (CO_2). Second, acidogenic and acetogenic bacteria convert organic acids to acetic acid. Finally, methanogenic bacteria convert acetate, hydrogen gas, and carbon dioxide to methane gas (CH_4) (Gavala *et al.* 2003). The overall fermentation process has a range of 30 to 60 days of retention time. Often, the process is split by the respective stages to improve efficiency, though the digestion rates of each stage vary with the biodegradability of the feedstock. For example, the acidification stage has a retention time that ranges from 10–30 days (Anderson & Bjornsson 2002; Held *et al.* 2002). Usually hydrolysis and acidification processes limit the overall reaction rate in comparison to the methanogenic stage (Yoshida *et al.* 2009).

Methods

The first experiments were performed to determine the speed of the hydrolysis reaction. The hydrolysis experiments involved six small reactors with a working volume of 1.1 litres. The reactors were closed airtight and equipped at the top with an unidirectional gas meter to record the volume of the biogas produced. The hydrolysis experiments were conducted at mesophilic temperatures (35°C) with a retention time of 1 day.

With the aid of biogas counter, the progress of hydrolysis was traced continuously. Analysis of the total solids (TS), total volatile solids (TVS), and organic acids indicates the degree of sludge stabilization. Further parameters such as ammonium, COD, N_{total} and pH-value were analysed to understand the processes within the reactors. All parameters were determined according to DEV (2008).

Also, the biogas composition shows the progress of the digestion process. As soon as methane is produced the hydrolysis stage is complete.

As explained before, samples from septic tanks were taken for these experiments. It should be noted that these samples are non-homogeneous due to different retention times of the septic tanks and the different methods of storage (one-chamber, three-chamber latrines).

Moreover, to improve the anaerobic digestion process, especially with biogas production, 10% of food waste was added to the septic sludge for co-fermentation. It was confirmed that a co-digestion of sludge with biowaste increased the yield of biogas (Fiessinger *et al.* 1996) Table 1.

Aerobic treatment of septic sludge overflows

Background information

Vertical flow bed systems, such as intermittent sand filtration, have been used with increasing frequency to treat wastewater, especially in small communities because of their simple maintenance and high quality effluents. Suspended solids and organic matter are removed by both biological degradation and physical processes such as, adsorption, filtration, and trapping. While adsorption occurs throughout the entire media bed, the biodegradation of the organic matter occurs mainly within the first 20 cm of the filter surface. This surface layer of the sand filter is considered the biologically active layer, containing much of the bacterial mass and other microorganisms.

The removal of ammonium occurs with nitrification, the two stage oxidation process of ammonium (NH_4^+) to nitrite (NO_2^-) and then of nitrite to nitrate (NO_3^-). Nitrification is a natural microbial process that occurs in soil under aerobic conditions so that plants can absorb nitrogen. Considering the mass balance of the system, the mass of nitrogen from ammonium should equal the mass of oxidized nitrogen of the produced nitrite and nitrate (accounting also for small losses) (Cooper *et al.* 1996).

Methods

Experiments involved a lab-scale vertical flow sand filter. It comprised of a perspex column, 10 cm in diameter and 100 cm in height, that was filled to 15 cm with 2/8 mm round gravel for the bottom layer. The main layer contained 50 cm of 0/2 mm lava sand, a type of sand with a high specific surface area (Figure 1).

It should be noted that the septic tanks usually had anaerobic conditions. Therefore, ammonification and COD decomposition processes had already started before the samples were collected, causing decreased organic and increased ammonium loads.

Three times per week the collection container was fed with primary sludge and wastewater inflow from the wastewater treatment plant in Berghausen, Germany. The collection container was supposed to serve as a conventional septic tank where sedimentation, anaerobic degradation and a considerable reduction of pathogens take place. Von Sperling *et al.* (2005) presented results of *E. coli* removal in polishing pond (anaerobic conditions). It was possible to produce *E. coli* concentrations lower than the WHO-guideline value of 1,000 MPN/100 ml for unrestricted irrigation (von Sperling *et al.* 2005).

After an adequate settling of solids, 1.4 L of supernatant was taken to charge the sand filter. With a filter surface area of 0.008 m^2, the hydraulic loading rate was 0.075 m/d.

In addition to measuring chemical parameters, the hydraulic conductivity was measured to examine potential

Table 1 | Composition of septic tank sludge and food waste

		COD (g/L)	Org. acids (mg/L)	NH_4-N (mg/L)	N_{tot} (mg/L)	TS (%)	TVS (%)	pH
Septic tank sludge	Max	28.9	257	153	1,002	2.9	66.9	8.1
	Min	1.1	8	92.3	142	0.2	45.4	7.7
Food waste	Average	230.8		390.8	2,457.7	17.7	89.1	3.9
Suspension*	Average	29.7	1,066.3	169.2	502.5	3.0	80.6	5.7

*Septic sludge mixed with 10% food waste.

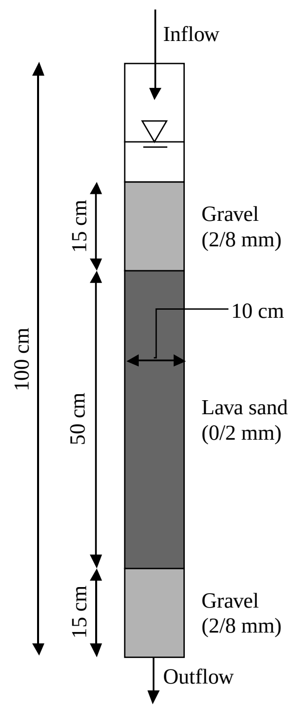

Figure 1 | Scheme of the sand filter column.

filter clogging. Hydraulic conductivity relates to the ability of liquid to flow through pore spaces, such as in soil. Clogging refers to the build up of organic matter in substratum pores. For example, in Lianfang Zhao's study of constructed wetlands in 2009, there was significant clogging in half of the wetlands after five years of operation. Results showed that organic matter accumulated within substratum pores and on the substratum surface. In effect, this produced anaerobic conditions that hindered the overall performance and efficiency of the wetland treatment process (Zhao *et al.* 2009).

The calculation of the hydraulic conductivity of an unsaturated zone is not easy. Therefore, the relative change in hydraulic conductivity Δv_f, a ratio in reference to the hydraulic conductivity of the initial flow, was calculated.

$$\Delta v_f = v_{fn}/v_{f0}[-]$$

Δv_f = Relative change of hydraulic conductivity [–]
v_{f0} = Hydraulic conductivity of the initial flow [m/s]
v_{fn} = Hydraulic conductivity of the flow n [m/s]

The entire system

The experimental findings support the development and implementation of an appropriate water and wastewater treatment system (Figure 2). The entire system comprises of two units, one for the water supply and one for wastewater treatment, which were built by the local people in two phases.

The conduits for the supply system and the drinking water treatment tanks were installed in the first phase, while the toilets and the wastewater treatment system were installed in the second phase. The system allows for the reuse of treated wastewater for irrigation and fertilization purposes (Figure 2). Utilizing the topography of the area, the entire system does not require any additional energy for pumping. Spring water containing high concentrations of fine particles and algae is collected through open water catchment. The raw water is discharged intermittently on the filtration units where organic and inorganic pollutants are removed with a high efficiency. The water is then available to supply the school and the inhabitants of Glompong, with the supply for the school as the priority. A considerable portion of the water is used with the toilets for personal hygiene and flushing.

RESULTS AND DISCUSSION

Anaerobic treatment of septic sludge- hydrolysis stage

The following Figure 3 shows the experimental results of the hydrolysis process and its gas production for three different samples. The first sample is just septic sludge, while the other two samples are mixtures of 90% septic sludge and 10% food waste. For each experiment, there was a different source of septic sludge, each ranging from 45 to 70% total volatile solids. Sludge with 45% TVS and greater is

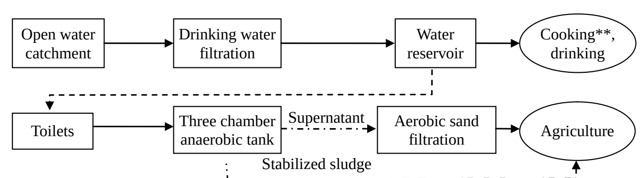

Figure 2 | Scheme of the proposed drinking water and wastewater treatment system in Glompong. **Boiling the water is usual in Indonesia as disinfection treatment.

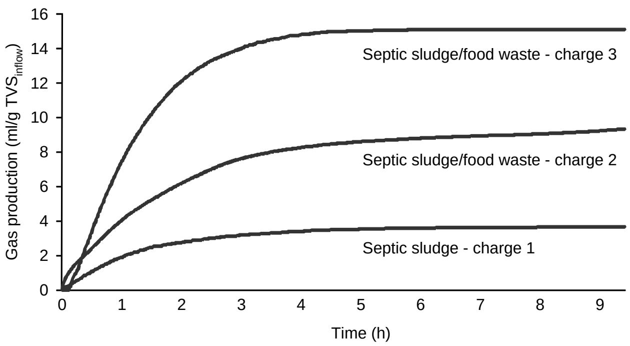

Figure 3 | Gas production during hydrolysis process of three different substrates.

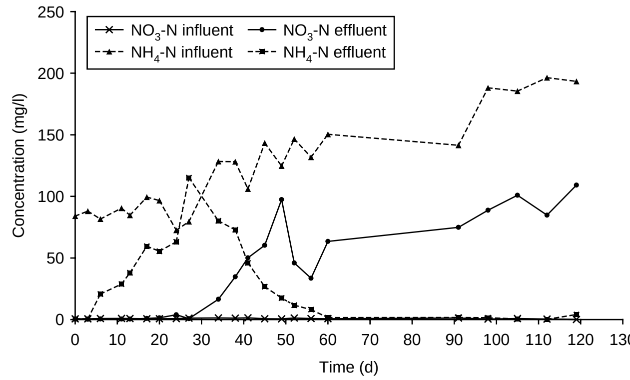

Figure 4 | Nitrification in the sand filter system.

identified as well stabilized sludge. Since each sample was divided and tested in 6 reactors with a volume of 2 litres, one curve of the figure shows the average results of the 6 reactors.

Figure 3 shows the results of 3 different charges–one curve represents the hydrolysis of the septic sludge, while the other two curves represent the co-fermentation of septic sludge and food waste. The majority of the gas production, 95%, occurs within the first 3 or 4 hours of hydrolysis step. At this point, the gas production rate has decreased significantly. After 6 hours, most of the gas production has finished. The composition of the biogas represents the progress of the fermentation process, and after 24 hours, hardly any methane gas was produced.

Thus, results show that the hydrolysis stage of anaerobic digestion finishes at least 4 hours with or without added substrates. The difference in the gas production reflects the variation of TVS of 3 charges.

Aerobic treatment of septic sludge overflows

Because of its low cost, simple operation and maintenance, and effectiveness in removing pollutants, sand filtration is an appropriate method of wastewater treatment in developing communities (Bahgat *et al.* 1999).

Figure 4 shows the nitrification process of the aerobic sand filter over a period of 120 days. Results show that the nitrification process started after day 27 indicated by increasing nitrate concentrations in the outflow. At day 27, the effluent ammonium concentration also began to decrease.

At day 60, effluent ammonium concentrations stabilized and remained between 0 and 4 mg/L for the rest of the period, signifying a steady state nitrification process. The steady increase of ammonium concentration in the influent was related to the storage conditions of the wastewater before the separation of the solids and supernatant. The storage conditions were anaerobic, causing increased ammonification.

Nevertheless, once nitrification processes reached a steady state, the ammonium concentration was consistently less than 4 mg/L. Consequently, the steady increase of inflow ammonium concentration also caused a steady increase of nitrtificants. This is evident by the increasing nitrate concentration in the outflow.

Figure 5 shows COD concentration analysis. The grey curves show the influent and effluent COD concentrations, while the black curves show the reduction of COD and the relative change in hydraulic conductivity. The maximum COD reduction was 2,300 mg/L or 58 g/(m^2 ∗ d) COD signifying a COD elimination rate of 85%. Results show that a filter run for 120 days with an average COD influent of 2,000 mg/L or 50 g/(m^2 ∗ d) did not cause filter clogging. Even in further experiments, after 250 days, no clogging was observed. Clogging was monitored by measuring the relative change of hydraulic conductivity. After the initial flow, Δv_f decreased to 0.3 due to high concentrations of organic and inorganic matter and the growth of biomass. The following values show a steady state between the death and growth of the biomass, but more importantly, it shows a relationship between the hydraulic conductivity and COD concentrations. If COD influent concentrations increase, the hydraulic conductivity decreases and vice versa. After periods without loading the sand filter, such as from day 60–90, the hydraulic conductivity increases again.

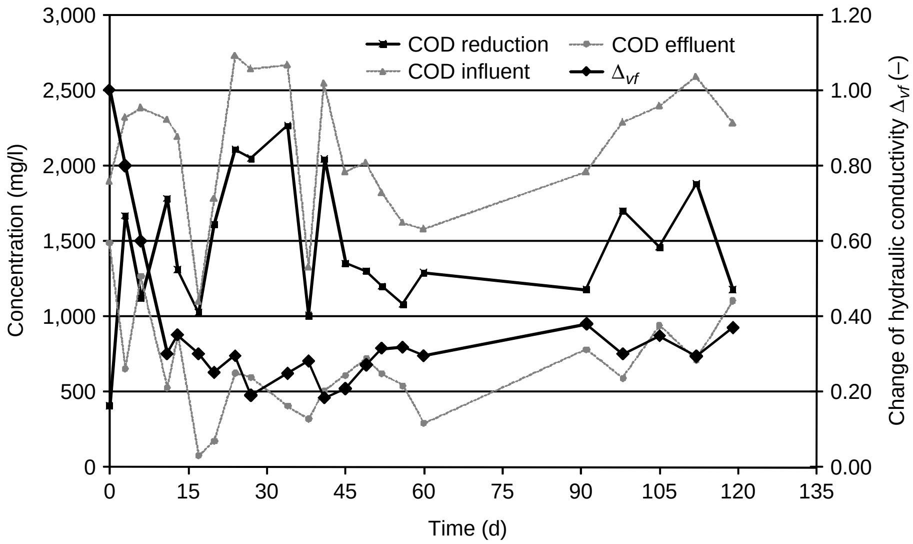

Figure 5 | Elimination in the sand filter system.

Results show that the anaerobic treatment of septic sludge older than 3 months is possible but not very effective when compared with literature (Blank 2008). This study achieved gas production between 30 and 60 ml/g TVS_{inflow} in the hydrolysis stage by co-digestion of primary sludge and food waste. The maximum gas production of the hydrolysis experiments in Karlsruhe was 15 ml/g TVS for the co-fermentation of sludge and food waste and 4 ml/g TVS for the fermentation of just sludge.

Therefore, the anaerobic treatment of septic sludge older than 3 months should be utilized only if high stabilization is needed. But high biogas production should not be expected.

If biogas production is desired, it is necessary to use "fresh" sludge for anaerobic treatment. Adding food waste to sludge increases biogas production.

Intermittent sand filtration is an appropriate solution for septic tank overflow. High removal efficiencies were achieved, including, at maximum, 99% for ammonium and 86% for COD at a hydraulic loading rate of 75 l/(m^2 ∗ day) and 140 g COD/(m^2 ∗ d). Despite the high COD loading, no clogging occurred.

CONCLUSIONS

Regarding the community's toilet water usage, a treatment system using anaerobic processes was found to be most suitable. Though experiments show small biogas production, anaerobic treatment of wastewater is necessary for stabilization, especially if reused in agriculture. Due to low gas production in the hydrolysis step, which shows a poor acidification and therefore a less biogas production (CH_4) in methanogenesis, a biogas collector was impractical and not installed. If there is excess biowaste (food waste), then it can be added to the sludge. In addition, as mentioned before, the tested storage tanks developed anaerobic conditions after long retention times, stabilizing the wastewater successfully without any mechanical stirring or heating. Thus the anaerobic treatment process comprises of an anaerobic septic tank, instead of an actual energy powered digester. This also eases the community's operational costs and requirements. Once the solids settle, it is estimated that two times per year (especially after the rainy season) it can be reused in agriculture. The lab experiments reveal that, this is possible even considering the hygienic requirements, due to reducing *E. coli* concentration in the sludge and also in the supernatant down to 10 MPN.

The second stage is to treat the septic tank overflow, the supernatant, with aerobic sand filtering. The anaerobic tank is expected to remove almost all settable solids and to reduce pathogens (<10 MPN) and organic compounds significantly. According to design parameters, the supernatant is intermittently discharged, (2 times a month), to the aerobic sand filtration unit for a further reduction of solids, pathogens, and COD (Hagendorf & Diehl 2001). The sand filter effluent then can be diluted and used as fertilizer.

Similar experiments with different conditions are currently under way. Primary goals include finding the maximum hydraulic, ammonium, and COD loads for the sand filter unit. Other goals involve optimizing the anaerobic conditions of the septic tank by varying retention time and temperature.

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