Working Paper

Integrated decentralised wastewater treatment for rural areas with focus on resource recovery

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> *"Adequately managed decentralized wastewater treatment systems can be a cost effective and long term option for meeting public health and water quality goals, particularly for small, suburban and rural areas."*
> *(US EPA 1997)*

Abstract

The most appropriate and sustainable solution for wastewater management in any setting is the one that is economically, environmentally, and technically sound, as well as socially acceptable for the specific community. Centralised wastewater collection and treatment systems are found to be resource intensive and complex, especially for low density population regions with dispersed households. Alternatively, the approach of decentralised wastewater treatment appears as a sustainable and logical solution to address issues related to rural wastewater management. This paper presents a review of the advantages and limitations of various centralised and decentralised approaches to wastewater treatment and management. A sustainable solution to wastewater management in rural areas based on the concept of ecological sanitation, with focus on water and nutrients recovery is presented. Based on extensive research and case studies, the potential of an integrated decentralised wastewater system for rural areas is examined from a technical, economic and environmental viewpoint.

Keywords: wastewater management; resource recovery, decentralised wastewater treatment; source separation; sustainability; centralised vs decentralised systems; rural areas; circular economy.

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Introduction

In spite of the continuous fast urbanisation, around half of the total global population still lives in rural areas. In the European Union (EU), around 91.4% of the settlements in Central and Eastern European (CEE) countries have inhabitants under 2000, which translates to 20 percent of the total CEE population (Bodík & Ridderstolpe 2007, p. 8). According to Eurostat (2017, p. 252), around 28.0% of EU-28 total population in 2015 lived in rural settings. Numerous regions of the world demonstrate a dominantly rural or peri-urban (settlements in the vicinity of extensive urban regions) character. 'United Nations Sustainable Development Goals' objective 6 anticipates to accomplish by 2030, access to safe and sustainable sanitation and hygiene for all, and reducing the percentage of untreated wastewater by half while considerably expanding and promoting recycling and safe reuse in developed and developing countries (UN-Water 2016). Despite the efforts to improve the wastewater treatment and management around the globe, around 4.5 billion people still lack access to safe and adequately managed sanitation services (UNICEF & WHO 2017, p. 29). According to UNESCO-WWAP (2017, p. 2), around 80 % of wastewater globally is returned to the ecosystem without proper treatment or reuse. The absence of adequate wastewater treatment is usually significantly higher in rural communities and small groups, that is, less than 10,000 Population Equivalent (PE) (WHO & UN-Water 2014).

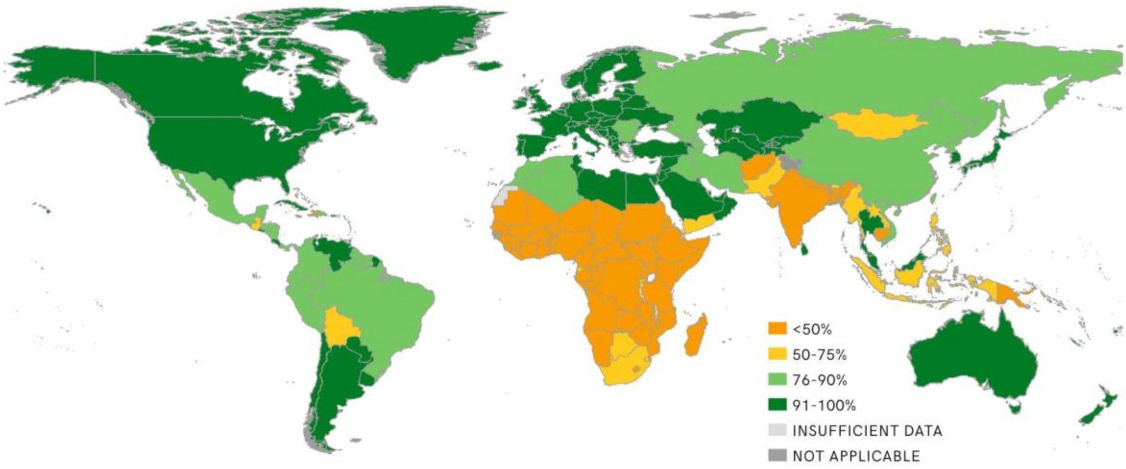

Figure 1: Proportion of national population using at least basic sanitation services (UNICEF & WHO 2017, p. 4)

The term wastewater is defined as a combination of liquid waste from domestic residences, commercial and institutional settings, industries, agriculture, farming practices, aquaculture, storm water and runoff from urban areas (eds Corcoran et al. 2010). Domestic wastewater consists of blackwater (faecal sludge, urine, flushing water and anal cleansing water or materials) and greywater (water used for washing food, dishes, clothes and wastewater from bathing and sinks). Blackwater is further divided into brownwater (mixture of faeces and flushing water, with or without anal cleansing water or materials) and yellowwater (Urine diluted with flushing water) (Tilley et al. 2014). Domestic wastewater approximately contains 99.9 % water and only 0.1 % is a mixture of dissolved and suspended solids, organic and inorganic compounds, pathogens and other microorganisms and nutrients, including phosphorus and nitrogen (Sperling 2007, p. 28). According to Sperling (2007, p. 57) domestic sewage wastewater composition can range from 250 - 400 mg of Biological Oxygen Demand (BOD), 500 - 900 mg of Total Dissolved Solids (TDS), 200 - 450 mg of Total Suspended Solids (TSS), 35 - 60 mg of nitrogen, and 4-15 mg of phosphorus per litre.

In rural communities, sanitation practices involve serious health, economic and social issues, that highlight the dire need to develop technologies which suit the local realities and are at the same time cost effective, more efficient and easy to maintain (Kadlec & Knight, Philippi & Sezerino, cited in Lutterbeck et al. 2017). Rural communities mainly depend on on-site wastewater treatment systems with little or no access to public sewers (Wu et al. 2011). Several options exist for on-site wastewater treatment technologies including septic tanks, lagoons, drain-field systems, aerobic biological treatment units, constructed wetlands (CW) and membrane biological reactors (MBR) (Nakajima, Fujimura & Inamori 1999). These advanced decentralised treatment systems make sustainable sanitation and safe water reuse applications possible, if not yet widely practised (Rodale Institute 2013).

The affordability and appropriateness of the technology plays a major role in the selection of the most suitable decentralised wastewater treatment system for a given community (Wu et al. 2011). In any situation, the most appropriate solution for wastewater management is the one that is economically, environmentally and technically sound, and socially acceptable for the community (Capodaglio 2017). To accomplish the goals of adequate wastewater treatment and sanitation, the community should evaluate all the treatment options available. This requires a lot of diligence for the community and reliable information from outside sources. Eco-innovation can be the solution to improving the sustainability of wastewater systems by reducing their environmental impact and by making them economically, environmentally and socially efficient (Capodaglio 2017).

Decentralised Wastewater Treatment vs Centralised Wastewater Treatment

In wastewater treatment science, the division centralisation-decentralisation is nowadays the focus of discussion and is a subject undergoing intense research. This global discussion has highlighted various economic, technological, environmental and social barriers in the centralisation/decentralisation division, making it difficult to prioritise one over the other, subsequently necessitating to consider the particular conditions of the site and settling on a case-by-case premise. Rural communities in the developing and the developed world also face the same question, that is, to prefer centralised or decentralised systems for effective wastewater management (Libralato, Volpi Ghirardini & Avezzù 2012).

Centralised Wastewater Treatment Systems

A centralised wastewater treatment system appears as a more feasible solution for densely populated regions, already connected to the sewerage collection and transport system (Hophmayer-Tokich 2006; Libralato, Volpi Ghirardini & Avezzù 2012). Around 80 - 90 % of the capital costs of centralised systems are subjected to the collection system (Bakir 2001, p. 325). In this way, the cost of the overall sewage system in centralised systems can be distributed over a large population (Jones et al. 2001). A centralised system is characterised by the collection and treatment of wastewater by a combination of centralised sewerage and a centralised treatment plant, treating the wastewater and disposing it under controlled conditions. These systems, by definition, serve large and densely populated areas with multiple dwellings and households. They require a certain inertia in finances, technical issues, organisational matters and system operations. One of the major advantages of centralised wastewater systems is uniformity, fulfilling the water demand, while meeting quality standards for a large area (Capodaglio 2017).

Decentralised Wastewater Treatment Systems

Decentralised wastewater management systems are designed for a relatively low volumetric flow of wastewater from houses or dwellings that are located comparatively close to each other (less than 3 – 5 km), and are not connected to a central sewer system and a centralised wastewater treatment plant (WWTP). Decentralised wastewater treatment systems when properly designed, constructed, maintained and operated are found to be cost competitive with centralised wastewater treatment systems, taking into consideration the costs associated with the sewerage collection system (Ho & Anda 2004; Tchobanoglous 2002). Decentralisation provides a solution based on a holistic approach, it reaps additional benefits by reducing the wastewater volume at source, thereby reducing the treatment costs and increasing the recycling or reuse of the resources in the wastewater. Local reuse of the components recovered from wastewater can help close the loops, therefore supporting the basic principles of circular economy[1] (Capodaglio 2017).

According to Orth (2007), decentralised systems mainly fall into three categories. (1) Simple sanitation systems minimising the sanitary issues through retention of faecal matter and discharge of the effluent (for example pit latrines, septic tanks and pour-flush toilets). (2) Small scale mechanical-biological treatment plants offering a natural-like treatment (for example septic tanks, constructed wetlands and lagoons). (3) Recycling systems maximising the potential of resource reuse and recycling (such as ecological sanitation). Different types of wastewater treatment systems ranging from a conventional large scale centralised system to an extremely local and individualistic decentralised treatment system are shown in figure 2 (Libralato, Volpi Ghirardini & Avezzù 2012).

Decentralised wastewater systems have several advantages over centralised wastewater systems and can be summarised in terms of cost efficiency (capital and operational costs), potential for resource recycling, improved water quality and availability, efficient land and energy usage, growth responsive and increased stakeholder involvement.

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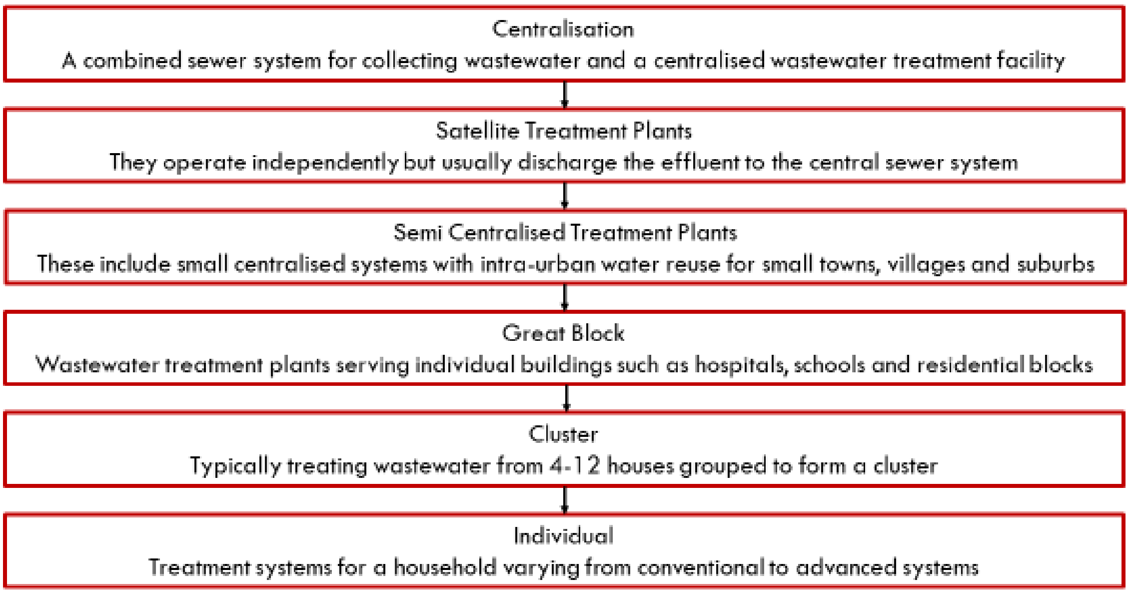
[1] “A circular economy describes an economic system that is based on business models which replace the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations.” (Kirchherr, Reike and Hekkert (2017).



Centralisation
A combined sewer system for collecting wastewater and a centralised wastewater treatment facility

Satellite Treatment Plants
They operate independently but usually discharge the effluent to the central sewer system

Semi Centralised Treatment Plants
These include small centralised systems with intra-urban water reuse for small towns, villages and suburbs

Great Block
Wastewater treatment plants serving individual buildings such as hospitals, schools and residential blocks

Cluster
Typically treating wastewater from 4-12 houses grouped to form a cluster

Individual
Treatment systems for a household varying from conventional to advanced systems

Figure 2: Different types of wastewater treatment systems based on Libralato, Volpi Ghirardini & Avezzù (2012)

As discussed by Brown, Jackson & Khalifé (2010), decentralised systems have the advantage of flexibility and can be built just in time to meet local demands. By taking advantage of state of the art cost effective technology, decentralised systems usually involve a small initial investment for a community, compared to large scale centralised systems. Decentralised systems can allow communities to delay or avoid costly infrastructure capacity upgrades involved in larger systems. A sustainable and financially sound solution for wastewater management in rural settings could be switching from conventional systems to local cluster-based on-site treatment systems (eds Novotny & Brown 2007).

According to Maurer, Rothenberger & Larsen (2005), after every 50 - 60 years, a centralised collection system or some parts of it require complete renovation, apart from mandatory periodic maintenance, therefore leading to increased maintenance costs and causing disruptions to public utilities. The operation and maintenance cost per unit of treated organic load associated with a decentralised system is becoming comparable to that of a centralised system (Fane & Fane 2005). Decentralised systems incorporate small and relatively simple technologies that are simple and cost effective. The experts and finances required to operate, maintain and replace the system is usually low. Additionally, decentralised systems treat wastewater close to the source and generally include passive treatment, such as soil dispersal, leading to considerable savings in energy costs (US EPA 2015).

According to Capodaglio (2017), decentralised wastewater treatment plants focused on on-site treatment can lead to higher environmental sustainability by facilitating the reuse of treated wastewater for various purposes, as well as resource recovery. Decentralised systems can lead to the reduction of the negative environmental effects, while prioritising public health and increasing the ultimate reuse and recycle of valuable resources in wastewater, depending on the technical options, community type and local settings (Ibrahim & Ali 2016). Decentralised systems can be designed to separate the contaminants at source, facilitating the treatment and potential resource reuse and energy savings (Brown, Jackson & Khalifé 2010; Tchobanoglous & Burton 1991).

Decentralised wastewater systems efficiently and effectively treat domestic sewage and protect local water quality and local water supplies. The wastewater, after being treated by decentralised systems, recharges the groundwater, as it seeps into the underlying ground, therefore benefitting the local watershed (US EPA 2015). Modern decentralised treatment systems have been proven to achieve the same level of reliable treatment as other conventional wastewater treatment alternatives, while being financially and technically sustainable (Ghimpusan et al. 2016). Capodaglio (2017) argues that centralised systems are more prone to destruction by natural disasters, whereas decentralised systems appear as a more resilient option for wastewater management with lower vulnerability to climate-induced extreme events, power outages, and sabotage episodes.

Decentralised systems also utilise the land efficiently and minimise the issues related to local site conditions. They are carefully designed for a specific community, taking into consideration the local soil and land properties, therefore avoiding the problems with groundwater tables, bedrock formations and soil infiltration rate (Massoud, Tarhini & Nasr 2009). Decentralised systems also take advantage of gravity flow rather than using energy to pump the wastewater, leading to reduced energy consumption (Jones et al. 2001).

Decentralised systems offer more flexibility and can handle the problems associated with suburban areas and rural centres (re)development and population growth more effectively (Wilderer and Schreff, Tchobanoglous, Tchobanoglous et al, Ho and Anda, Ho, Lamichhane, Weber et al, Brown et al, cited in Libralato, Volpi Ghirardini & Avezzù 2012). They can be designed to meet specific growth goals, considering the expected growth pattern of the community. They tend to have small environmental footprints and can provide opportunities to build green spaces in the region (US EPA 2015).

According to a report published by US EPA (2015), decentralised systems could lead to greater economic opportunity for local stakeholders such as installers, inspectors and designers. Local experts and engineers, with better understanding of the culture and values, can effectively help in designing an efficient wastewater treatment system. Decentralised management of wastewater can lead to greater stakeholder involvement, as they provide more opportunities for awareness, involvement and participation of local users than centralised systems, which leads to increased acceptance of their objectives and advantages (Capodaglio 2017).

Considering the advantages of decentralised wastewater treatments, the decentralisation approach constitutes as a sensible and sustainable way to address the wastewater issues in sparsely located and low income regions (Capodaglio 2017).

Rural Decentralised Wastewater Treatment Technologies

In decentralised wastewater treatment, there are numerous approaches for the collection, treatment and dispersal/reuse of wastewater for clusters of homes or businesses, individual dwellings and entire communities. Treatment options range from simple on site or septic systems, providing passive treatment with the effluent being dispersed to the soil, to complex systems utilising mechanical or biological processes with high treatment efficiency, dispersing the treated effluent to the soil or to water bodies (US EPA 2015). They usually treat the wastewater near the point where the wastewater is generated (Massoud, Tarhini & Nasr 2009). The typical systems are discussed in the following section.

Primary Wastewater Treatment Systems

Primary treatment methods are inexpensive and simple to operate and maintain but the efficiency of the system to remove phosphorus and nitrate compounds and pathogenic organisms is generally low (Massoud, Tarhini & Nasr 2009). These systems can be used prior to further treatment and disposal. Based on the literature review, the advantages and limitations of primary treatment methods are summarised in Table 1.

Table 1: Advantages and limitations of primary treatment methods (Joubert et al. 2005; Washington State Department of Health 2004; Wendland et al. 2007; Zhang 2012)

Primary Treatment Methods	**Advantages**	**Limitations**
Septic Tank	- Simple in design - Cost effective - Low maintenance - Low energy requirements - Removes most of the settleable solids	- Removes only 30-35 % of BOD and 25-35% Chemical Oxygen Demand (COD) (Sperling 2007, p. 221) - Not considered a nitrogen reducing treatment option - Odour problems if not properly maintained - Pre-treatment required
Cesspools	- Simple in design - Low maintenance and capital costs - Energy independent systems	- High risk to water quality and public health - Discharge of untreated water to the subsurface - Requires periodic replacements and upgrades
Holding Tanks	- Flexible operation - Temporary solution for difficult sites	- Energy intensive because of periodic pumping - Not a permanent solution - No treatment provided
Ecological Sanitation	- Cost effective - Suitable for low income regions - Low maintenance - Low energy requirement - Resource recovery and reuse	- May require a lifestyle adjustment - Odour problems if not properly maintained

The most typical primary treatment methods are discussed as follows.

Septic Tanks

The conventional septic tank constitutes a simple, cost effective and low maintenance treatment option for areas with low population density and favourable soils. The treatment system consists of a septic tank followed by a drain field, alternatively known as a leach field. The wastewater from the house enters the septic tank where it is anaerobically degraded, the solid fraction is retained, while the liquid fraction exits the tank by means of an outlet pipe (Joubert et al. 2005).

Cesspools

Cesspools are old fashioned systems that retain the solid portion of the wastewater in the interior, while the liquid fraction seeps into the surrounding soil. Cesspools typically comprise of a covered pit with walls made of loose, dry fitted rock with a concrete or steel leaking chamber. The use of cesspools can lead to deterioration of the local water quality and hazards to public health because of the possible discharge of untreated and hazardous wastewater to the surrounding soil and the nearby waterbodies (Joubert et al. 2005).

Holding Tanks

As a last resort, a holding tank, alternatively known as a tight tank, can be used if allowed by local bodies on extremely difficult sites. It is similar to a septic tank but without an outlet to a drain field, which has to be regularly pumped or drained when full. Usually regulatory programs prohibit the use of holding tanks; they may be only used as a brief arrangement while a repair for a site is finished, or as a standalone treatment system for complex sites where advanced systems are to a great degree impractical or unfeasible (Joubert et al. 2005).

Ecological Sanitation

Ecological sanitation is based on the concept of source separation of domestic wastewater streams into grey, brown and yellow water, with appropriate treatment of each stream in decentralised systems to facilitate the reuse of water and recycling of nutrients (Wendland et al. 2007). The greywater component, comprising mainly of water from sinks, showers, kitchen and washing machines, corresponds to nearly 65 % of total domestic wastewater (Tilley et al. 2014, p. 11). Having a very low concentration of pathogens, it can be effectively treated via systems such as constructed wetlands and then reused as a valuable water resource for non-potable purposes (Behrendt et al. 2006). Brownwater is rich in organic material as well as nutrients like nitrogen, phosphorus and potassium; and it can be applied on the field for non-food crops to enhance soil fertility. Before applying it to the soil, it has to be treated to assure sanitisation by processes such as vermicomposting (Bettendorf, Stoeckl & Otterpohl 2014). The yellowwater component is rich in nutrients necessary for plant growth and can be used as a direct fertiliser supporting non-food crop production; moreover, it can replace the need for additional treatment steps required to remove phosphorus from wastewater in conventional wastewater treatment systems (WHO 2006).

Primary treatment options do not constitute a standalone option for adequate wastewater treatment. They must be integrated with other treatment options to ensure the effective removal of harmful and hazardous substances present in the wastewater. The choice of the best primary treatment option is however subjective to the given site conditions and resources available.

Secondary Wastewater Treatment Systems

Various secondary treatment methods exist for decentralised wastewater treatment, having numerous advantages and limitations. Integrated decentralised treatment systems are different from conventional systems in the way that an additional treatment unit further treats the wastewater from primary treatment units, before it is finally discharged to the drain field; the additional treatment step enables the system to achieve high and consistent efficiency (Joubert et al. 2005). Based on the literature review, the advantages and limitations of the secondary treatment methods are summarised in table 2.

Table 2: Advantages and limitations of secondary treatment options (Capodaglio 2017; Joubert et al. 2005; Parkinson & Tayler 2003; Wendland & Albold 2010)

Secondary Treatment Options	**Advantages**	**Limitations**
Waste Stabilisation Ponds	- Removal of more than 75 % COD (Wendland & Albold 2010, p. 13) - Low capital costs and simple operation - Energy is required only for pumping - Simple operation and maintenance - No electromechanical machinery - Partial removal of nutrients	- High evaporation rate - Quality of discharge varies according to season - Space demand can be very high - Predictable nuisances may include odours, insects, and pests
Media Filters	- Single pass filters are efficient in pathogen removal while recirculating media filters can also lead to nitrogen reduction - Removal of >75 % COD (Wendland & Albold 2010, p. 13) - High quality effluent especially for BOD and TSS - No chemicals required	- High installation and operational costs - High energy consumption - High costs associated with filter media - Efficiency may be reduced over time
Membrane Biological Reactors	- Effective in removal of organic matter; some types of micro pollutants and nutrients if operated properly - Medium operational costs per unit	- High energy demand - High capital and construction costs - Complex systems - Skilled labour required

Secondary Treatment Options	**Advantages**	**Limitations**
	of organic pollutant removed - The treated water meets the requirements for water to be reused for non-drinking purposes - Low space requirement	- Nuisances including odours, noise pollution, and traffic problems - Extremely high cost of aeration and filter media
Anaerobic Digestion	- Effective in removing organic matter - Low energy demand - Effluent and excess sludge high in nutrients - Energy recovery as biogas - Low costs associated with physical infrastructure - Personnel do not need complex skilled training	- Little disinfection performed - Effluent usually needs post-processing - Nuisances including odours, noise pollution, and traffic problems
Constructed Wetlands	- Effective removal of organic matter and to some extent, nutrients - Integration with existing ecosystems is possible and feasible - Returns water to the natural cycle - Nutrients are recycled into biomass - Very low energy requirements and emissions - Cost effective and robust - Simple to construct and operate	- Possible water losses due to high evaporation in arid countries - Requirement to remove and dispose biomass periodically - Nuisances including odours, insects, and pests - Main limitation is the surface area needed for construction
Terra Preta Sanitation (TPS)	- Conversion of organic waste and faeces or excreta into highly fertile black soil - Allows carbon sequestration - Stable process - High pathogen reduction - Cost effective - Nutrients are recycled as fertilisers - Soil enhancement	- May require a life style adjustment - Odour problems if not properly maintained - Requires input of charcoal, lactic acid bacteria, woodchips and external carbon source if only faeces or excreta are treated (e.g. kitchen waste or molasses)

The typical secondary treatment options are discussed as follows.

Waste Stabilisation Ponds

Waste stabilisation ponds include simple systems such as aerobic, anaerobic and facultative ponds that combine aerobic and anaerobic processes. The major advantages of waste stabilisation ponds are their simplicity and a long retention time, constituting an effective treatment option for the reduction of pathogen levels. Additional economic benefits can be reaped as they provide a good environment in ponds to support aquatic life such as tilapia fish. A high algae concentration in the effluent from ponds makes it suitable for irrigation purposes. One of the major limitations of waste stabilisation ponds is their large land area requirements (Parkinson & Tayler 2003).

Media Filters

Media filters are composed of a lined or watertight structure containing media. They utilise different physical and biological processes to degrade the wastewater and remove the contaminants. The effluent from a septic tank is pumped and introduced from the top of the filter over the media surface. The media containing bacteria and other microorganisms provides the surface area and the required detention time for the wastewater to be degraded (Joubert et al. 2005).

The most conventional type of media filter bed is a single pass sand filter, it has been known for long as the industry standard. Single pass sand filters effectively remove the pathogens from the wastewater, but they are not considered a nitrogen reduction option. While in recirculating filters, the effluent from the media is recirculated between the tank and the filter several times before finally discharging it to the nearby drain field. In recent years, non-absorbent granular media such as sand has been replaced by alternative media like peat and textile to achieve a more efficient wastewater treatment (Joubert et al. 2005).

Membrane Biological Reactors

Membrane biological reactors involve biological degradation of wastewater by membrane filtration. MBRs are extremely efficient for domestic or industrial wastewater treatment, as they can effectively remove organic and inorganic particles and biological material from the wastewater (eds Judd & Judd 2011). When properly maintained and operated, MBRs can remove nutrients and to a certain extent also micro pollutants (Capodaglio 2017). Some of the limitations of MBRs include high installation costs of the membranes and the physical structure, high maintenance costs due to frequent fouling of membranes and high energy requirements (eds Judd & Judd 2011).

Anaerobic Digestion

Anaerobic digestion is regarded as an effective and feasible option to treat the blackwater originating from household latrines (Parkinson & Tayler 2003). As compared to aerobic systems, these compact systems produce a well stabilised sludge in smaller quantities (Parkinson & Tayler 2003). The systems convert the organic matter into biogas (about 40 - 70 % Methane), which can serve as a sustainable substitute for energy sources such as firewood (Behrendt et al. 2006, p. 7). The slurry, containing plant nutrients such as nitrogen, phosphorus and potassium, can be either used as liquid fertiliser or separated into a solid and liquid part with further composting of the solid fraction. Anaerobic digesters, if properly operated, can remove up to 85 - 90 % of the organic load (Parkinson & Tayler 2003, p. 83). According to the study by deGraaff et al. (2010a, p. 108) anaerobic digestion treatment systems, such as up-flow anaerobic sludge blanket (UASB) reactor, with proper setup, can reach an average COD removal of 74 % for a wastewater having a COD concentration as high as 9800 mg/l.

Constructed Wetlands

Constructed wetlands have been proven as a cost effective method for rural wastewater treatment (Garfí, Flores & Ferrer 2017). CWs are a modified version of natural wetland systems, they include a planted soil filter through which the wastewater flows and is treated through physical processes such as adsorption and biological processes taking place in the biofilm and physical filter. CWs provide efficient removal of organic solids i.e. more than 80% COD removal and pathogenic microorganisms, however the phosphorus and nitrogen removal is limited (Wendland & Albold 2010, p. 20). To improve the biological activity and to enhance the efficiency of the process, the soil filter is planted with plants such as reed (Behrendt et al. 2006). One of the limitations of CWs is unit area land requirements, ranging from about 2 m^2/PE in warm climates to 12 m^2/PE in cold climates (Capodaglio 2017, p. 5).

Terra Preta Sanitation

Terra Preta Sanitation is an efficient and cost effective bio-waste/sanitation system based on an ancient Amazonian sanitation practice (Factura et al. 2010). It is an integrated wastewater management concept, which focuses on resource recovery, therefore offering a sustainable solution to major environmental challenges such as poor sanitation, soil depletion and food insecurity (Prabhu et al. 2014). The concept involves conversion of excreta and bio-waste to a highly fertile black soil through lactic acid fermentation (LAF), addition of charcoal and woodchips followed by composting. LAF facilitates the sanitisation and suppression of odour, while the addition of charcoal and woodchips makes the mixture dry enough to be suitable for composting. Subsequent composting techniques such as vermicomposting and thermophilic composting further sanitise the substrate, resulting in nutrient rich humus (ed. DBU 2015; Factura et al. 2010). The final product can be utilised as a fertiliser for non-food crops in forestry or agriculture (Prabhu et al. 2014). Depending on the available resources, faeces and urine can be either collected separately or combined in the TPS system. In regions where non-flush toilet based sanitation systems are acceptable, urine diverting dry toilets can reap additional benefits for TPS systems, including reduced input of dry material for odour control (ed. DBU 2015). According to Gisi, Petta & Wendland (2014), TPS systems can exist as dry systems (without flush water) and systems with flush water (low-flush). TPS can be integrated into existing toilets by adapting to low-flush toilets, thus reducing the amount of water and volume to be treated. With proper hygiene measures, pit latrines with liner and a cover to facilitate anaerobic fermentation, can also be adapted to the TPS system (ed. DBU 2015). Dry TPS systems are recommended as it makes it easier to handle the mixture and dehydrate the faeces. However, there exists several projects and research applying TPS with low-flush toilets, acknowledging the use of flush toilets as a standard in most of the regions worldwide (Gisi, Petta & Wendland 2014).

Several secondary treatment options exist with varying treatment efficiencies, resource requirements, advantages and limitations. The appropriateness and effectiveness of each technology however depends on the wastewater input, available financial and technical resources and their desired use.

Disposal Methods

The various disposal methods further improve the quality of the wastewater collected from secondary treatment before finally disposing it. Disposal methods can be simple including evaporation and evapotranspiration, surface water discharge or subsurface discharge. With proper setup and site conditions, the usually preferred method for a single household to dispose wastewater is subsurface soil absorption, because of numerous advantages such as simplicity, cost effectiveness and stability (Massoud, Tarhini & Nasr 2009). The most common types of subsurface soil absorption systems are discussed as follows.

Traditional Leach Field Systems

The traditional leach field systems are a preferred choice for sites with low water table and where the land is not readily available (Massoud, Tarhini & Nasr 2009). Land treatment systems utilise the plant-soil-water matrix to further enhance the degree of treatment (Crites & Tchobanoglous 1998). The pollutant removal efficiency of these systems is high and one major advantage is that the nutrients are recycled back to the soil (Massoud, Tarhini & Nasr 2009). For areas with impermeable and heavy clay soils, traditional leach field systems are likely to fail, and treatment provided in areas with higher water tables and soils having high permeability is inadequate (Wu et al. 2011).

Raised, Mounded Fill Systems

Fill systems are a modified version of traditional leach field systems and are a replacement for sites where water tables are very high. Gravel sand fill is used to raise the leach above the water table in order to increase the separation distance (Joubert et al. 2005). In mounds, the sandy fill material being used as filler is specified and analysed through sieve analysis. The specified material in the mounds improves the treatment efficiency and is recommended for sites with high infiltration, high water table, porous or creviced bedrock (New York State Department of Health 2012).

There are various treatment options with specific advantages and disadvantages, but there exists no single recommended treatment technology that meets the specific conditions and treatment objectives of every community. However, for a given rural area, the ecological sanitation concept involving source separation of wastewater streams, combined with appropriate decentralised treatment of wastewater streams appears as a sustainable and cost effective technology for wastewater management.

Integrated Decentralised Wastewater System for Rural Communities

The affordability and appropriateness of the treatment system are the main issues to consider in the selection of the most suitable wastewater system for a given community (Grau 1996). In areas with low population density, decentralised systems provide cost effective treatment of wastewater (Parkinson & Tayler 2003). Decentralisation, with effective localised governance, is progressively perceived as a possibly successful route to ensure availability of clean water and safe sanitation to the world's population, while providing increased opportunities for resource recovery and reuse of wastewater for various purposes (Bieker, Cornel & Wagner, IDRC, Larsen & Maurer, cited in (Libralato, Volpi Ghirardini & Avezzù 2012).

Design of Integrated Decentralised Systems

The recommended system is to utilise complex biological principles and natural processes to provide efficient yet cost effective wastewater treatment, it should be based on a simple design, flexible in treatment capacity, easy to construct, maintain and operate, socially acceptable and pleasing to the eye (Rodale Institute 2013). As shown in Figure 3, the recommended integrated decentralised system is based on the concept of ecological sanitation, involving separation of brown, grey and yellow water through source control schemes and incorporates both traditional and alternative systems in a multi-step process. It focuses on the extraction of nutrients from brown and yellow water and reuse of greywater for non-potable purposes. It includes a combination of septic tank and a constructed wetland for the greywater treatment with the effluent being applied to the fields. Depending on the specific use, dry or low flush toilets, with or without urine diversion, are used for faeces, brownwater or blackwater to be converted into highly fertile black soil, and application of sanitised urine as a soil enhancer. Any effluent from the CWs or the urine sanitisation chamber that is not utilised can be finally disposed by subsurface drip infiltration. The integrated system is discussed in detail in the following sections.

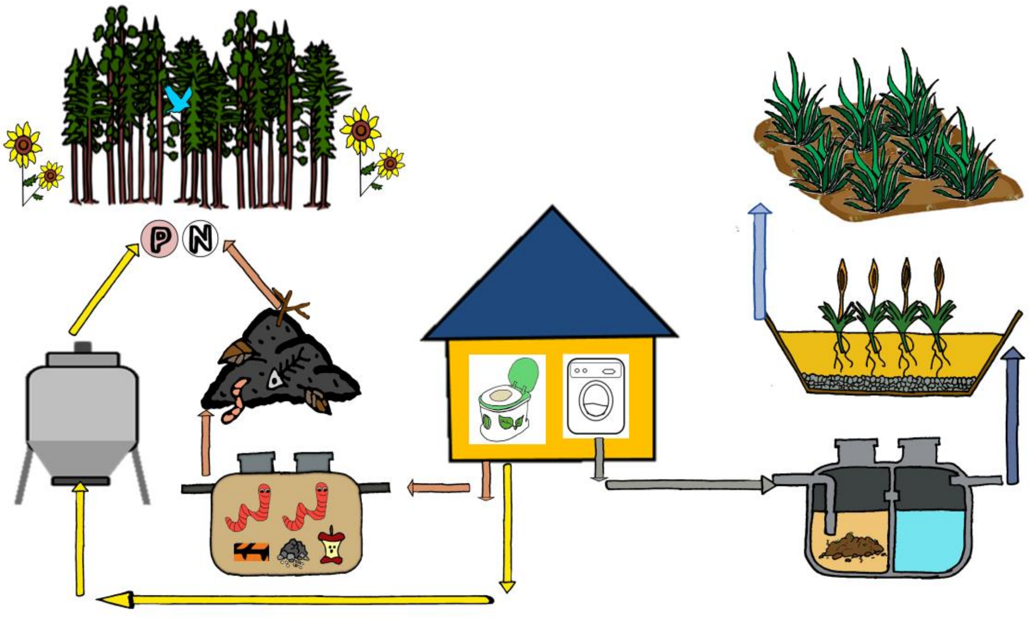


Figure 3: Recommended integrated decentralised rural wastewater treatment system

Ecological Sanitation

As suggested by Kjerstadius, Haghighatafshar & Davidsson (2015), effective handling of domestic and municipal waste could be enhanced through the introduction of source control wastewater systems to separate the different streams of grey, brown and yellow water, with focus on resource recovery. Greywater contains some traces of excreta and pathogens, while the concentration of nutrients and pathogens in brown and yellow water is significantly high (Tilley et al. 2014). Brown and yellow water contain a high percentage of nutrients, generally phosphorus and nitrogen, with a higher concentration of organic matter in relatively less volume, therefore making it more preferable for nutrient recovery (ed. DBU 2015). Urine diversion and water saving measures such as low flush toilets and dry toilets can concentrate the nutrients in the wastewater streams, making the decentralised systems more efficient and cost effective (Behrendt et al. 2006). With integrated application of source separation, non-conventional conveyance options and extremely low flush devices, COD values could increase more than tenfold, up to 10–15 g/l (Capodaglio 2017, p. 13).

Treatment of Grey, Brown and Yellow Wastewater

The most commonly used decentralised system for primary treatment of wastewater is a simple septic tank (Massoud, Tarhini & Nasr 2009). The removal efficiency of septic tanks ranges from 30-35 % of BOD, 25-35% of COD and 55-65% of SS (Sperling 2007, p. 221). Septic systems only allow a partial treatment; they do not offer much with local water reuse and resource recovery. However, it can be modified and integrated with other systems to treat the wastewater more efficiently and adequately (Massoud, Tarhini & Nasr 2009).

The separately collected, less concentrated greywater, after on-site treatment, could be used as an alternative water source (Bakir 2001). It is first treated in a septic tank to remove most of the settleable solids; after which the effluent can be effectively treated in a small horizontal flow constructed wetland. According to Rodale Institute (2013, p. 12), with proper setup and operation, CWs can remove 40-80 % of the influent nitrogen content and 99.0-99.9 % of faecal coliforms, pathogens and viruses present in the wastewater. Moreover, the operating energy cost of a wetland is only $0 (Rodale Institute 2013, p. 12). The effluent from the CW can then be reused for non-food irrigation purposes; however, more research is required to evaluate the appropriateness of the effluent use in irrigation (Barbagallo et al. 2014).

According to Tilley et al. (2014, p. 11, p. 142), although the nutrients in the excreta vary according to diet, gender, age, region, etc., faeces contain roughly 12% nitrogen, 39% phosphorus and 26% potassium, while urine contains 88% nitrogen, 61% phosphorus and 74% potassium of the total nutrients excreted. The urine fraction contains the highest percentage of nutrients including potassium, nitrogen and phosphorus, while faeces contain a higher percentage of organic matter (Rose et al. 2015). Due to less dilution that occurs in decentralised systems, the nutrients in the brown and grey water can be easily and more efficiently recovered and reused. According to Prabhu et al. (2014) TPS provides a great potential for soil enrichment and nutrient recovery from household wastewater. Concentrated faeces from dry or low flush toilets treated via LAF, with addition of kitchen waste as a low cost sugar supplement, charcoal and woodchips, followed by vermicomposting or thermophilic composting, results into highly fertile black soil, which can be applied as a fertiliser for agroforestry (ed. DBU 2015). The TPS process results in the stabilisation of waste through the reduction in biological activity, reduction in pathogens, reduction in odour, reduction in total dry matter content and improvement of fertilisation value (Factura et al. 2010). Source separated nutrient-rich yellowwater can be applied to the soil as fertiliser for agroforestry, providing the opportunity to recover the nutrients and reduce the use of chemical fertilisers (ed. DBU 2015). Health risks linked with use of urine as fertiliser for non-food crop production are very low, provided that no contact takes place with the faeces, however it should be stored anaerobically in containers made of resistant material, e.g. plastic or high quality concrete to avoid ammonia emissions (Jönsson et al. 2004). Vinnerås et al. (2008, p. 4067), recommends that the urine can be sanitised by anaerobically storing it for 6 months at 20°C or higher if any cross contamination takes place.

Effluent Disposal

For effluent disposal, with appropriate site, soil and groundwater conditions subsurface wastewater drip infiltration systems may prove out to be the best option (Massoud, Tarhini & Nasr 2009). The complex ecology of upper layers of local soil provides a natural system to effectively remove, isolate and transform the nutrients, compounds and pathogens that are harmful to the water bodies. Soil systems can effectively transform, sequester or remove compounds such as ammonia, nitrogen and phosphorus compounds, pesticides, suspended and dissolved matter, carbonaceous compounds, heavy metals, medications, cosmetics and pathogens such as faecal coliforms and viruses. The disposal of the remaining effluent from CWs and the urine sanitisation chamber to the soil system further improves the water quality (Rodale Institute 2013).

Sustainability of Integrated System

The three phases of wastewater management: collection, treatment and disposal can have huge implications on the environment as well as the economy, at local and global scales. Sustainability of wastewater treatment technology is the measure of the system's ability to be environmentally sound, economically affordable and socially acceptable (Capodaglio 2017). To assess the sustainability of the recommended integrated system, sustainability criteria as shown in figure 4 should be considered.

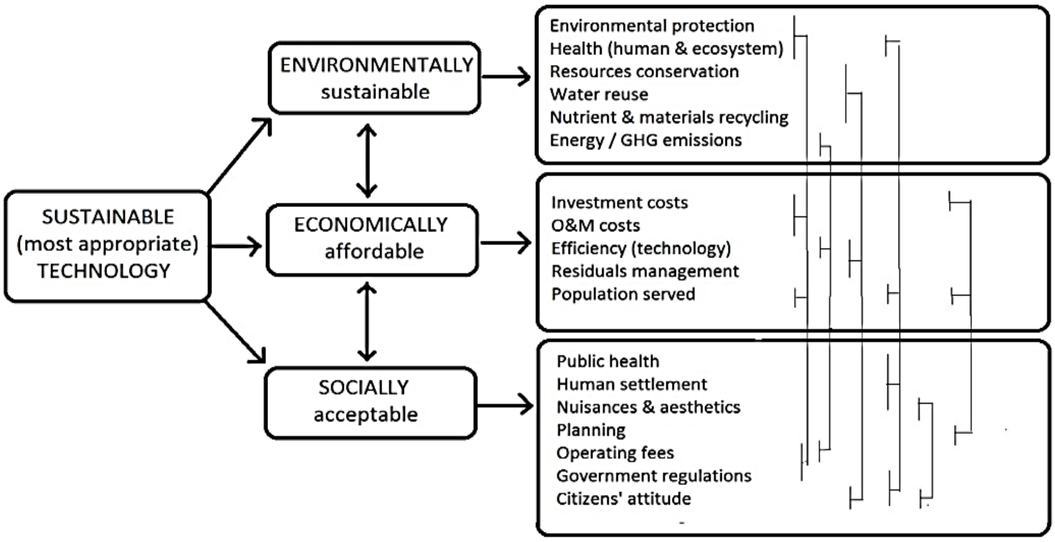


Figure 4: Integrated system sustainability criteria (Capodaglio 2017)

The integrated decentralised system with source separation provides the opportunity for energy savings and resource recycling. The potential of the system is discussed as follows.

Potential for Energy Savings

The recommended integrated decentralised system provides great potential for energy savings. Tervahauta et al. (2013) conducted a study in Dutch conditions to evaluate the primary energy consumption of centralised and decentralised systems, with and without source separation of wastewater streams. Their observation concluded that centralised sanitation systems consume the most primary energy with 914 MJ/a per person. Source separation of blackwater and greywater along with kitchen waste in a decentralised system can result in a reduced energy consumption of 767 MJ/a per person and 522 MJ/a per person by including the indirect energy gains from water savings, reuse and nutrient recovery. Source separation of urine, faeces and greywater along with kitchen waste in a decentralised system with gravity based toilets can result in the reduced energy consumption of 567 MJ/a per person, which is further reduced to 208 MJ/a per person by including the indirect energy gains (Tervahauta et al. 2013, p. 1023).

Potential for Water Savings

Conventional centralised wastewater treatment systems are usually not efficient when it comes to water use. In fact, brown, grey and yellow water usually end up in the sewage system, and are then treated in high capacity treatment plants, leading to water loss due to leakage (Rutsch, Rieckermann & Krebs 2006). Moreover, these systems also require additional water for the transport of wastewater to the centralised treatment facility. In the most effective decentralised wastewater treatment system, water savings can be achieved by minimising the wastewater component as soon as possible; and separating, treating and reusing the different wastewater types (US EPA 2015). The recommended application of marginally treated greywater for flushing purposes allows savings of potable water. The greywater can also be reused on-site for non-food irrigation since it contains nutrients useful to plants (Al-Jayyousi 2003). According to Friedler (2004, p. 997), the use of decentralised treatment systems with greywater reuse can save up to 65 - 70 l/d per person of potable water.

Potential for Nutrient Recovery

Around 90 % of the nitrogen and 90 % of the phosphorus in the excreta are contained within the blackwater (Jönsson et al., cited in Spångberg, Tidåker & Jönsson 2014, p. 210). There lies a great potential to recover nutrients from household wastewater through source control techniques and decentralised wastewater systems. Malisie, Prihandrijanti & Otterpohl (2007, p. 142) reported a possible recovery of up to 86 % of nitrogen, 21 % of phosphorous and 69 % of potassium from urine and 12 % of nitrogen, 68 % of phosphorous and 20 % of potassium from faeces, by use of urine diverting toilets. Faeces and urine contain nutrients that are essential for plants and can replace the need for artificial fertilisers. According to deGraaff et al. (2010b, p. 7) one tenth of the existing worldwide production of anthropogenic phosphorous fertiliser can be fulfilled by recovering phosphates from blackwater using struvite precipitation. Wielemaker, Weijma & Zeeman (2018) analysed the implication and possibilities of a closed loop resource cycle for integrated decentralised sanitation, with focus on nutrient recovery and urban agriculture. By recycling and reusing the nutrients contained within the domestic wastewater, a possible demand minimisation of phosphorus by 100 % and of nitrogen and carbon compounds by 65 - 85 % for urban agriculture can be reached (Wielemaker, Weijma & Zeeman 2018, p. 426). Jönsson et al. (2004, p. 1) concluded in their research that direct application of urine from one person to the soil can fertilise 300-400 m^2 (N-fertilisation) and 600 m^2 (P-

Fertilisation) of land in a year respectively. The TPS systems can further enhance the availability of nutrients to be applied to the soil, Krause et al. (2015, p. 4045) investigated the potential of nutrients recycling by TPS and found that TPS compost contains 3.6 times more phosphorus than the normal compost.

The adoption of the recommended integrated decentralised wastewater treatment system provides a great potential to recover and reuse valuable resources from wastewater while effectively treating the wastewater. It could significantly and sustainably help to close resource use loops in wastewater management.

Case Studies of Integrated Decentralised Wastewater Management

The concept of integrated decentralised wastewater management has been implemented in various developed and developing regions of the world. Some of the case studies are summarised as follows.

Hamburg Water Cycle in Jenfelder Au, Germany

The integrated decentralised wastewater management concept is realised on a big scale within the urban development project 'Jenfelder Au' in the eastern part of Hamburg. Jenfelder Au is a project under construction, and is expected to inhabit approximately 2000 residents on 35 ha of land (Augustin et al. 2014, p. 13). The sanitation system is based on the idea of a separate collection of wastewater streams and the use of water saving toilets i.e. vacuum toilets. The system is designed to have separate streams for rainwater, blackwater and greywater. As shown in figure 5, the blackwater is treated separately by anaerobic treatment and results in the production of biogas, whose heat and energy recovery is cycled back to the residential areas. Separately collected greywater is treated and released back to water bodies. The digestate from the biogas can then be applied in fields as a bio-fertiliser to increase the productivity of the soil. One important feature of the Jenfelder wastewater system is the rainwater reuse. The rainwater flows into retention ponds, thereby reducing the burden on the sewer network. The retention ponds and lakes can also serve as flood protection besides adding to the attractiveness of the area (Hamburg Wasser 2018).

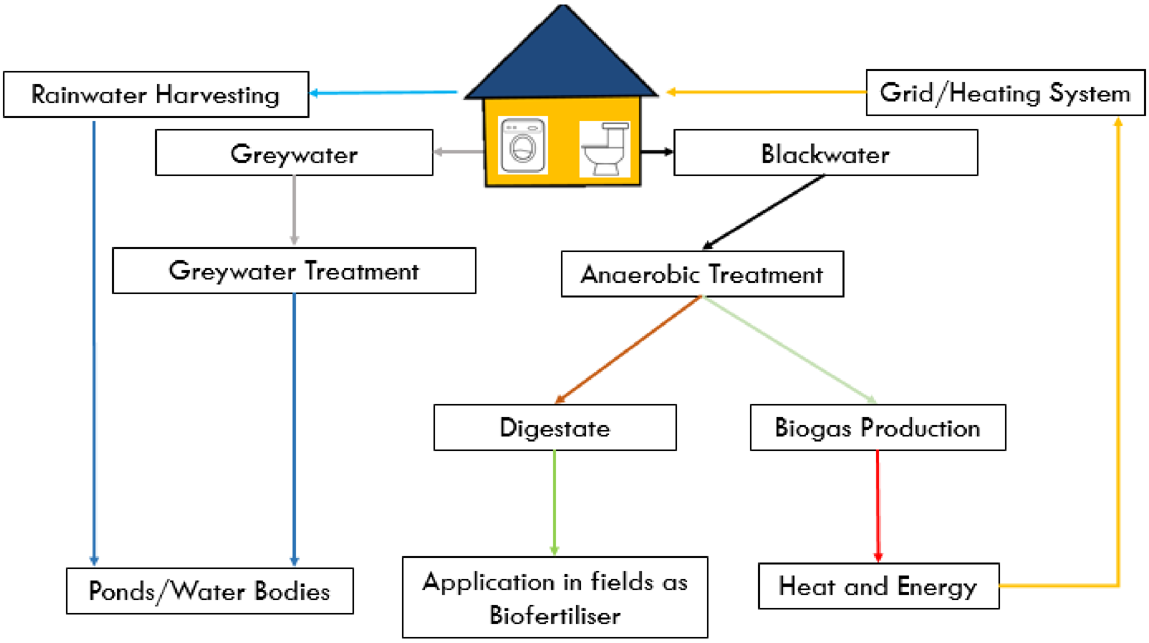


Figure 5: Efficient recycling of different streams of wastewater based on Hamburg Wasser (2018)

According to the European Commission (2010), the innovative system will comprise of approximately 1000 vacuum toilets and a vacuum pipe system. It is expected to reduce water consumption by 7.3 m^3/a per person. A biogas combined heat and power generation plant is expected to generate approximately 800 kWh/a per person. Overall, as expected, the system will save around 500 tonnes/a of CO_2 equivalents and Jenfelder Au will be self-sufficient in terms of wastewater treatment and heat supply. It is expected to meet 50 % of its energy demand locally.

Ecological Sanitation Pilot Plant in in Surabaya, Indonesia

The ecological sanitation concept is adopted in a wastewater system in Surabaya, East Java, Indonesia. Household wastewater is separated at the source into brownwater, yellowwater and greywater. Source separated yellowwater is stored in an anaerobic storage tank at room temperature for 6 months for sanitisation. The brownwater component of the stream is collected in a solid-liquid separation tank, where a fish net hanging in the tank separates the solid part of the brownwater. The liquid part and greywater is further treated by a small constructed wetland. The circular flow of the water and nutrients in the Surabaya plant is demonstrated in figure 6. To achieve the recommended sanitisation levels, vermicomposting with specific types of earthworms is utilised to stabilise the organic material and convert it into humus to be used as a fertiliser. After only one month of vermicomposting faecal matter, a good quality compost is produced with a suitable C/N ratio while containing very low amounts of E.coli (Malisie, Prihandrijanti & Otterpohl 2007).

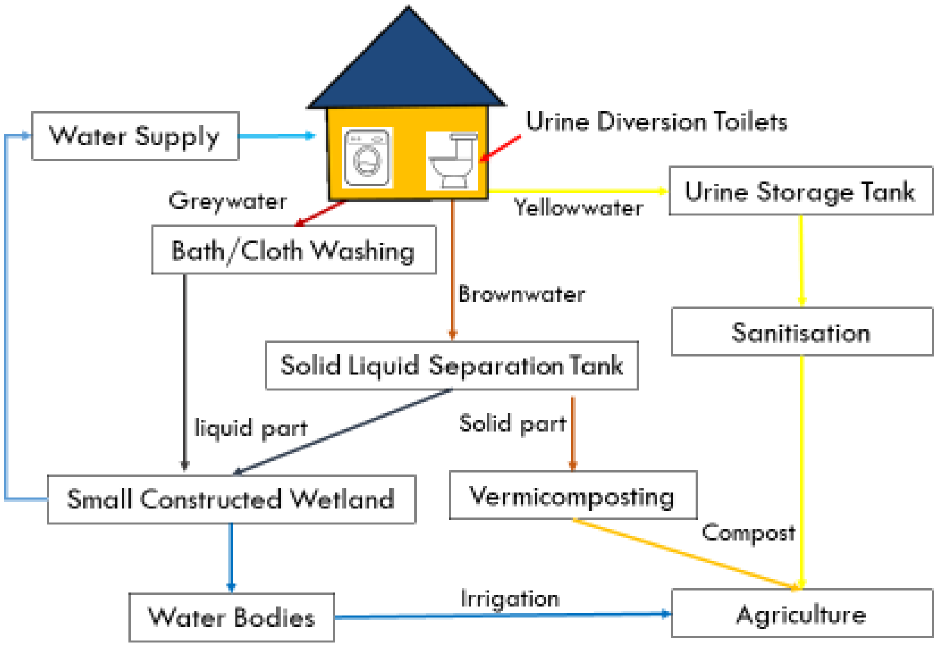


Figure 6: Circular flow of water and nutrient at the pilot plant in Surabaya inspired by Malisie, Prihandrijanti & Otterpohl (2007).

Malisie, Prihandrijanti & Otterpohl (2007) conducted research to assess the potential of nutrient reuse from a source separation domestic wastewater system in Indonesia. Small scale cultivation experiments with baby rose (*Rosa Multiflora*) were carried out to assess the potential of compost to be used as a fertiliser. This plant was chosen based on its rapid growth (2 - 3 months) and its ability to be planted in every season. The growth rate of baby roses with urine and faecal fertilisers was observed; the results concluded that the application of urine fertiliser gives the best and fastest growth to the baby roses, acting as a quick fertiliser because of its higher nitrogen content compared to other fertilisers. The research revealed that human excreta could effectively substitute the use of chemical fertiliser, after complete sanitisation.

Integrated decentralised wastewater treatment systems have been implemented in different rural and peri-urban regions of the world, and case studies have revealed that they constitute a sustainable and cost effective treatment option for rural wastewater.

Conclusion

This paper analysed the possibilities of a decentralised wastewater treatment in comparison to a centralised wastewater treatment in a rural community. The technical, economic and environmental aspects of decentralised rural wastewater management with a focus on resource recovery were discussed. Based on extensive literature review, decentralised management based on the ecological sanitation concept appeared as a sustainable and economically sound option for wastewater treatment in rural areas, with a potential for nutrients recovery, water reuse and energy savings.

As highlighted throughout the paper, there exists no single universal solution to the technological, financial, social and environmental issues related to wastewater treatment and management. However, the decisions regarding selection, construction, maintenance and operation of wastewater treatment systems, based on the principles of sustainability and circular economy, could tackle the problems sensibly without exporting them to future generations. In the light of extensive research, an integrated decentralised wastewater system comprising source separation, a conventional septic tank, a constructed wetland, TPS with or without urine diversion and a subsurface drip irrigation system is recommended for rural wastewater treatment.

While the results of publications and case studies showed that in rural communities decentralised wastewater systems are a good alternative to centralised wastewater systems, further research based on financial, economic and environmental feasibility with regards to water savings, nutrients recovery and energy production is required for developments where centralised wastewater treatment plants are already in place.

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