A review on full-scale decentralized wastewater treatment systems: techno-economical approach

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ABSTRACT

As a solution to the shortcomings of centralized systems, over the last two decades large numbers of decentralized wastewater treatment plants of different technology types have been installed all over the world. This paper aims at deriving lessons learned from existing decentralized wastewater treatment plants that are relevant for smaller towns (and peri-urban areas) as well as rural communities in developing countries, such as India. Only full-scale implemented decentralized wastewater treatment systems are reviewed in terms of performance, land area requirement, capital cost, and operation and maintenance costs. The results are presented in tables comparing different technology types with respect to those parameters.

Key words | decentralized systems, performance indicators, small community, sustainability indicators, wastewater

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INTRODUCTION

Rapid growth in population, urbanization, industrialization, and demand of energy has drawn attention of many researchers towards the scarcity of clean water. Globally, billions of people are suffering due to inappropriate sanitation and wastewater treatment and unavailability of useable water. The situation is particularly grave in smaller towns (or peri-urban areas) and rural communities in developing countries. Worldwide, around 40% of the population lacks basic sanitation and 25% of the developing country urban dwellers lack access to sanitation services, with a much higher percentage for the rural populations of developing countries reaching up to 82% (Ho 2005; Massoud *et al.* 2009; Chong *et al.* 2012). The adverse effect of this situation on hygienic, environmental and ultimately social aspects is well documented (Abegglen & Siegrist 2006; Fach & Fuchs 2010).

Limited financial resources demand environmental engineers to design environmentally and economically sustainable wastewater treatment systems. From an economic perspective in particular, the differentiation in centralized and decentralized systems is of relevance. A definition of both types of system as well as an overview of their respective advantages and disadvantages can be found in Starkl *et al.* (2012). This paper focuses on decentralized wastewater treatment systems, which are often considered as more sustainable options as compared with centralized alternatives, in particular in small towns and peri-urban areas as well as rural communities in developing countries (Nanninga *et al.* 2012). Further, many centralized treatment plants have been found to be unable to cope with stringent environment legislation in developing countries (Schories 2008). Consequently, over the last decade many researchers have studied various decentralized options for wastewater management, for example, Beausejour & Nguyen (2007), Galvao *et al.* (2005), Fane & Fane (2005), Starkl *et al.* (2007) and Meuler *et al.* (2008). Some of the typical advantages attributed to decentralized systems are that they can be installed without requiring a huge budget especially at isolated locations or that they save money otherwise required for a sewerage network and increase the possibility of reuse of treated water without extra expenditure required for the water supply network (Massoud *et al.* 2009; Wang 2014).

The objective of this paper is to summarize the information available in literature on full-scale decentralized wastewater treatment plants worldwide. The review will help in identifying current knowledge gaps with respect to decentralized wastewater management.

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CLASSIFICATION OF DECENTRALIZED WASTEWATER TREATMENT SYSTEMS

For structuring the review, the following classification of (decentralized) wastewater treatment systems has been used:

1. Natural treatment systems
2. Aerobic systems
   (a) Suspended growth
   (b) Attached growth
   (c) Combined suspended and attached growth
3. Anaerobic systems
   (a) Suspended growth
   (b) Attached growth
4. Combined (aerobic/anaerobic/natural) systems
   (a) Anaerobic–aerobic
   (b) Anaerobic–natural
   (c) Anaerobic–aerobic–natural

The following sections give a brief overview of those systems.

Natural treatment systems

Natural wastewater treatment systems can provide cheap solutions for wastewater treatment. The simplest system is a pond system, where the algal–bacterial symbiotic relationship is used for wastewater treatment. Other common systems are designed to work with natural media like soil and plants for filtration and biochemical reactions. These systems are generally adopted in developing countries due to their low operational and maintenance cost and can be used either as a secondary treatment or as a combination of primary and secondary treatment. Some have also been used for tertiary treatment, such as duckweed pond systems (DPS), waste stabilization ponds (WSP), facultative pond, and constructed wetlands (CWs) (Vymazal 2010). These systems involve combined treatment by earthen material, plants and microorganism. Besides the chemical and biological action, these systems are supported by some physical and chemical methods like precipitation and adsorption (Surampalli *et al.* 2007). Like other treatment systems, these systems are capable of removing the nutrient and organic load from wastewater. Natural systems are generally used in those places where there large space is available and funds are limited. Despite their low cost and satisfactory wastewater treatment, natural systems require a large space and longer hydraulic retention time (HRT) than other treatment systems, and may produce bad odors not suited for hot climates where evapotranspiration from plants takes place. Natural systems are also capable of coping with shock load and load fluctuation by using the combinations of two or more natural systems. Availability of raw material makes these processes a good choice for wastewater treatment in low income countries (Surampalli *et al.* 2007; Yoon *et al.* 2008). An overview of natural wastewater treatment systems in India can be found in Starkl *et al.* (2013).

These systems are more appropriate for warm tropical and subtropical regions. Treatment capability of natural treatment systems, specifically CWs, are limited by various components such as sunlight, wind, soil characteristics and geology, hydraulics, health and sustainability of vegetation, and seasonal variations in water surface elevation (Thullen *et al.* 2005). Adoptability of these systems is also limited due to lack of awareness, lack of knowledge of tropical wetland ecology and native wetland species, prevalence of mixed domestic/industrial wastewaters, and limited knowledge and experience with design and management (Kivaisi 2001; Smith & Moelyowati 2001). Major problems associated with adoptability and faced by designers and operators of natural treatment systems include disordered vegetation growth, nuisance control (e.g. insect vectors, nuisance animals), slow treatment rate, wastewater exposure, and fast macrophyte growth rate (Verhoeven *et al.* 1999; Vymazal 2005; Jing *et al.* 2008).

Aerobic treatment systems

Aerobic treatment methods involve the use of oxygen utilized by microorganisms for degradation of organics into the simplest degradation products, i.e. carbon dioxide and water. Further, these systems can be classified as those systems which requiring forced aeration or mechanical aeration equipment. The footprint of these systems is small in comparison to natural systems but energy consumption is high. In comparison with natural systems, aerobic systems are capable of providing good quality effluents which can easily meet the effluent discharge standards. The biggest advantage of aerobic systems is that they require only semi-skilled personnel, which make them a good choice of wastewater treatment technology in low income and developing countries. These systems are considered as high rate systems and can be categorized as attached growth processes, suspended growth processes, and hybrid processes. These systems are also capable of satisfying the discharge standards of various developed countries. Sometimes aerobic systems are practiced as a post-treatment option for the effluents of anaerobic systems. Some well-documented and full-scale implemented aerobic systems include extended aeration process (EA), moving bed biofilm reactor (MBBR), oxidation ditches, membrane bioreactor (MBR), submerged aerobic fixed film (SAFF) reactor, rotating biological contactor (RBC) and sequential bioreactor (SBR). These systems are generally practiced for the treatment of domestic wastewaters (having chemical oxygen demand (COD) concentration of less than 1,000 mg/L). Aerobic treatment systems are also able to produce high quality effluent with good sludge settling characteristics (Seghezzo *et al.* 1998; Fane & Fane 2005; Abegglen & Siegrist 2006; DeCarolis & Adham 2007; Meuler *et al.* 2008).

Usage of these systems requires more sophisticated operation control, knowledgeable operators, higher level of maintenance, semi-skilled personnel, high specific energy consumption, high biomass production resulting in frequent sludge disposal (Eckenfelder 1988; Al-Rekabi *et al.* 2007). Major problems associated with these systems include plugging of aeration devices during operation, difficult scale-up, and mechanical failures (Cortez *et al.* 2008; Singh & Srivastava 2011).

Anaerobic treatment systems

These treatment systems govern the biological treatment by the production of methane and biomass through a basic mechanism involving hydrolysis, acidogenesis, acetogenesis and methanogenesis in the absence of oxygen. Anaerobic treatment systems are low energy consuming biological treatment systems. Despite the low organic and nutrient removal, anaerobic treatment systems are cheap and simple and can be an energy provider. However, these systems achieve only poor to moderate effluent quality and take a long time to start up (around 3–4 months), while aerobic systems have much shorter start-up time (around 2–4 weeks) (Alexiou & Mara 2003; Melidis *et al.* 2009). To meet the discharge standard most of the anaerobic treatment systems are followed by aerobic systems (Yeoh 1995; Chan *et al.* 2009). Examples of these types of system include upflow anaerobic sludge blanket (UASB), anaerobic baffled reactor and septic tank, but most of the anaerobic systems are practiced with other aerobic/natural processes. Many anaerobic systems are also practiced in combined treatment systems. Further, these systems are most suitable for treating high strength wastewaters (having COD >4,000 mg/L).

Treatment efficiency of anaerobic systems is limited by low temperatures zones, long HRT and effluents of these systems requiring post-treatment for removing the remaining COD, nutrients and pathogens (Al-Rekabi *et al.* 2007), while potential problems of these systems include slow start-up and potential odor problems and corrosion (Eckenfelder *et al.* 1988; Cortez *et al.* 2008).

Combined (aerobic/anaerobic/natural) systems

These systems incorporate the features of all three natural, anaerobic and aerobic systems. Such systems often are based on a combination of various technical components such as septic tank, Imhoff tank, anaerobic filter, baffled septic tank, trickling filter, hybrid and some natural systems.

TECHNICAL AND ECONOMICAL EVALUATION OF WASTEWATER TREATMENT SYSTEMS

The present review focuses on full-scale implemented decentralized wastewater treatment systems in terms of cost (capital, land and operation and maintenance (O&M)) and performance in terms of their targeted pollutant removal.

Technical evaluation of decentralized wastewater treatment systems

Tables 1–3 summarize the common performance parameters of various wastewater treatment systems implemented at full scale across all over the world. The performance of each technology is presented in terms of removal of their targeted pollutant.

From Table 2, it can be stated clearly that aerobic treatment systems are capable of providing the highest level of efficiency among all systems. Aerobic systems are efficient to produce treated effluents which can meet the discharge standards, and anaerobic processes are energy providers but less efficient than aerobic and advanced aerobic processes. Based on the performance efficiency data of natural systems (Table 1), it can be clearly stated that natural treatment systems can be a good option and are comparable to aerobic processes.

Economic evaluation of decentralized wastewater treatment systems

Tables 4 and 5 provide an economic evaluation of these systems in terms of capital or investment cost, and O&M cost.

Capital costs include cost incurred in land acquisition, and construction and design cost of facilities.

Table 1 | Performance inventory of full-scale natural treatment systems

			Removal (%)										
Treatment process	**Capacity**	**Unit**	**BOD**	**COD**	**TSS**	**TN**	**TKN**	**NH_3-N**	**TP**	**TC/FC**	**Country**	**References**	**Remarks**
DPS	5,000	p.e.	~ 95	~ 90	–	87	–	–	43	–	Zimbabwe	Nhapi *et al.* (2003)	Treatment scheme includes anaerobic and maturation pond
	10,000	p.e.	–	–	–	56	–	–	11	–			
	2,000–3,000	p.e.	–	–	–	–	74–77	> 90	–	–	The Netherlands	Alaerts *et al.* (1996)	–
WSP	2,000	p.e.	75	70	60	51	–	–	51	–	Spain	Rodríguez (2009)	–
	30–60	m^3/d	94	–	63	–	–	72	–	–	Greece	Papadopoulos & Tsihrintzis (2011)	WSP utilizes duckweed plants
	3,000	p.e.	50.6	48.9	44.3	–	–	–	–	98.8 and 95.6	Egypt	Ghazy & El-Senousy (2008)	The scheme comprises anaerobic, facultative and maturation ponds
	5,000	m^3/d	–	6.7 (sol)	16.3	–	–	3.6	18.1	–	Israel	Avsar *et al.* (2008)	Scheme comprises two sedimentation tanks followed by a pond
	–	–	75	55	48	44	–	–	46	1.6 log unit FC	Brazil	Sperling & Oliveira (2009)	–
Horizontal flow constructed wetland (HFCW)	1,750	p.e.	–	98.7	93.1	94	–	91.9	92.4	–	Ireland	Dzakpasu *et al.* (2012)	Combined treatment of domestic sewage and mountain water river
	–	–	96	–	–	–	–	88.4	87.8	–	China	Wu *et al.* (2011)	Preceded by a settling tank
	< 2,000	p.e.	> 78	–	> 78	40–60	–	–	40–60	–	Spain	Vera *et al.* (2011)	Treatment scheme includes septic tank as pretreatment followed by HFCW and WSP as post-treatment unit
	350	p.e.	> 90	> 90	95.6	–	–	–	–	–	France	Merlin *et al.* (2002)	Septic tank followed by HFCW
	100	p.e.	97	94.5	99.4	–	–	–	62.5	–	Czech Republic	Vymazal (2011)	Pretreatment by septic tank and screen followed by HFCW
	20	p.e.	–	79.2	64.7	–	–	–	–	–	Italy	Pucci *et al.* (2000)	Imhoff tank followed by HFCW
Vertical flow constructed wetland (VFCW)	1,000	p.e.	92.3	91.7	93.2	–	80.3	87.5	61.3	99.9	France	Gikas *et al.* (2007)	Treatment scheme includes screening, primary sedimentation tank (PST) and sludge tank followed by VFCW
	72	p.e.	> 60	> 55	> 80	–	–	–	–	–	Tunisia	Sellami *et al.* (2009)	Septic tank followed by VFCW
	–	–	–	93	96	–	–	86	75	–	Nepal	Bista & Khatiwada (2004)	Septic tank followed by reed bed based vertical and horizontal wetland

BOD: biochemical oxygen demand; COD: chemical oxygen demand; TSS: total suspended solids; TN: total nitrogen; TKN: total Kjeldahl nitrogen; TP: total phosphorus; TC/FC: ratio of total coliforms to fecal coliforms; p.e.: population equivalent.

Table 2 | Performance inventory of full-scale aerobic treatment systems

			Removal (%)										
Treatment process	**Capacity**	**Unit**	**BOD**	**COD**	**TSS**	**TN**	**TKN**	**NH_3-N**	**TP**	**TC/FC**	**Country**	**References**	**Remarks**
Oxidation ditch[a]	–	–	91.3	81.6	79.7	–	–	41.3	51.5	–	Nepal	Sah (2004)	–
Conventional and extended aeration activated sludge process[a]	–	–	85	81	76	50	–	–	46	2 Log unit	Brazil	Sperling & Oliveira (2009)	–
SBR[a]	–	–	90–98	–	84.7–97.2	–	–	90.8–96.8	–	–	USA	Surampalli *et al.* (2000)	–
Aerated lagoon (AL)[a]	637	p.e.	75	–	73	–	–	59	–	–	USA	Surampalli *et al.* (1999)	Aerated lagoon followed by polishing pond
MBR[a]	95	m^3/d	> 98	> 91.7	–	–	–	> 97.7	–	–	California	DeCarolis & Adham (2007)	–
	–	–	> 99	> 91	–	–	> 96.8	–	> 24	–	The Netherlands	Krzeminski *et al.* (2012)	–
	240	m^3/d	–	94.8	–	–	–	98.3	–	–	–	Zhang *et al.* (2003)	–
RBC[b]	1,000	m^3/d	76.2	–	70	41.2	–	–	–	–	Japan	Tanaka *et al.* (1987)	Grit chamber and primary clarifier followed by RBC
MBBR[c]	$< 2{,}000$	p.e.	> 90	> 90	> 92	–	–	–	–	–	Norway and Sweden	Rusten *et al.* (1997)	Treatment scheme includes PST and MBBR is followed by chemical precipitation
SAFF reactor[c]	250	p.e.	87–95	67–73		60–90	–	> 94	> 65	–	–	Nabizadeh & Mesdaghinia (2006); Pramanik *et al.* (2012)	–

[a] Suspended growth systems.

[b] Attached growth systems.

[c] Hybrid growth systems.

Table 3 | Performance inventory of full-scale anaerobic and combined treatment systems

			Removal (%)										
Treatment process	**Capacity**	**Unit**	**BOD**	**COD**	**TSS**	**TN**	**TKN**	**NH_3-N**	**TP**	**TC/FC**	**Country**	**References**	**Remarks**
UASB[a]	250–500	p.e.	67	60	78	–	–	–	–	–	Brazil	Vieira *et al.* (1994)	–
	–	–	72	59	67	−13	–	–	−1	0.6 log FC	Brazil	Sperling & Oliveira (2009)	–
	35	m^3	80	66	69	–	–	–	–	–	Colombia	Schellinkhout & Collazos (1992)	UASB followed by anaerobic pond system
Anaerobic suspended followed by aerobic attached[b]	250–500	p.e.	82	79	83	–	40	40	–	–	Brazil	Vieira *et al.* (2013)	UASB followed by trickling filter
Aerobic suspended followed by aerobic attached[b]	10.8	m^3/d	88	89	–	–	–	70	9	–	Mexico	Norouzian & Martinez (1985)	AST followed by RBC
Anaerobic suspended followed by anaerobic attached[b]	–	–	59	51	66	24	–	–	30	1 log unit	Brazil	Sperling & Oliveira (2009)	Septic tank + anaerobic filter

[a] Anaerobic–suspended growth systems

[b] Combined systems.

The presented inventory shows that performance is independent of size of plant, whereas total cost is directly proportional to size of the community.

DISCUSSION AND CONCLUSIONS

It can be seen that there is a large number of technologies available, which have been successfully implemented in a decentralized context. Whereas performance data and land requirement give a good comparison of the different technology types, it is more difficult to compare the technologies with respect to their costs as these depend on the local economic conditions. The following key lessons can be derived from the tables presented in this review.

- Very limited information is available on the performance and economic analysis of decentralized wastewater systems operating in developing countries. However, some information is available from developed countries, which are highlighted in the tables. Moreover, it may be possible that data may exist in governmental reports but not easily accessible to the scientific community. So there is a strong need for the performance and economic evaluation of decentralized treatment systems for both developed and developing countries like India and other Asian countries.
- Developing countries generally use anaerobic and combined treatment systems for small communities; however, only limited performance evaluation data are available, and economic evaluation is almost non-existent.
- It is very difficult to compare the cost of different wastewater treatment systems because commodities prices and cost incurred in laying of sewers is much higher in developed countries. So it is essential to include cost of commodities and sewer systems in economic evaluation.
- On the basis of performance, it was found that aerobic systems provide better quality in terms of organics and nutrients removal, and can be placed in a much smaller area, but higher O&M cost limits its use. However,

Table 4 | Economic evaluation of natural treatment systems

Treatment process	Capacity	Unit	Capital cost	Unit	Land requirement	Unit	Annual (O&M) cost	Unit	Country	Reference	Remarks
WSP	100–100,000	$\mathrm{m^3/d}$	854	US$/($\mathrm{m^3 \cdot d}$)	16	$\mathrm{m^2/m^3}$	19	US$/($\mathrm{m^3 \cdot d}$)	Thailand	Singhirunnusorn & Stenstrom (2010); Comas *et al.* (2003)	1 THB = 0.0231 US$ (2003), 1 THB = 0.03 US$ (2010)
	1,500	PE[a]	0.298	M€	–	–	0.011	M€/year	Spain	Senante *et al.* (2012)	1 € = 1.3197 US$ (2013)
Facultative lagoon along with WSP	< 18,930	$\mathrm{m^3/d}$	1–4	$/GPD[b]	49–161	acre/MGD[c]	0.15–0.75	$/MGD	USA	Muga & Mihelcic (2008)	–
	–	–	0.54	$/1,000 GPD	25	$\mathrm{m^2/m^3}$	0.21	$/1,000 GPD	USA	Tecle *et al.* (1988)	–
Anaerobic lagoon	< 18,930	$\mathrm{m^3/d}$	1–4	$/GPD	49–161	acre/MGD	0.15–0.75	$/MGD	USA	Muga & Mihelcic (2008)	–
Intermittent sand filter	1,500	PE[c]	0.172	M€	–	–	0.022	M€/year	Spain	Senante *et al.* (2012)	1 € = 1.33 US$ (2013)
HFCW	1500	PE	0.36	M€	30	$\mathrm{m^2/m^3}$	0.026	M€/year	Spain	Nogueira *et al.* (2009); Comas *et al.* (2003); Senante *et al.* (2012)	1 € = 1.0503 US$ (2003), 1 € = 1.3955 US$ (2009), 1 € = 1.3197 US$ (2013)
	124	PE	503	€/PE	–	–	58	€/(PE·year)	Spain	Puigagut *et al.* (2007)	1 € = 1.3146 US$ (2007)
	100	PE	20,834	€	–	–	2,576	€/year	Spain	Nogueira *et al.* (2009)	1 € = 1.3955 US$ (2009)
VFCW	98	PE	295	€/PE	–	–	28	€/(PE·year)	Spain	Puigagut *et al.* (2007)	1 € = 1.3146 US$ (2007)

[a] PE: population equivalent.

[b] GPD: gallons per day.

[c] MGD: million gallons per day.

Table 5 | Economic evaluation of aerobic treatment systems

Treatment process	Capacity	Unit	Capital cost	Unit	Land requirement	Unit	Annual (O&M) cost	Unit	Country	Reference	Remarks
AL[a]	100–100,000	m^3/d	0.392	€/m^3	6	m^2/(m^3·d)	27	US$/(m^3·d)	Thailand	Singhirunnusorn & Stenstrom (2010)	1 THB = 0.03 US$ (2010)
SBR[a]	400	m^3/d	0.632	M€	353	m^2/MLD[d]	0.020	M€/year	Spain & India	Kalbar *et al.* (2012a), (2012b); Comas *et al.* (2003); Senante *et al.* (2012)	1 € = 1.33 US$ (2013), 1 € = 1.0503 US$ (2003), 1 Rs = 0.0188 US$ (2012)
EA[a]	400	m^3/d	0.358	M€	–	–	0.059	M€/year	Spain	Comas *et al.* (2003); Senante *et al.* (2012)	1 € = 1.33 US$ (2013), 1 € = 1.0503 US$ (2003)
Oxidation ditch[a]	3,785–25,740	m^3/d	$2.5–$4	Per GPD	–	–	–	–	–	USEPA (2000)	–
MBR[a]	400	m^3/d	0.440	M€	300–800	m^2/MLD	0.048	M€/year	Spain	Kalbar *et al.* (2012b); Senante *et al.* (2012); Khalil *et al.* (2008)	1 € = 1.33 US$ (2013)
RBC[b]	1,500	PE	0.533	M€	3,266	ft^2/MGD	0.025	M€/year	Spain	Comas *et al.* (2003); Senante *et al.* (2012); Williams & Williams (2011)	1 € = 1.0503 US$ (2003), 1 € = 1.3385 US$ (2011), 1 € = 1.33 US$ (2013)
Trickling filter[b]	1,500	PE	0.522	M€	1,620	m^2/MLD	0.026	M€/year	Spain	Comas *et al.* (2003); Senante *et al.* (2012); Khalil *et al.* (2008)	1 € = 1.0503 US$ (2003), 1 € = 1.33 US$ (2013), 1 Rs = 0.0254 US$ (2008)
MBBR[c]	1,500	PE	0.533	M€	450	m^2/MLD	0.025	M€/year	Spain & India	Senante *et al.* (2012); Khalil *et al.* (2008)	1 € = 1.33 US$ (2013), 1 Rs = 0.0254 US$ (2008)

[a] Suspended growth systems.

[b] Attached growth systems.

[c] Hybrid systems.

[d] MLD: million litres per day.

natural systems require a larger area and are limited by their performance especially in nutrient removal.

Further, it can be seen that data are mainly published from developed countries, and few literature studies could be found that report data from Asia, in particular India. Hence, there is a need to conduct more evaluations of the performance of such technologies in these regions.

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