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Research article

Key criteria for considering decentralization in municipal wastewater management

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ABSTRACT

Wastewater pollution problems are associated with population growth and the concentration of population in large urban centers. According to United Nations projections for 2050, the world population will reach 9 billion people, increasing the pressures on water resources due to their demand and pollution. Based on UNICEF and World Health Organization estimates, 2.4 billion people worldwide currently lack access to improved sanitation facilities, with 946 million practicing open defecation. Decentralized wastewater treatment systems are a viable and necessary alternative for wastewater management, thus, minimizing environmental impacts, facilitating resource recovery, and providing rural and peri-urban inhabitants with access to basic sanitation. This literature review article uses the multicriteria analysis tool to present the key economic, institutional, social, environmental, and technological aspects, criteria, and indicators that must be considered for successful decentralized system implementation planning to strengthen basic sanitation service coverage in the rural and peri-urban areas where it does not exist.

1. Introduction

Wastewater pollution problems are associated with population growth and the concentration of population in large urban centers. The historical growth trends at a global level indicate that the population doubled its size in a period of 40 years, between 1950 and 1990, from 2.6 Billion to 5.2 Billion. According to projections, it is estimated that, by 2050, the size of the world population will be 9 billion people, of which 7.8 billion will be in developing countries (Nas et al., 2020; UN, 2019; Daigger, 2007). According to UNICEF and World Health Organization (WHO) estimates, 2.4 billion people worldwide do not have access to improved sanitation facilities, of which 946 million practice open defecation (UNICEF & WHO, 2015).

The conventional approach uses potable water for irrigation, washing, and toilet flushing activities, even though these actions do not require high standards of physical, chemical, and microbiological quality. With respect to wastewater, its treatment and disposal is widely practiced by developing countries, with a high percentage of the population (over 90%) connected to centralized treatment systems (Burton et al., 2014). However, decentralized systems are becoming particularly attractive because of the possibility of reducing long-term treatment costs and the potential for wastewater reuse (Daigger, 2009; Roefs et al., 2017; Jung et al., 2018). Considering the three basic components of a wastewater management system—collection, treatment and disposal, and collection—costs account for ~60% of the total budget for a centralized system. In decentralized systems, this component is reduced and focused mainly on wastewater treatment and disposal (Massoud et al., 2009; Eggimann et al., 2016).

Understanding a decentralized system as one in which wastewater is treated as close as possible to its source of generation (Libralato et al., 2011) becomes a viable and necessary alternative for wastewater management, minimizing environmental impacts, and facilitating resource recovery (Nhapi, 2004; Opher and Friedler, 2016; Capodaglio, 2017). The decentralization approach is aimed at developing systems that are more financially consistent, socially responsible, and environmentally benign than centralized conventional systems (Burkhard et al., 2000; Nhapi, 2004), filling the gap between on-site systems and centralized conventional systems (Capodaglio et al., 2017).

The implementation of decentralized systems involves different planning, where feasibility, design, and implementation must be performed by independent service areas, with particular contexts and whose solutions must respond to their individual needs, considering the

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heterogeneity that occurs within a same urban center, where social, environmental, geographic, economic, and technological conditions can vary widely (Liang and van Dijk, 2008; Purnomo and Khairina, 2016; Roefs et al., 2017). Decentralized systems have the advantage of easily adapting to local conditions in urban areas, as well as expanding their capacity in accordance with population growth. This decentralized approach facilitates reusing water and treatment byproducts, such as nutrients, sludge, and energy (Capodaglio, 2017; Eggimann et al., 2018).

Another environmental advantage offered by the use of decentralized wastewater treatment systems is the reduction in the amount of pollutant that water bodies receive after exiting the plant, taking into account that the flows treated by decentralized systems are lower, thus, facilitating pollutant dilution and reducing its environmental impact on parameters such as diluted oxygen, chemical oxygen demand, and biochemical oxygen demand (Singh et al., 2019).

Finally, the planning and implementation of decentralized wastewater treatment systems must also consider their resilience, which is the degree to which the system reduces the magnitude of failures caused by exceptional conditions while rendering services in its lifetime. This factor invites us to think about the robustness and speed of the response capacity of the treatment system from its design to external stressors factors, such as natural disasters, wars, diseases, and epidemics (Juan-García et al., 2017; Kohler et al., 2020).

For the abovementioned reasons, this article introduces the state of the art of decentralization in wastewater treatment based on economic, social, technological, environmental, and institutional criteria to facilitate a relevant implementation of this approach in any context.

2. Methodology

To establish the competitive advantages of decentralized wastewater treatment systems against centralized systems, key decentralization aspects and variables were identified based on our state of the art review. This process identified the most relevant decision-making indicators from the economic and institutional, technological, social, and environmental dimensions in the implementation of decentralized wastewater treatment systems (Capodaglio, 2017; Singh et al., 2019).

After the process of identifying key aspects for the decentralization of wastewater treatment systems, multicriteria analysis was used as a decision tool to assess and prioritize the most relevant quantitative and qualitative indicators from economic, institutional, technological, social, and environmental factors based on the results from a survey of experts from different fields (academic, environmental, institutional, and consulting companies) within the water and treatment sectors, estimating their relative importance for the formulation and efficient implementation of decentralized systems (Hama et al., 2019). Specifically, the survey was filled out by 35 professionals and the results were analyzed by using descriptive statistics measures including, average, standard deviation, mode and maximums and minimums as it can be found in Appendix 1 and 2. During the development of this study, the information obtained was assessed and classified as per the corresponding Rating and Ranking to estimate indicators that would convert subjective and objective information to values on a digital scale (Singhirunnusorn, 2009; Hama et al., 2019).

Using this Ranking methodology, a score was assigned to each decision element, reflecting its degree of importance on a scale from 1 to 9, where 1 is not important and 9 is very important, with a regular classification where two or more criteria may have the same score, which is appropriate when you want to select indicators across a wide range of decision elements (Singhirunnusorn, 2009; Hama et al., 2019; Vladeanu and Matthews, 2019).

In the case of the Rating methodology, its degree of importance is also reflected, but in this case the scale goes from 0 to 100, with the condition that the sum of all the elements is 100, thus, guaranteeing a measure of cardinal and ordinal importance for each indicator (Singhirunnusorn, 2009; Wu et al., 2017). Once scores and ratings were assigned for each decision element, the relative weight and combined weight of the decision indicators were calculated (Macoun and Prabhu, 1999).

For Rankings, the relative weight was obtained dividing the average score of each indicator by the sum of the average scores of the variable assessed. For Ratings, as aforementioned, the score assigned to each decision element ranges from 0 to 100, with the condition that its final sum is 100. Finally, the combined weight is the result of the average of the relative Rating and Ranking weight for each decision element (Singhirunnusorn, 2009; Hama et al., 2019; Vladeanu and Matthews, 2019).

In addition to the identification of the key decentralization aspects and variables, the technological wastewater treatment offer associated with the centralization level and with the treatment objectives was assessed using the Multicriteria Ranking Analysis Method. The results yielded the applicability level for the different technological options based on different aspects, where each element was assigned an applicability score from 1 to 9, with 1 meaning that the option is non-applicable and 9 that it is highly applicable. Once all the scores for each technology have been added up, the relative weights associated to each of the technological options are calculated dividing each score by the total sum of scores, taking into account that the total sum of relative weights must be 100.

3. Results

3.1. Identification of key decentralization aspects, variables, and indicators in wastewater management

The review of the state of the art on wastewater management decentralization in urban areas identified key indicators directly related to technological, economical, institutional, and social and environmental aspects, which, although also being considered in centralized and hybrid systems, their importance ranges from one approach to another (Jung et al., 2018; Singh et al., 2019). The combined weights of the indicators included in the survey are denoted below (Table 1).

The degree of centralization or decentralization of a wastewater treatment system will depend largely on the degree of industrialization of the country where the system is installed. Highly industrialized countries generally implement centralized systems connecting different regions and communities, because they have the technical and economic support required to guarantee the sustainability of these systems. In contrast, in developing countries, which usually lack full coverage or the proper governmental, economic, and technical support required to guarantee system durability; decentralization is seen as a viable solution for low basic sanitation coverage issues (Roefs et al., 2017; Chirisa et al., 2017).

From the economic and institutional aspects, the most important indicators were identified as system operation and maintenance costs, sewage system investment costs, treatment system investment costs, and institutional and political support. The success of a decentralized management program for urban areas will depend largely on institutional support because, even though the system's installation, operation, and maintenance costs may be reduced, they run the risk of failing to continue operations in the long term due to financial crises, especially since micro local governments generally lack the resources required for investing in infrastructure improvements to provide better services (Spirandelli et al., 2019; Kreter and Cardona, 2017).

In the implementation of decentralized treatment systems in developing countries, it is necessary to align land use plans with water resource planning, taking into account the land uses, economic activities, spatial distribution, and geographical features of the cities to determine the level of centralization and evaluate the reuse potential in each sector. However, this implies reforms at the administrative and legal levels to promote decentralization as a solution not only for deficiencies in basic sanitation coverage but also as an alternative for economic return or added value through a resource-based sanitation approach (Capodaglio, 2017; Hama et al., 2019; Iribarnegaray et al., 2018; Leigh and Lee, 2019; Xu et al., 2019).

Table 1. Combined weights of the indicators included in the expert survey.

Aspect	Variable	Indicator	Rating Methodology		Ranking Methodology		Combined Weight
			Avg.	Relative weight	Avg.	Relative weight	
Economic and institutional	Costs	Investment in treatment system	30,43	30,43	7,97	26,17	28,30
		Operation & Maintenance (O&M) of treatment system	26,93	26,93	8,20	26,92	26,93
		Investment in sewage systems	22,29	22,29	7,31	24,02	23,15
		O&M in sewage systems	20,36	20,36	6,97	22,89	21,62
	Planning	Institutional support for decentralized schemes	44,66	44,66	8,09	36,19	40,42
		Interest of service companies in management and O&M	25,51	25,51	6,77	30,31	27,91
		Peri-urban and expansion areas without wastewater treatment coverage	29,83	29,83	7,49	33,50	31,67
Technological	Technological features	Reuse potential	33,57	33,57	7,34	32,61	33,09
		Sewer coverage	32,14	32,14	7,63	33,88	33,01
		Centralization level	34,29	34,29	7,54	33,50	33,89
	Area features	Area availability	31,71	31,71	8,03	27,07	29,39
		Quality goals	27,00	27,00	7,71	26,01	26,51
		Distance to the treatment point	20,14	20,14	6,60	22,25	21,20
		Area topography	21,14	21,14	7,31	24,66	22,90
	Reuse type	Agriculture	25,79	25,79	6,31	25,11	25,45
		Aquaculture	16,64	16,64	5,34	21,25	18,95
		Urban development (irrigation of parks and green areas), street washing	32,43	32,43	7,03	27,95	30,19
		Energy recovery	25,14	25,14	6,46	25,68	25,41
Social	Community	Reuse acceptation	46,86	46,9	7,66	49,54	48,20
		Community participation in system management and O&M	53,14	53,1	7,80	50,46	51,80
	Demographics	Population size	39,32	39,3	7,29	34,05	36,68
		Population distribution	30,32	30,3	7,00	32,71	31,80
		Population density	30,35	30,4	7,11	33,24	31,52
Environmental	Environmental Impact	Nutrient recycling	22,14	22,1	6,86	23,23	22,69
		Water availability	25,71	25,7	7,34	24,88	25,30
		Sludge production	21,57	21,6	7,20	24,39	22,98
		Smell/noise/insects/landscaping	30,57	30,6	8,11	27,49	29,03

Decentralization is thought to increase the potential for peri-urban and growing areas uncovered by wastewater treatment. This fact reduces the costs of investment in sewerage, which may be reflecting in an increase of the treatment coverages, a reduction of impacts from contamination of untreated wastewater, and less risk of diseases associated with contaminated water (Eggimann et al., 2016; Jung et al., 2018).

Based on technological aspects, three key indicators were identified: reuse potential, sewage system coverage, and the potential for combining centralized and decentralized systems. A thorough analysis of these factors is critical for project planning using a decentralized approach (Opher and Friedler, 2016; Capodaglio, 2017).

The potential for wastewater reuse is a common indicator when reviewing experiences at the global level, constituting another competitive advantage of decentralized systems when facing water availability issues in some urban regions, either due to quantity associated with long drought periods, or to quality due to supply source contamination. Regarding reuse potential, reusing water for landscape/urban purposes, such as toilet flushing, gardening, street washing, and urban irrigation, scored the highest, closely followed by reusing water in agriculture and for energy recovery (Caicedo and Bernal, 2014; Maaß and Grundmann, 2016; Salgot and Folch, 2018; Maryam and Büyükgüngör, 2019).

The coverage and the existence of sewer systems are one of the most relevant indicators, especially since, when there is not complete sewer coverage, the planning of decentralized wastewater management systems is facilitated by step-by-step planning aimed at increasing sewer and treatment coverage (Eggimann et al., 2016; Roefs et al., 2017; Leigh and Lee, 2019).

The potential for combining centralized and decentralized systems is another crucial indicator, allowing to expand the coverage of wastewater management to other areas as peri-urban, or growing areas not currently connected into the main system of the urban area. This approach defines the level of centralization for an urban area and combines several of these levels into a single unit. For example, cities with centralized treatment plants and satellite treatment plants that can offer multiple uses for the effluent treated according with water quality standards (Alvarado et al., 2017; Roefs et al., 2017; Capodaglio, 2017).

For social aspects, the most relevant indicators are environmental awareness, reuse acceptance, community participation in system management and operation and maintenance. The success of a decentralized system will depend on acceptance from the population associated with access to information, environmental education, and water culture (Eales et al., 2013; Narayan et al., 2020). Public acceptance of reuse of water from decentralized systems is driven by environmental and social responsibility to reduce household water demands. In this sense, there is clear evidence that public acceptance of alternative reused water sources is influenced by risk perceptions in the public health (Maryam and Büyükgüngör, 2019; Mu'azu et al., 2020).

Another important wastewater management decentralization aspect is a greater involvement of users in system planning, implementation, and operation. Sixty-eight percent of the experiences reviewed considered community participation fundamental for achieving ownership of both the decentralized system and the technological alternatives (Caicedo and Bernal, 2014; Saliba et al., 2018; Yulistyorini et al., 2019). There is a direct relationship between system user interest, environmental awareness, and participation and the cases in which water resources are scarce. The most successful cases (lasting over time) are those in which there is a greater user knowledge about how decentralized treatment systems operate (Caicedo and Bernal, 2014; Capodaglio, 2017; Yulistyorini et al., 2019).

Other relevant social indicators are related to population size, density, and distribution. Currently and anticipating the future, with the growing trend in urban population, an approach toward decentralization is required. Additionally, population distribution in urban area is a determining factor in defining centralization levels, planning, and managing wastewater collection, the number of technological alternatives to be implemented, and their location within the urban space based on land uses, since, the greatest implementation potential for these systems is in new urban areas, peri-urban areas, and growing areas (Caicedo and Bernal, 2014; Roefs et al., 2017; Hama et al., 2019; Leigh and Lee, 2019).

Among the relevant environmental indicators are the conservation of natural resources, the removal of pathogens and contaminants, and water availability. The main goal of water treatment systems is to mitigate or reduce impacts on natural resources and on the ecosystem services they provide (Opher and Friedler, 2016; Singh et al., 2019). In decentralized systems, wastewater streams are smaller at all points, which means less environmental damage. The construction of a decentralized system also generates less disturbance to the environment as collection pipe diameters and lengths are smaller, and pipes are installed at shallow depths and exhibit a more flexible design (Nhapi, 2004; Opher and Friedler, 2016; Masmoudi Jabri et al., 2020).

Water availability is also a key indicator for selecting treatment technologies. When water is scarce, new sustainable water supply sources are needed, such as wastewater treated in decentralized facilities, which is not only economically feasible but also facilitates resource conservation, water balances, and rainfall rates. Additionally, they are associated with water availability and the need to implement reuses for each specific case (Caicedo and Bernal, 2014; Arias et al., 2020).

In recent times, a new key aspect—system resilience—has emerged, which has become relevant in the planning and implementation of wastewater treatment systems according to centralization or decentralization levels. Within this context, system resilience is understood as the degree to which the system reduces the magnitude of the failures caused by exceptional conditions when rendering services during its lifetime. According to the environmental, public, and geographic conditions where the treatment system is installed, system resilience will determine whether or not the treatment system will be able to prevail against crises generated by external stressors (Juan-García et al., 2017; Leigh and Lee, 2019; Kohler et al., 2020).

The stressors that may exert an impact in the sustainability of a decentralized wastewater treatment system come from different environmental or social sources. Among others, the most important stressors that must be considered when planning and implementing the infrastructure and operation of a decentralized wastewater treatment system are earthquakes, floods, landslides, hurricanes or tropical storms, fires (natural or man-made), volcanic eruptions, droughts or flow variations in nearby watersheds, wars and terrorist attacks, political stability, and diseases with epidemic or pandemic potential (Khayambashi, 2017; Juan-García et al., 2017).

A resilient decentralized wastewater treatment system must be robust. Particularly, it must have the ability to mitigate the severity of unusual disturbances and keep operating under dynamic conditions. It must be flexible or adaptive, providing a defined response to internal and external system changes. It must also provide good connectivity so that services are only suspended in some operating units and not in the entire system, and it must exhibit a proven ability for operating beyond normal capacities (Juan-García et al., 2017; Leigh and Lee, 2019; Kohler et al., 2020).

On the other hand, despite the fact that decentralized wastewater treatment systems are an interesting alternative for developing countries that have not achieved wide coverage in the sanitation service, especially in rural and peri-urban areas, there are aspects in which cannot exceed the effectiveness of centralized systems in terms of sustainability (Kazora and Mourad, 2018; Singh et al., 2019). In general terms, the environmental performance of the decentralized treatment system will be determined by the level of complexity of the technology used to decontaminate the effluents. In the case of decentralized systems, low complexity solutions are preferred to facilitate their implementation in peri-urban or rural areas (Ribeiro et al., 2017; Starkl et al., 2018; Koottatep et al., 2020).

The implementation of low complexity solutions in decentralized wastewater treatment systems mitigates the pollutant load that can reach surface and groundwater, but depending on the activity that generates it, the degree of removal may not be desired (Starkl et al., 2018). This situation is evident in the case of peri-urban and/or rural areas in which families live off agriculture and agricultural production, where wastewater could contain pesticide residues or emerging pollutants such as antibiotics, hormones and drugs used in the livestock production, in which technologies such as activated sludge and other types of anaerobic treatments would not achieve the complete removal of these contaminants (Rizzo et al., 2020).

Another important factor that must be considered in the decentralized systems is that, due to its low complexity, usually the greenhouse gases from anaerobic treatments are not used and this could become an environmental problem in the future (Cashman et al., 2018; Singh and Kansal, 2018). This should be considered in the design of small-scale biodigesters for the treatment of wastewater for agricultural and livestock activities to take advantage of the biogas as a source of energy (Ramírez-Islas et al., 2020).

3.2. Potential for the application of conventional and natural technologies in decentralized systems

There is no consensus on defining decentralized wastewater management system sizes. Centralization levels are related to local regulations and the categorization given by each expert in urban water management planning from their engineering and environmental perspective. Some authors consider that decentralized systems can serve 2500–5000 people; however, at the regulatory level, this threshold can accommodate up to 10,000 people according to the US Environmental Protection Agency or up to 30,000 people according to the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM).

Table 2 below lists technological alternatives for decentralized systems, which also applies to on-site treatment systems, with the difference that the latter are systems located within the same facilities, which is not the case at decentralized levels (Ulrich et al., 2009; Singh, 2010; Capodaglio, 2017).

González and Bernal (2014) assessed the application potentials for conventional and natural technological alternatives in centralized and decentralized systems through a survey of professionals in the water and sanitation sector. Table 3 denotes the relative weights obtained for the different technological alternatives, wherein the technology with the greatest applicability for centralized systems is activated sludge, followed by UASB reactors and biodisks (González and Bernal, 2014; Capodaglio, 2017).

Likewise, the weighting for the same technologies varies when assessing their applicability for decentralized systems, wherein, according to the relative weights obtained, septic tanks, UASB reactors, and developed wetlands and lagoon systems demonstrate greater applicability, as it can be observed in Table 4 below (González and Bernal, 2014; Capodaglio, 2017).

Therefore, natural treatment alternatives exhibit greater application potential for decentralized wastewater management systems. As the level of centralization increases, the application potential of conventional treatment alternatives also increases, where activated sludge comes first (González and Bernal, 2014; Capodaglio, 2017).

In relation to the conventional and natural technological offers for the four levels of centralization proposed (on-site, decentralized, semi-centralized, and centralized), conventional systems, such as activated sludge and UASB reactors, denote more flexibility for being placed at different levels of centralization, especially since their optimal operating flow has a wider range. However, there is a trend for the implementation

Table 2. Wastewater treatment technologies in decentralized systems.

Treatment level	Technology
Primary	Septic tanks
	Anaerobic ponds
Secondary	Anaerobic filters
	Facultative ponds
	Free Surface Flow Constructed Wetlands
	Subsurface Flow Constructed Wetlands
Tertiary	Maturation ponds
	Duckweed ponds
Land treatment	Slow rate systems
	Rapid infiltration systems
	Overland flow systems

Source: Adapted from Ulrich et al. (2009); Singh (2010); Capodaglio (2017).

Table 3. Relative weights and applicability of technology to centralized systems.

Technology	Relative weight	Applicability
Activated sludge	15, 31	High
UASB Reactor	14,23	
Biodisc	13,88	
Trickling filter	13,34	
Ponds systems	12,09	
Constructed wetlands	9,94	Medium
Aquatic plants systems	9,58	
Septic tank	7,07	Low
Land treatment systems	4,57	
TOTAL	100,00	

Source: Adapted from González and Bernal (2014).

Table 4. Relative weights and applicability of technologies to decentralized systems.

Technology	Relative weight	Applicability
Septic tank	15,11	High
UASB reactor	12,91	
Constructed wetlands	12,91	
Ponds systems	12,24	
Aquatic plants systems	11,22	Medium
Trickling filter	10,72	
Land treatment systems	10,04	
Biodisc	7,85	Low
Activated sludge	7,00	
TOTAL	100,00	

Source: Adapted from González and Bernal (2014).

of conventional technological alternatives in semi-centralized and centralized management systems, which is the opposite of what occurs with natural treatment technologies. In fact, the application of natural treatment technologies increases as wastewater management is decentralized, which is associated with high implementation requirements coupled with the operational simplicity and low costs associated with smaller treatment systems (Figure 1) (González and Bernal, 2014; Guo et al., 2014; Capodaglio, 2017).

The most favorable reuse potential is for agriculture, followed by urban reuse and energy recovery. Similarly, it has a stronger association with natural treatment alternatives than with conventional technologies (Figure 2).

The highest application reuse potential in agriculture was reported by natural treatment systems such as lagoons (17.4%), artificial wetlands (14.9%), lagoons with aquatic plants (11.6%), and land disposal and septic tank systems (7.4%). Regarding conventional treatment alternatives, the same agricultural reuse potential was identified for activated sludge, trickling filter, and biodisks (10.7%) followed by UASB reactors (9.1%) (Maryam and Büyükgüngör, 2019).

The same trend was identified for urban water reuses, where natural treatment alternatives also exhibit the highest reuse potential in lagoons and artificial wetlands (20.5%), lagoons with aquatic plants (13.6%), and land disposal and septic tank systems (3.4%) (Salgot and Folch, 2018; Maryam and Büyükgüngör, 2019).

For energy recovery, the UASB reactor presents the highest applicability at 45.7%, followed by activated sludge at 15.2% and lagoon systems at 13.0%. All of the other technologies reported applicability

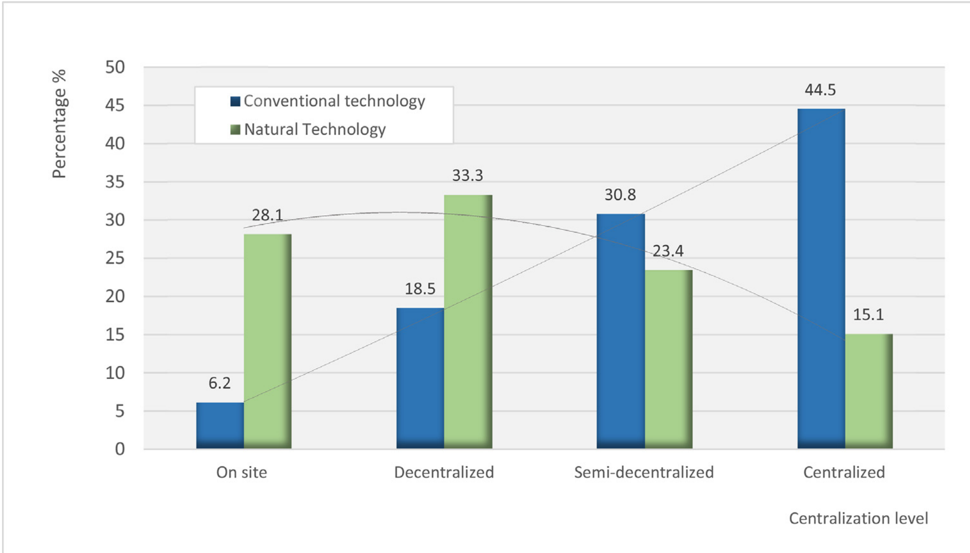

Figure 1. Applicability of conventional and natural technological alternatives at each centralization level.

percentages below 8% for energy recovery (Maaß and Grundmann, 2016).

Although the results of this study show the benefits of decentralized systems as an adequate option for wastewater treatment for developing countries, based on the technical concepts of experts in the area, it is important to highlight that the results could vary, if the study took into account the opinions of experts from developed countries in which institutional, environmental, economic and social factors could favor a greater degree of centralization to strengthen the existing infrastructure for the treatment of emerging pollutants (Capodaglio, 2017; Rizzo et al., 2020).

4. Conclusions

As a conclusion, in general terms, we can say that the higher the level of centralization, the lower the potential for agricultural and urban reuse and the higher the potential for energy recovery (for which technological alternatives with energy generation potential must be considered). Likewise, to the extent to which it is possible to plan the decentralized management of wastewater, the potential for the application of natural treatment technologies thereby increases. In addition, there are some competitive advantages of decentralization that it is important to consider for the planning management of wastewater for urban, peri-urban and rural areas of developing countries; as there is a better distribution of sewage investment costs by reducing distances, diameters, and sometimes pumping stations; the chance to extend wastewater treatment coverages and reducing environmental impacts and risks to public health due to contamination; the possibilities for stage planning, which implies that the design flow of the treatment system is reduced, thus, providing better hydraulic system operation and more concentrated wastewater and facilitating its treatment and the reuse potential for agriculture and other urban activities implies, as the case may be, less pressure on water resources, lower high-quality water demands, greater

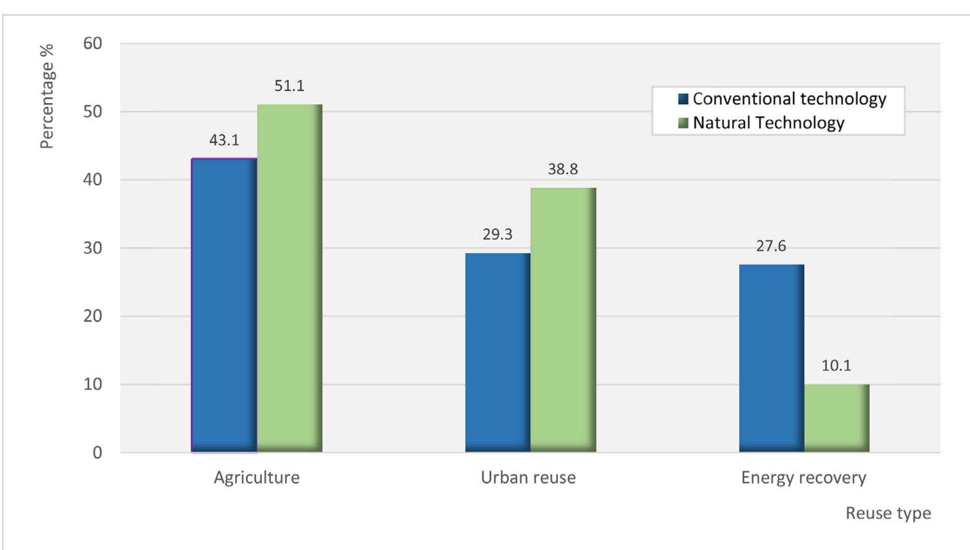

Figure 2. Application potential according to reuse type and its relationship with natural and conventional technological alternatives.

return on investment rates, less fertilizer consumption, and greater nutrient use and energy recovery.

Declarations

Author contribution statement

Diana Bernal & Inés Restrepo: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Simón Grueso-Casquete: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest statement

The authors declare no conflict of interest.

Additional information

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References

Alvarado, A., Larriva, J., Sánchez, E., Idrovo, D., Cisneros, J.F., 2017. Assessment of decentralized wastewater treatment systems in the rural area of Cuenca, Ecuador. Water Pract. Technol. 12 (1), 240–249.
Arias, A., Rama, M., González-García, S., Feijoo, G., Moreira, M.T., 2020. Environmental analysis of servicing centralised and decentralised wastewater treatment for population living in neighbourhoods. J. Water Process Eng. 37, 101469 (June).
Burkhard, R., Deletic, A., Craig, A., 2000. Techniques for water and wastewater management: a review of techniques and their integration in planning. Urban Water 2, 197–221.
Burton, F.L., Stensel, H. David, Tchobanoglous, G., 2014. Wastewater Engineering: Treatment and Resource Recovery, fifth ed. McGraw-Hill Higher Education, New York.
Caicedo, J.C., Bernal, D., 2014. Aspectos claves para la selección de esquemas descentralizados en el manejo de aguas residuales municipales en Colombia. Trabajo de grado. Programa de Ingeniería Sanitaria y Ambiental. Universidad del Valle, Cali.
Capodaglio, Andrea G., 2017. Integrated, decentralized wastewater management for resource recovery in rural and peri-urban areas. Resources 6 (2).
Capodaglio, A.G., Callegari, A., Cecconet, D., Molognoni, D., 2017. Sustainability of decentralized wastewater treatment technologies. Water Pract. Technol. 12 (2), 463–477.
Cashman, S., Ma, X., Mosley, J., Garland, J., Crone, B., Xue, X., 2018. Energy and greenhouse gas life cycle assessment and cost analysis of aerobic and anaerobic membrane bioreactor systems: influence of scale, population density, climate, and methane recovery. Bioresour. Technol. 254, 56–66.
Chirisa, I., Bandauko, E., Matamanda, A., Mandisvika, G., 2017. Decentralized domestic wastewater systems in developing countries: the case study of Harare (Zimbabwe). Appl. Water Sci. 7 (3), 1069–1078.
Daigger, G., 2007. Wastewater management in the 21st century. J. Environ. Eng. 133 (7), 671–680.
Daigger, G., 2009. Evolving urban water and residuals management paradigms: water reclamation and reuse, decentralization, and resource recovery. Water Environ. Res. 81 (8), 809–823.
Eales, K., Blackett, I., Siregar, R., Febriani, E., 2013. Review of Community-Managed Decentralized Wastewater Treatment Systems in Indonesia. Water and Sanitation Program Technical Paper; WSP. World Bank. World Bank, Washington, Dc. https://openknowledge.worldbank.org/handle/10986/17751.
Eggimann, S., Truffer, B., Maurer, M., 2016. The cost of hybrid waste water systems: a systematic framework for specifying minimum cost-connection rates. Water Res. 103, 472–484.
Eggimann, S., Truffer, B., Feldmann, U., Maurer, M., 2018. Screening European market potentials for small modular wastewater treatment systems – an inroad to sustainability transitions in urban water management? Land Use Pol. 78, 711–725 (August 2017).
González, G., Bernal, D., 2014. Caracterización de la oferta tecnológica para el tratamiento de las aguas residuales en esquemas descentralizados en zonas urbanas de Colombia. Trabajo de Grado. Programa de Ingeniería Sanitaria y Ambiental. Universidad del Valle, Cali.
Guo, X., Liu, Z., Chen, M., Liu, J., Yang, M., 2014. Decentralized wastewater treatment technologies and management in Chinese villages. Front. Environ. Sci. Eng. 8 (6), 929–936.
Hama, A.R., Al-Suhili, R.H., Ghafour, Z.J., 2019. A multi-criteria GIS model for suitability analysis of locations of decentralized wastewater treatment units: case study in Sulaimania, Iraq. Heliyon 5 (3), e01355.
Iribarnegaray, M.A., Rodriguez-Alvarez, M.S., Moraña, L.B., Tejerina, W.A., Seghezzo, L., 2018. Management challenges for a more decentralized treatment and reuse of domestic wastewater in metropolitan areas. J. Water Sanit. Hyg. Dev. 8 (1), 113–122.
Juan-García, P., Butler, D., Comas, J., Darch, G., Sweetapple, C., Thornton, A., Corominas, L., 2017. Resilience theory incorporated into urban wastewater systems management. State of the art. Water Res. 115, 149–161.
Jung, Y.T., Narayanan, N.C., Cheng, Y.L., 2018. Cost comparison of centralized and decentralized wastewater management systems using optimization model. J. Environ. Manag. 213, 90–97.
Kazora, A.S., Mourad, K.A., 2018. Assessing the sustainability of decentralized wastewater treatment systems in Rwanda. Sustainability (Switzerland) 10 (12).
Kohler, L.E., Silverstein, J.A., Rajagopalan, B., 2020. Resilience of on-site wastewater treatment systems after extreme storm event. J. Sustain. Water Built Environ. 6 (2), 1–9.
Koottatep, T., Connelly, S., Pussayanavin, T., Khamyai, S., Sangchun, W., Sloan, W., Polprasert, C., 2020. 'Solar septic tank': evaluation of innovative decentralized treatment of blackwater in developing countries. J. Water Sanit. Hyg. Dev. 10 (4), 828–840.
Kreter, K., Cardona, J.A., 2017. Steps towards implementing decentralized rural sanitation solutions: an institutional assessment of the Brazilian sanitation sector. Water Pract. Technol. 12 (2), 363–371.
Khayambashi, Eshan, 2017. Spatial location of urban water and wastewater installations, with the aim of increasing the resilience of crises. Socio-Spatial Stud. 1, 56–66.
Leigh, Nancey Green, Lee, Heonyeong, 2019. Sustainable and resilient urban water systems: the role of decentralization and planning. Sustainability 11 (3).
Liang, X., van Dijk, M.P., 2008. Economic and financial analisys of decentralized water recycling systems in Beijing. In: Ponencia presentada al 3rd SWITCH Scientific Meeting.
Libralato, G., Volpi Ghirardini, A., Avezzù, F., 2011. To centralise or to decentralise: an overview of the most recent trends in wastewater treatment management. J. Environ. Manag. 94 (1), 61–68.
Maaß, O., Grundmann, P., 2016. Added-value from linking the value chains of wastewater treatment, crop production and bioenergy production: a case study on reusing wastewater and sludge in crop production in Braunschweig (Germany). Resour. Conserv. Recycl. 107, 195–211.
Macoun, P., Prabhu, R., 1999. Guidelines for Applying Multi-Criteria Analysis to the Assessment of Criteria and Indicators, Vol. 9. CIFOR.
Maryam, B., Büyükgüngör, H., 2019. Wastewater reclamation and reuse trends in Turkey: opportunities and challenges. J. Water Process Eng. 30, 100501 (November 2016).
Masmoudi Jabri, K., Nolde, E., Ciroth, A., Bousselmi, L., 2020. Life cycle assessment of a decentralized greywater treatment alternative for non-potable reuse application. Int. J. Environ. Sci. Technol. 17 (1), 433–444.
Massoud, M.A., Tarhini, A., Nasr, J.A., 2009. Decentralized approaches to wastewater treatment and management: applicability in developing countries. J. Environ. Manag. 90 (1), 652–659.
Mu'azu, N.D., Abubakar, I.R., Blaisi, N.I., 2020. Public acceptability of treated wastewater reuse in Saudi Arabia: implications for water management policy. Sci. Total Environ. 721.
Narayan, A.S., Fischer, M., Lüthi, C., 2020. Social network analysis for water, sanitation, and hygiene (WASH): application in governance of decentralized wastewater treatment in India using a novel validation methodology. Front. Environ. Sci. 7, 18.
Nas, B., Uyanik, S., Aygün, A., Dogan, S., Erul, G., Batuhan Nas, K., Dolu, T., 2020. Wastewater reuse in Turkey: from present status to future potential. Water Sci. Technol. Water Supply 20 (1), 73–82.
Nhapi, I., 2004. A framework for the decentralised management of wastewater in Zimbabwe. Phys. Chem. Earth 29, 1265–1273.
Opher, T., Friedler, E., 2016. Comparative LCA of decentralized wastewater treatment alternatives for non-potable urban reuse. J. Environ. Manag. 182, 464–476.
Purnomo, A., Khairina, N., 2016. Planning of decentralised wastewater treatment in RW 9 Genteng Subdistrict, Surabaya city. Proc. - Soc. Behav. Sci. 227, 791–798.
Ramírez-Islas, M.E., Güereca, L.P., Sosa-Rodriguez, F.S., Cobos-Peralta, M.A., 2020. Environmental assessment of energy production from anaerobic digestion of pig manure at medium-scale using life cycle assessment. Waste Manag. 102, 85–96.
Ribeiro, T.B., Brandt, E.M.F., de Almeida, P.G.S., Flórez, C.A.D., Chernicharo, C.A. de L., 2017. Technological improvements in compact UASB/SBTF systems for decentralized sewage treatment in developing countries. Desalination Water Treat. 91, 112–120.
Rizzo, L., Gernjak, W., Krzeminski, P., Malato, S., McArdell, C.S., Perez, J.A.S., Fatta-Kassinos, D., 2020. Best available technologies and treatment trains to address current challenges in urban wastewater reuse for irrigation of crops in EU countries. Sci. Total Environ. 710, 136312.
Roefs, I., Meulman, B., Vreeburg, J.H.G., Spiller, M., 2017. Centralised, decentralised or hybrid sanitation systems? Economic evaluation under urban development uncertainty and phased expansion. Water Res. 109, 274–286.

Salgot, M., Folch, M., 2018. Wastewater treatment and water reuse. Curr. Opin. Environ. Sci. Health 2 (1), 64–74.

Saliba, R., Callieris, R., D'Agostino, D., Roma, R., Scardigno, A., 2018. Stakeholders' attitude towards the reuse of treated wastewater for irrigation in Mediterranean agriculture. Agric. Water Manag. 204, 60–68 (September 2017).

Singh, K., 2010. Decentralised wastewater treatment system (DEWATS). In: Paper presented at the Forum on Eco-Efficient Water Infrastructure Development for Green Growth in Asia and the Pacific. Ministerial Conference on Environment and Development in Asia and the Pacific 2010, Astana, Kazakhstan.

Singh, P., Kansal, A., 2018. Energy and GHG accounting for wastewater infrastructure. Resour. Conserv. Recycl. 128, 499–507.

Singh, A., Sawant, M., Kamble, S.J., Herlekar, M., Starkl, M., Aymerich, E., Kazmi, A., 2019. Performance evaluation of a decentralized wastewater treatment system in India. Environ. Sci. Pollut. Control Ser. 26 (21), 21172–21188.

Singhirunnusorn, W., 2009. An Appropriate Wastewater Treatment System in Developing Countries: Thailand as a Case Study. University of California, Los Angeles.

Spirandelli, D., Dean, T., Babcock, R., Braich, E., 2019. Policy gap analysis of decentralized wastewater management on a developed pacific island. J. Environ. Plann. Manag. 62 (14), 2506–2528.

Starkl, M., Anthony, J., Aymerich, E., Brunner, N., Chubilleau, C., Das, S., Singh, A., 2018. Interpreting best available technologies more flexibly: a policy perspective for municipal wastewater management in India and other developing countries. Environ. Impact Assess. Rev. 71, 132–141 (October 2017).

Ulrich, Andreas, Reuter, Stefan, Gutterer, Bernd, 2009. Decentralised Wastewater Treatment Systems (DEWATS) and sanitation in developing Countries. A practical guide. Bremen Overseas Research and Development Association.

UN (United Nations), 2019. World Population Prospects 2019: Highlights, ST/ESA/SER.A/423. Population Division, Department of Economic and Social Affairs, United Nations, New York, USA.

UNICEF & WHO, 2015. Progress on Sanitation and Drinking Water – 2015 Update and MDG Assessment. Genova. WHO.

Vladeanu, G., Matthews, J., 2019. Wastewater pipe condition rating model using multicriteria decision analysis. J. Water Resour. Plann. Manag. 145 (12), 1–10.

Wu, L., Mao, X., Yang, X., Li, Z., Fang, S., 2017. Sustainability assessment of urban water planning using a multicriteria analytical tool - a case study in Ningbo, China. Water Pol. 19 (3), 532–555.

Xu, M., Zhu, S., Zhang, Y., Wang, H., Fan, B., 2019. Spatial-temporal economic analysis of modern sustainable sanitation in rural China: resource-oriented system. J. Clean. Prod. 233, 340–347.

Yulistyorini, A., Camargo-Valero, M.A., Sukarni, S., Suryoputro, N., Mujiyono, M., Santoso, H., Rahayu, E.T., 2019. Performance of anaerobic baffled reactor for decentralized waste water treatment in urban Malang, Indonesia. Processes 7 (4), 1–12.