

Review Article

A Review on Sludge Management Options in Small Communities Based on Different Wastewater Treatment Alternatives

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Abstract

Sludge management represents a critical challenge in wastewater treatment, particularly for small communities in developing countries where technical and economic limitations hinder the implementation of conventional treatment systems. This review aimed to evaluate sludge management options in small communities based on different wastewater treatment alternatives, addressing environmental and health implications. Wastewater treatment methods in small communities were categorized into three groups based on sludge production: sludge-less (including subsurface constructed wetlands, trickling filters, and intermittent sand filters), low-sludge (including septic tanks, biogas settlers, anaerobic baffled reactors, and anaerobic filters), and high-sludge (including conventional activated sludge-based systems, rotating biological contactors, and membrane bioreactors). The findings revealed substantial variations in sludge quantity across different treatment processes, with conventional activated sludge systems producing the highest sludge volumes while constructed wetlands and trickling filters generate minimal sludge. Two main sludge management approaches—centralized and on-site—were identified, with on-site methods such as planted sludge drying beds and sludge treatment wetlands offering more suitable options for small communities due to their lower operational and energy requirements. However, health and environmental concerns, including pathogen content, heavy metals, nutrients, and potential groundwater contamination, necessitate proper sludge stabilization before agricultural reuse. This review provides essential criteria for sludge management in small communities that support decision-makers in selecting appropriate options based on local characteristics and emphasizes the critical influence of wastewater treatment method selection on sludge management outcomes in rural areas.

Keywords: Sludge reuse, Small-scale wastewater, Low-cost treatment, Rural areas

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Introduction

Increasing water demand and water resources management are a serious challenge in many countries.¹ One of the most important factors in the management of water resources is the prevention of water pollution, especially in arid and semi-arid countries located in the desert belt.² Municipal and industrial wastewaters, and agricultural effluent are the most important sources of water pollution. Therefore, wastewater treatment is one of the water quality control activities, which is especially necessary in areas with water stress.³ In addition, wastewater pathogens are the cause of many diseases, which has made wastewater treatment

a necessity to prevent health consequences.⁴ Therefore, wastewater treatment has two main goals: controlling the environmental consequences and disease prevention, which are done by different methods according to technical and economic factors.⁵

The coverage ratio of wastewater treatment in cities and big communities is usually higher than in small communities. In some cases, the lack of funds has caused small communities' wastewater, especially in remote areas, to be discharged without treatment into water sources such as rivers.⁶ In general, the lack of financial support, operational skills, and organization and responsibility



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have made it difficult to apply conventional wastewater treatment systems in small communities.⁷ In this condition, natural treatment methods and easy-to-operate methods such as constructed wetlands, sand filter, anaerobic baffled reactors, and septic tanks have been proposed as a suggested approach for small community wastewater treatment.⁸ These methods are specially adapted to the characteristics of small communities, and if well designed, they can provide wastewater management with lower costs than conventional methods.⁹ These methods enable wastewater reuse for local needs.⁸ However, sludge management in small communities is a challenge in wastewater management.

Although the development of wastewater treatment in small communities such as rural areas has been considered by local policy-makers in recent decades to achieve sustainable development goals,¹⁰ available sludge management methods are generally not suitable for small-scale treatment plants. Simple sludge management methods, such as disposal of the slurry on land owing to the presence of microorganisms or contaminants such as heavy metals, can lead to health risks.¹¹ Considering the high costs of conventional sludge treatment systems such as thickening and dewatering, small communities, especially in developing countries, will face serious challenges in managing sewage sludge.¹² In this context, uncontrolled disposal of sewage sludge in small communities is a potential risk to the environment because of soil and water resource contamination.¹³ However, considering the potential of sludge for agricultural use can be a key point in sludge management in small communities.¹⁴ Sludge is an inevitable by-product of biological wastewater treatment processes,¹⁵ which are usually dumped in nearby lands in rural areas owing to equipment limitations, and are the source of subsequent health and environmental problems.¹⁶ Also, if the sludge landfilled, it can cause pollution in groundwater by leachate leakage.¹⁷ But the potential for sludge utilization has focused on the importance of its management in small communities. For example, due to the presence of significant phosphorus and nitrogen in the sludge, it is useful for agricultural land and land reclamation.¹⁸ However, conventional sludge treatment processes used in large treatment plants require operational skills as well as capital and operating costs, which is a limitation in small communities.^{7,9}

Therefore, this study is an innovative review of sludge management methods in small communities and rural areas, which was a gap in previous studies. This study also dealt with differences in sludge quantity and characteristics among various wastewater treatment methods, adding to the innovative nature of this research. The aim of this study was to review sludge management methods in small communities. In this review, the requirements for sludge management of different wastewater treatment alternatives in small communities were studied. This comparison helps decision-makers in choosing wastewater management methods in rural

areas. This review can help local policymakers in selecting optimal methods based on local characteristics from the categorized options. To achieve the study objectives, this research sought to answer one main question: "What are the appropriate methods of sludge management according to the characteristics of small communities?" Additionally, this study addressed the following questions:

What is the difference in the quantity of sludge in different wastewater treatment methods for small communities?

What are the environmental aspects of sludge management in small communities?

What are the health aspects of sludge management in small communities?

Selection of Articles

To answer the research questions, A search protocol was used based on relative keywords and three stages of screening were performed by the authors for select final article.^{19,20} In the first step, considering the titles, articles mentioning wastewater treatment in small communities were selected. In the second step, the abstracts of the articles selected in the first stage were reviewed, and articles investigating wastewater treatment and sludge management methods in small communities were selected. In the third step, full-text articles with relevant information about the research questions were selected. The inclusion criterion was providing information on sludge management methods in small communities or rural areas.

Results and Discussion

The results of this study were categorized and discussed in headings included wastewater treatment approach, wastewater treatment alternatives in small communities, sludge management methods in small communities, and environmental and health considerations.

Wastewater Treatment Approach for Small Communities

The most common form of wastewater treatment includes collecting wastewater from producing sources by a network of pipelines and transferring it to a central treatment plant.²¹ One of the main characteristics of the centralized approach is the extensive collection network. Along the network, the diameter of the pipes will increase and more network facilities and depth will be required.²² Therefore, the implementation of the network will be associated with higher capital and operating costs. Another characteristic of this approach is the need for advanced methods, technology, and energy due to the large volume of wastewater reaching the treatment plant.^{21,22} Centralized wastewater treatment methods that use processes such as activated sludge result in the production of significant volumes of sludge that must be managed in subsequent processes.²³

As shown in [Figure 1](#), in the decentralized approach, wastewater is collected and treated in the nearest location using natural processes with minimal need for advanced

equipment (pumping, aeration, mixing) and chemicals.²⁴ In the decentralized approach, the wastewater collection network is shorter and several small, simple treatment systems are used instead of a large central treatment plant.²⁵ Common processes in decentralized wastewater treatment methods such as septic tanks, anaerobic baffled reactors, anaerobic filters, lagoons, and constructed wetland can pose risks from sludge dumping in the environment and subsequent health and environmental impacts.⁷ One of the consequences of using a decentralized approach is the reduction of sludge production on account of the use of natural treatment processes.²⁶

In many small communities, economic limitation prevents the development of a collection network and the construction of a treatment plant. In this situation, the on-site treatment approach is a preferred option for wastewater management in small communities.²⁷ On-site treatment includes a simple process and follow-up of effluent management tools in the land. The use of these simple systems requires the presence of a permeable area with a suitable structure to accept effluent.^{27,28} The very suitable capabilities as well as easy operation and maintenance conditions have caused the use of the on-site approach to expand.²⁹ The main problems in these systems are improper operation such as delayed sludge disposal, excessive hydraulic loading owing to the connection of new sources or load because of temporary residents.³⁰

Wastewater Treatment Alternatives in Small Communities

Different methods of wastewater treatment can be chosen using the mentioned approaches. Each method differs in terms of sludge volume and disposal frequency. As shown in Table 1, wastewater treatment methods in small communities include sludge-less, low-sludge, and high-sludge categories. Therefore, the need for sludge management varies across methods, which can be an influential factor in decision-making for wastewater management design in small communities.

The settler is the simplest primary wastewater treatment method for small communities.³² This structure works like primary sedimentation in centralized treatment plants and, by providing retention time, causes solids to settle.²⁵ This method requires frequent sludge disposal. Therefore, it is a simple wastewater treatment method, but it requires planning for sludge management.^{25,32} As shown in Figure 2, septic tanks are containers made of concrete, plastic, fiberglass, or PVC in which sedimentation and anaerobic processes are carried out.³³ These units provide medium-level treatment and are used for wastewater treatment in small communities or as pre-treatment in decentralized systems.³⁴ A septic tank consists of at least two, sometimes three chambers. The chamber walls extend 15-30 cm above the wastewater level. Measures to avoid infiltration of surface water or precipitation during the rainy season should be considered. The outlet is built

Table 1. Sludge Production in Wastewater Treatment Methods.^{7,23,31}

Types	Alternatives	Remarks
Sludge less	Subsurface constructed wetlands	Sludge production is very low. Sludge management is performed by removing the surface layer of the bed at infrequent intervals.
	Trickling filters	
	Intermittent sand filters	
Low sludge	Septic tanks	Sludge production is low. Sludge removal is required at regular intervals. Stabilization is necessary owing to the sludge characteristics.
	Biogas settlers	
	Anaerobic baffled reactors	
	Anaerobic filters	
High sludge	Conventional activated sludge-based systems	Sludge production is high. Sludge is discharged at short intervals or daily. Stabilization is necessary owing to the sludge characteristics.
	Rotating Biological Contactors (RBC)	
	Membrane Bioreactors (MBR)	

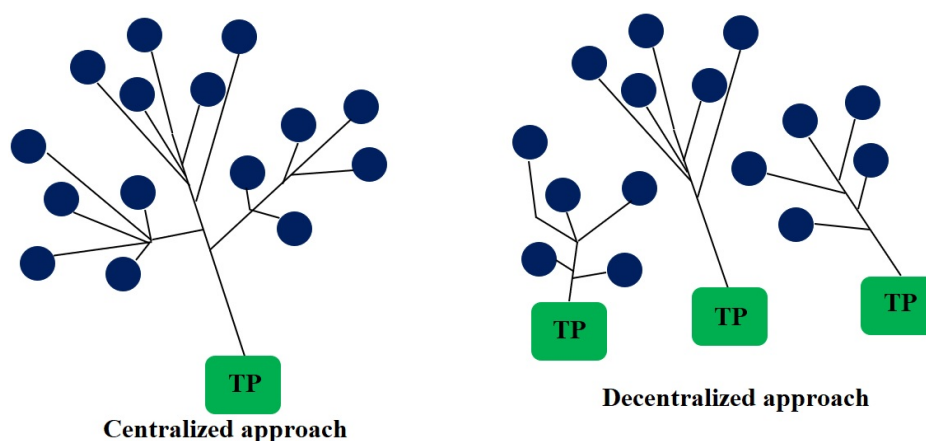


Figure 1. Wastewater Management Approaches; TP: Treatment Plant

10-15 cm below the inlet.³⁵ The first chamber makes up about two-thirds of the total volume of the septic tank. The total volume of a septic tank can be estimated by assuming 80 to 100 liters for each household user, but the exact volume calculation depends on the wastewater characteristics. Hydraulic residence time is typically 2 days. The efficiency of septic tank treatment ranges from 25 to 50% removal of chemical oxygen demand.³⁶ When the accumulated sludge fills more than two-thirds of the tank, the rate of organic matter removal decreases drastically, so periodic sludge disposal is necessary.^{35,36} The biogas settler is usually a dome-shaped structure. The microbial digestion process is completed in anaerobic conditions and leads to the production of biogas.²⁵ This process is often used as an alternative to a septic tank or settler because it provides a similar level of treatment, but its advantage is the production of biogas.³⁷

Considering that the hydraulic retention time is usually between 15 and 30 days, less sludge is produced in this method.^{25,37}

Other wastewater treatment methods in small communities that are more efficient at reducing organic matter include the anaerobic baffled reactor and anaerobic filter.³⁸ The anaerobic baffled reactor is a modified septic tank with a series of baffles. Increasing contact time with active biomass (sludge) leads to improved treatment.³⁹ By using this structure, biological oxygen demand can be reduced by 70 to 90%, which is much more than the removal of organic matter in a normal septic tank.⁴⁰ This system consists of 3 to 5 series chambers, and its volume is determined based on a hydraulic retention time of 8 hours.^{38,39} However, as shown in Figure 3, an anaerobic filter is a fixed-bed reactor in an anaerobic contact process with one or more filtration chambers in series.^{38,40,41} When

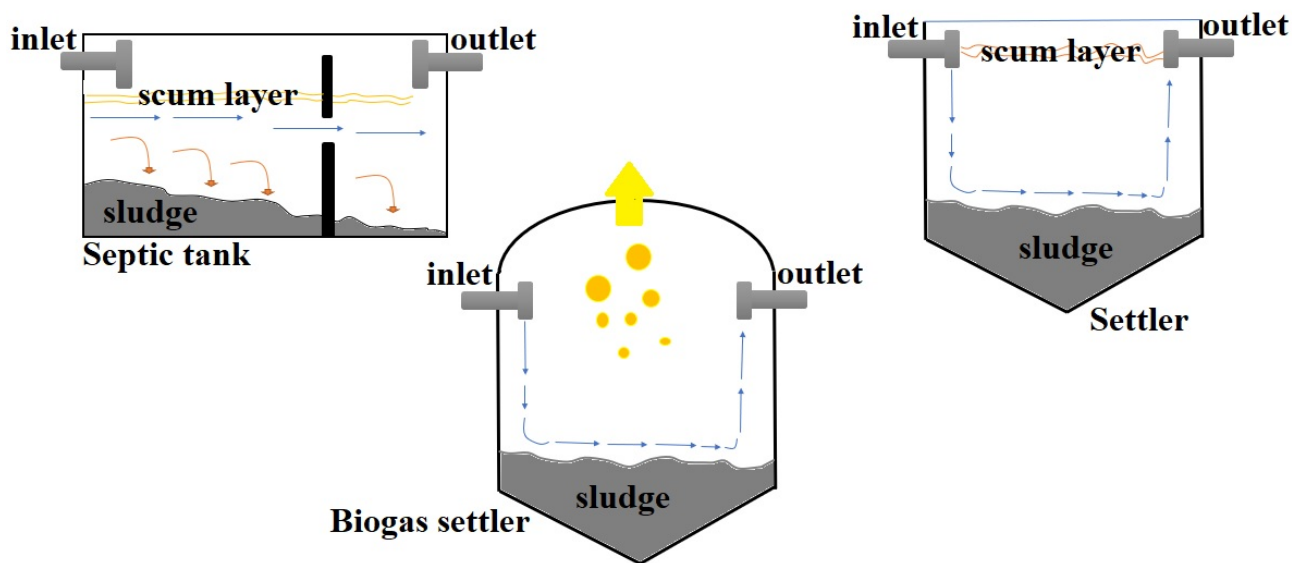


Figure 2. Some Wastewater Treatment Methods for Small Communities

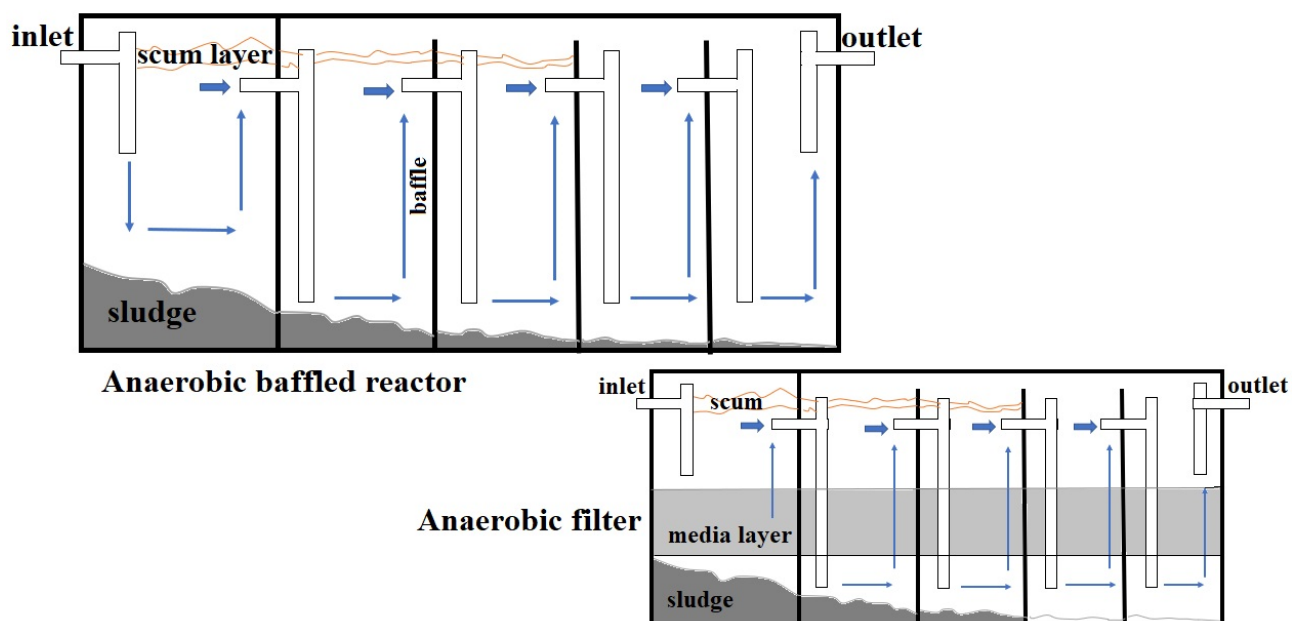


Figure 3. Anaerobic Baffled Reactor and Anaerobic Filter

the wastewater passes through the filter, particles are trapped and organic matter is decomposed by the active biomass that is attached to the filter media.⁴² The filter material can be sand, stone, or special plastic granules. The hydraulic residence time for domestic wastewater is about 1.5 to 2 days. One of the characteristics of the anaerobic baffled reactor and the anaerobic filter is the production of less sludge as well as more stabilized sludge compared to septic tanks and settling tanks.^{38,42}

Some other methods are also used for further treatment to achieve reuse or discharge standards. For example, aerobic methods are used for complete nitrogen removal.⁴³ Methods such as constructed wetlands, lagoons, aerobic filters, and trickling filters are among the most widely used for wastewater treatment in small communities.^{7,33} However, most of these methods are part of sludge-less systems. Therefore, sludge management in small communities often includes settled solids in settling tanks, septic tanks, biogas settlers, anaerobic baffled reactors, and anaerobic filters.

Sludge Management Methods in Small Communities

Technical and economic characteristics of small communities have led to two main approaches to sludge management. As shown in Table 2, two main approaches—centralized sludge management and on-site sludge management—can be defined for small communities. In the centralized approach, the sludge collected from treatment units is transferred to a central management system. This approach can provide conditioning, stabilization, and disinfection units. However, in the decentralized approach, simpler sludge management methods that require more land are used. The health and environmental risks of transferring un-stabilized sludge, as well as the limitations of operating conventional sludge treatment systems in small communities, are serious concerns when using a centralized approach.^{44,45} Thus, sludge management in small communities is often based on land treatment systems or reuse to improve soil structure.⁴⁶

Sludge dewatering is an important goal, because sludge contains a high proportion of liquid, and reducing this volume simplifies and greatly reduces the costs of the next steps.⁵⁰ The most important health goal of sludge management is pathogen reduction.⁴⁸ Also, environmental goals are achieved through pathogen reduction, stabilization of organic matter, reduction of nutrients, and reuse or safe disposal of final treatment products.⁴⁵

Unplanted Sludge Drying Beds

Sludge drying is an effective method to reduce the volume of sludge, which is especially important when it has to be transferred to another place for further treatment, final use or disposal.⁵¹ However, this method is not effective in stabilizing the organic component of the sludge or reducing the pathogen content. This process is the best option for small communities where there is available land.⁵² This process is a low-cost option that can be used in warm and temperate climates but heavy rain may prevent proper sludge drying.⁴⁹ Unplanted sludge drying beds are a simple and permeable bed. When loaded with sludge, it collects leachate and dries the sludge by evaporation. Approximately 50 to 80% of the sludge volume is reduced as liquid or vaporized.⁴⁹ The liquid collection network is embedded in the bottom of the bed and on it there is a maximum 20 cm layer of sand to provide effective drying.⁵³ In this method, the final water content after 10 to 15 days of drying should be approximately 60%.⁵³ Table 3 compares the advantages and limitations of unplanted sludge drying beds with other methods.

Planted Sludge Drying Beds

Planted sludge drying beds are an improved form of unplanted sludge drying beds in which plants provide additional benefits for sludge treatment.⁵⁴ An important advantage of this process is that the filters do not need sludge removal after each load, so fresh sludge can be loaded directly onto the previous layer. Another advantage of plants is their root system, which increases the porosity of the filter and prevents clogging.⁵⁵ Hence, in addition to dewatering, this method also provides advantages for sludge stabilization. Furthermore, the roots of the plants create channels through the media that allow water to drain easily.⁵⁶

Sludge Treatment Wetlands

All types of sludge, including sludge from septic tanks and other wastewater treatment methods in small communities, can be loaded into sludge treatment wetlands.⁵⁷ The main purpose of this system is sludge dewatering. However, the advantages of the bed and the plants also lead to the reduction of organic matter and stabilization of the sludge.⁵⁸ Requirements such as the slope of the floor and the loading rate are the reason for the difference between sludge treatment wetlands and sludge drying beds. However, the combination of filtration and the advantage of plants is the reason for

Table 2. Sludge Management Approaches for Small Communities.^{44,47-49}

Approaches	Advantage	Limitation
Centralized	It is possible to complete sludge treatment processes. It is possible to produce biogas. It is possible to reduce the risk of pollutant emission to the environment. It is possible to require less land.	Operation is more difficult. Energy requirements are higher. Construction costs are higher. The risk of sludge leakage during collection and transportation is higher.
On-site	No skilled operator is needed. No energy input is required. Construction and operating costs are lower.	Land requirement is higher. The risk of water pollution exists in case of improper operation. Biogas production is not possible.

Table 3. Advantages and Limitations of Sludge Management Methods.⁵³⁻⁵⁶

Method	Advantage	Limitation
Unplanted Sludge Drying Beds	Simple operation. Optimum volume reduction up to 80%. Optimum dewatering up to 40%.	Land requirement. Odor problem. Vector problem. Less stabilization than other methods.
Planted Sludge Drying Beds	Providing additional benefits for sludge treatment through plants Less clogging No sludge removal required Simple operation	Land requirement Harvesting requirement Odor and vector problems Reuse limitation
Sludge treatment wetlands	Better stabilization Additional benefits for sludge treatment through plants Simple operation No sludge removal required	High land requirement Need for harvesting Limited reuse Groundwater pollution prevention requirements
Digestion	Greater stabilization than other methods Less land requirement Biogas production Safe for soil and water resources Providing reuse standards	High-cost technology requirement Skilled operator requirement

the similarity in performance between these two systems. Sludge loading in wetlands is intermittent, and the interval between two loadings can be several days to several weeks depending on the thickness of the sludge and climatic conditions.⁵⁹ These conditions are suitable for sludge management in small communities because the discharge of sludge from treatment units such as septic tanks and anaerobic baffled reactors is intermittent. Also, in on-site wastewater treatment approaches, the discharge of sludge from the treatment units does not occur simultaneously. Dewatering, represented by an increase in sludge solids, has been reported at 15 to 30%, and the ability of this system to reduce volatile solids has been reported at 25 to 50%.^{55,59} This potential for dewatering and stabilization of sludge means that the sludge coming out of sludge treatment wetlands can be used in agriculture and land reclamation without the need for further treatment.^{55,59}

Environmental and Health Considerations

Sludge contains various compounds, including heavy metals, nutrients, and metalloids, whose concentration depends on the nature of the wastewater, wastewater treatment method, and sludge treatment method.⁵⁷ Many of these compounds are known as pollutants or toxic compounds in the environment, and their entry into the environment from sludge is a health and environmental threat.⁶⁰ It is even possible that many compounds in sludge with negative consequences for health and the environment have not yet been identified. For example, it has been reported that tens of thousands of chemical compounds are used in industry, agriculture, and households, and eventually a large part of them will enter the wastewater flow and accumulate in sludge.^{61,62} Therefore, it is important to pay attention to health and environmental risks in the stages of sludge management, especially reuse. Considering that the processes of wastewater treatment and sludge management in small communities are limited to biological processes,^{8,9} the increasing concentration of compounds resistant to biological degradation in the sludge of small communities is a serious concern. In addition, some biodegradable

compounds are not completely removed in biological processes, and the efficiency of natural processes to remove them is limited.^{62,63} Various compounds, such as nutrients, linear alkylbenzene sulfonates (LASs), polychlorinated biphenyls (PCBs), and polynuclear aromatic hydrocarbons (PAHs), if present in the wastewater of small communities, accumulate in the sludge and are not removed by available processes.^{62,64} Moreover, the increasing concentration of drugs and health care compounds in wastewater and sludge, such as pharmaceuticals and personal care products, hormones, and steroids, is one of the concerns of sludge management and reuse.^{65,66} The immediate concern about the use of sludge in agriculture and land reclamation is its pathogens.⁶⁷ Several pathogens from the categories of bacteria, viruses, fungi, and eggs of parasitic worms naturally exist in wastewater and are found in sludge.⁶⁸ It has been reported that the colony concentration of different pathogens in the sludge, such as *Salmonella* spp., *Escherichia coli*, enteroviruses, and protozoa, was 10^2 – 10^6 per gram of dry matter, which would be a serious health threat if it enters the soil and water sources.⁶² Therefore, sludge management methods, especially for reuse in agriculture, should have the potential to reduce pathogens.⁶⁹ For instance, the concentration of *Escherichia coli* and *Clostridium perfringens* spores in sludge for use in agriculture should not exceed 1,000 and 3,000 CFU per gram of dry matter, respectively.⁶² Hence, although the use of sludge is known as a solution for soil fertility and land reclamation, it also has health and environmental risks. For example, excessive sludge loading and increasing nutrients in the soil will cause surface and groundwater pollution with phosphorus and nitrogen, which has environmental consequences such as eutrophication and nitrate-related health problems. Also, the accumulation of heavy metals and metalloids in plants and their entry into the food chain can cause the accumulation of these pollutants in human tissue.⁶² This study had strengths and limitations. The classification of wastewater treatment methods in small communities based on sludge production potential and

the classification of types of sludge management methods were strengths of this study. The lack of estimation of the economic consequences of available sludge management options in small communities was a limitation of this study that could be considered in future studies. Based on the findings of this review, the following are suggested:

Increasing the use of on-site treatment methods for small and dispersed communities

Using methods that produce less sludge, such as constructed wetlands, in wastewater treatment for small communities

Using land treatment and phytoremediation methods in sludge management due to economic and operational benefits

Conclusion

Wastewater treatment alternatives in small communities are divided into three categories based on sludge production, where the largest amount of sludge is produced in settling tanks and septic tanks. Sludge produced in the anaerobic baffled reactor and anaerobic filter methods has a smaller volume and is relatively stabilized. The use of low-sludge wastewater treatment methods, such as constructed wetlands and trickling filters, reduces the subsequent consequences of sludge management in small communities. However, on-site sludge management may provide more suitable options for local decision-makers due to economic and operational advantages. Due to health and environmental concerns, it is necessary to treat sludge before using it in agriculture and soil reclamation. Due to the technical and economic limitations in small communities, the use of planted sludge drying bed methods and sludge treatment wetlands, which have the ability to reduce solids and stabilize organic materials, is a suitable option for sludge management.

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Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that might have influenced the research presented in this paper.

Ethical Approval

All ethical principles were considered in this article.

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