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From Centralized to Decentralized: a Comparative Analysis of Six Decentralized Domestic Wastewater Treatment Technologies

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Abstract: With the growing urban population and water requirement, the need for decentralized wastewater treatment to complement centralized systems is imminent. This paper reviews six decentralized domestic wastewater treatment technologies and evaluates them with efficiency, cost-effectiveness, environmental impact, and applicability. RAF-HRBC and GDMBR technologies are best suited for urban areas since their high efficiency and small footprint. In contrast, artificial wetlands are more suitable for rural environments due to the large amount of land they require. Despite the promise of these technologies, most of them are unable to meet drinking water standards, suggesting that they still need to be supplemented with other treatment methods to achieve potable water quality.

Keywords: Decentralized Systems, Domestic Wastewater Treatment, Application in Urban Areas.

1. Introduction

1.1. Background

Water resources are very important for human survival and development. With growing populations and industrial expansion, water shortages and pollution have worsened. A quarter of the global population faces severe water scarcity, and water pollution poses increasing public health risks [1]. This has heightened the focus on water pollution treatment.

1.2. Water treatment technology

Water treatment technologies are mainly categorized into centralized and decentralized systems. Densely populated areas favor centralized systems because of economic of scale [2], while decentralized systems allow for on-site treatment, resource recovery, and greater adaptability, reducing environmental impacts and resource waste [3].

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1.3. Problems for today

As populations grow, water scarcity and pollution worsen. Traditional centralized treatment systems face challenges like high costs and aging infrastructure, and limited ability to cope with growing populations and urban expansion [3]. Against this backdrop, decentralized wastewater treatment methods have emerged as a viable alternative. These systems offer a few advantages over centralized treatment, including greater flexibility, lower costs, adaptability to different scales of needs, and ease of operation and maintenance [3]. Decentralized systems can meet the needs of different communities and households, especially in areas where water resources are scarce, and infrastructure is not well developed.

1.4. Study objective

This paper will review several decentralized methods of treating domestic wastewater that are available today. It will also evaluate the performance of each decentralized domestic wastewater treatment method and its advantages and disadvantages. At the same time, an attempt is made to compare and combine several decentralized wastewater treatment methods to find a suitable process for treating domestic wastewater and to provide insights into replacing traditional centralized wastewater treatment with decentralized systems, offering a practical solution to address water shortage challenges.

2. Water treatment method

2.1. Constructed wetland treatment [4]

Constructed Wetlands (CWs) are designed systems that treat domestic wastewater, by using vegetation, soil, and microorganisms to replicate the functions of natural wetlands [4]. Constructed Wetlands offer a practical method to treat wastewater in developing nations due to their low cost and self-sustainability and are well suited to areas that cannot afford expensive centralized treatment facilities [5].

There are several types of constructed wetlands, each with its own corresponding design and targeted removal components. Free Water Surface Wetlands (FWS CWs) are shallow ponds with open water surfaces and submerged or floating plants that eliminate total suspended solids (TSS) and organic matter through sedimentation, filtration, and microbial degradation [4]. Horizontal Subsurface Flow Wetlands (HSSF CWs) effluent flows horizontally through porous media beds planted with vegetation and are effective in removing organic matter and nitrogen [4]. Vertical Subsurface Flow Constructed Wetlands (VSSF CWs) systems significantly enhance oxygen transfer and promote the nitrification process through vertical infiltration of effluent through media beds, thereby effectively removing nitrogen and organic matter from the effluent [4]. Floating Treatment Wetlands (FTWs) are small, constructed platforms that enable aquatic macrophytes to grow in water bodies that are typically too deep. The plant's root system extends through the floating mats into the water column, forming a dense root network, which not only facilitates nutrient and pollutant uptake, but also provides extensive surface area for microbial growth, contributing to water quality improvement [4]. Hybrid wetlands, on the other hand, by combining different wetland configurations, hybrid wetlands can achieve more efficient pollutant removal, and are particularly good at treating complex effluents. These systems utilize the benefits of each wetland type to provide a superior treatment solution [6].

Case studies [4] in China have amply demonstrated the effectiveness of constructed wetlands in treating domestic wastewater. The experimental influent, effluent, and corresponding removal efficiency data and a table comparing them with the national emission standards [7], are shown in

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Table 1. This combined system utilizes the advantages of multiple wetland configurations to improve pollutant removal efficiency. At the same time, the wastewater discharge in this case also meets the Chinese water quality standards for farmland irrigation [4].

Table 1: Experimental data related to constructed wetland case studies in China [4] with Chinese emission standards [7]

Parameter	First class-A standard	First class-B standard	Secondary class	Effluent (mg/L)	Influent (mg/L)	Removal Efficiency
Chemical oxygen demand (COD)	≤50 mg/L	≤ 60 mg/L	≤ 100 mg/L	54.86–69.34	280.25–340.86	Around 80%
Biochemical oxygen demand (BOD)	≤10 mg/L	≤ 20 mg/L	≤ 30 mg/L	-	-	-
NH_4^+-N	≤5 mg/L	≤ 8 mg/L	No clear regulations	25.44–30.45	64.88–70.17	Around 60%
Total Nitrogen (TN)	≤15 mg/L	≤ 20 mg/L	No clear regulations	3.95–6.30	4.44–7.55	Around 23%
Total Phosphorus (TP)	≤0.5 mg/L	≤ 1 mg/L	≤ 3 mg/L	46.04–55.73	66.32–71.03	Around 13%
Total suspended solid (TSS)	≤10 mg/L	≤ 20 mg/L	≤ 30 mg/L	-	-	-

2.2. Integrated Hydroponics-Microbial Electrochemical Technology (iHydroMET) [8]

The iHydroMET system [8] is a novel decentralized approach to wastewater treatment that combines drip irrigation hydroponics and microbial electrochemical technology, specifically designed for household-level domestic wastewater treatment. An integration of physical, chemical, and biological techniques is used by the system to comprehensively eliminate various pollutants from wastewater.

The iHydroMET system also showed excellent results when tested for removal efficiency [9]. It is 93% efficient in removing organics, 98% efficient in removing turbidity, and over 95% efficient in removing emerging contaminants such as steroids. The results [9] show that the iHydroMET system is effective in removing most of the common pollutants when treating domestic wastewater, significantly improving the effluent quality. However, the system is less capable of treating nitrogen and phosphorus, but it meets the standards for agricultural irrigation, making the treated water safe for irrigation and decreasing reliance on freshwater resources [9].

Furthermore, the iHydroMET system has a resource recovery function [8]. Through microbial electrochemical reactions, the system is able to achieve low levels of power production, and although this power output is low, it still has some application value in decentralized wastewater treatment systems [8]. The Catharanthus roseus planted in the system not only has aesthetic value, but also absorbs nutrients from the wastewater through its root system, further improving water quality and providing some ecological and environmental benefits [9].

2.3. Solar-powered electrochemical treatment [10]

Electrochemical advanced oxidation processes (EAOPs) and solar photovoltaic power generation are combined in this innovative wastewater treatment technology [11]. The core of the treatment system consists of an electrochemical wastewater treatment reactor, an H_2O_2 electrosynthesis reactor and a photovoltaic power generator [10]. The H2O2 electrosynthesis reactor utilizes a Natural Air Diffusion Electrode (NADE) cathode as its foundation [10], which is capable of efficiently generating H_2O_2 under non-aerated conditions [10]. The electrochemical wastewater treatment reactor [10] integrates a variety of advanced oxidation processes such as Fenton-like oxidation, UV/H_2O_2 and electro-

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oxidation, thus efficiently eliminating a broad spectrum of pollutants from the wastewater [10]. The photovoltaic power generation equipment supplies the necessary energy for system operation, ensuring its sustainability [10].

The experimental results [10] showed that the system was able to produce H_2O_2 stably under solar power with yields ranging from 1474 to 1535 mg/h, which could consistently provide enough oxidant (H_2O_2) to degrade organic pollutants. Between 77.4% and 80.6% of the electrical energy was efficiently utilized for H_2O_2 generation [10] instead of being wasted on side reactions or other unnecessary energy consumption, which is economical and environmentally friendly12. In a practical application in a rural area of Northwest China [10], decentralized domestic wastewater was treated at a rate of 500 liters per day by the system, effectively removing COD, NH3-N, TP, and bacteria. The experimental effluent, as well as the corresponding removal efficiency data and a table comparing them with the national emission standards [7], are shown in Table 2.

Table 2: Solar-powered electrochemical treatment experimental data [10] with Chinese emission standards [7]

Parameter	First class-A standard	First class-B standard	Secondary class	Effluent (mg/L)	Removal efficiency
Chemical oxygen demand (COD)	⩽ 50 mg/L	⩽ 60 mg/L	⩽ 100 mg/L	Less than 80	34-72%
Biochemical oxygen demand (BOD)	⩽ 10 mg/L	⩽ 20 mg/L	⩽ 30 mg/L	-	-
NH_4^+-N	⩽ 5 mg/L	⩽ 8 mg/L	No clear regulations	About 17	18-40%
Total Nitrogen (TN)	⩽ 15 mg/L	⩽ 20 mg/L	No clear regulations	-	-
Total Phosphorus (TP)	⩽ 0.5 mg/L	⩽ 1 mg/L	⩽ 3 mg/L	Less than 0.5	-
Total suspended solid (TSS)	⩽ 10 mg/L	⩽ 20 mg/L	⩽ 30 mg/L	Less than 10	-

The article [10] also points out that the system has a significant bactericidal effect, and bacterial counts in the treated effluent were reduced to below 2000 per 100 mL, and the bactericidal rate reaching 99.999%. However, the ammonia nitrogen removal effect is slightly worse, so the system's ability to remove nitrogen is slightly weak. However, the other pollutants discharged can meet the rural domestic wastewater discharge standards.

2.4. The Retention Anoxic Filter-Hydraulic Rotating Biological Contactor (RAF-HRBC) [13]

RAF-HRBC is an innovative decentralized wastewater treatment process. The process achieves on-site deodorization and efficient pollutant removal by integrating an anoxic filter and a hydraulic rotating biological contactor [13].

The basic principles and structural components of the process consist of two main parts: the Retention Anoxic Filter and the Hydraulic Rotating Biological Contactor [13]. RAF is used for nitrification under anoxic conditions [13], while HRBC utilizes rotating biofilms for organic matter degradation and ammonia-nitrogen oxidation under aerobic conditions [13]. The system's deodorization and contaminant removal efficiency can be enhanced by modifying operational parameters such as Rotational Speed, Hydraulic Retention Time, Reflux Ratio, and Hydraulic Retention Time [14].

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During the experiments, the researchers identified the best operational parameters for the RAF-HRBC process [13], including a reflux ratio of 175%, a hydraulic residence time of 5 hours for RAF and 2.5 hours for HRBC, and a rotation rate of 8 revolutions per minute. The system was continued for 50 days and the corresponding data were obtained which are shown in Table 3.

Table 3: Experimental data of RAF-HRBC [13]

Parameter	Influent (mg/L)	Effluent (mg/L)	Removal Efficiency
Chemical Oxygen Demand (COD)	185.24±29.09	33.4±3.08	84.79±3.87
NH_4^+-N	40.84±4.28	772±0.96	82.71±2.06
Total Nitrogen (TN)	51.79±3.96	12.96±1.17	74.83±2.06
S^{2-} from RAF	18.66±1.93	1.57±0.47	91.68±2.22
Threshold Odor Number (TON) from RAF	231.04±8.02	2523±1.82	89.04±1.68

Although the RAF-HRBC process showed high removal efficiency in general, total phosphorus (TP) and the removal of pathogens were not mentioned in the experiments. These may be parts of the process that are not addressed by this device and require supplemental or ancillary treatment methods to achieve the desired removal efficiencies.

2.5. Gravity-driven membrane bioreactor (GDMBR)[15]

GDMBR[15] is a new type of low-cost and efficient decentralized domestic wastewater treatment technology. The system primarily comprises an influent tank, a membrane tank, and a collection bottle[15]. The water is driven to flow through the membrane by gravity pressure, eliminating the need for backwashing and chemical cleaning, making it simple to operate and low maintenance[15]. Highly efficient wastewater treatment can be achieved with low energy consumption.

Polyethersulfone (PES) membranes with different pore sizes were used in the experiments [15], and the GDMBR system's flux capacity and pollutant removal effectiveness were assessed for the treatment technology under 45 mbar pressure. It has been shown through research [16] that larger membrane pore sizes tend to lead to more contaminant accumulation, but smaller membrane pore sizes lead to a rapid decrease in flux. Therefore, the advantages and potential disadvantages need to be weighed when selecting the membrane pore size to achieve optimal wastewater treatment.

The experimental results [15] are shown in Table 4, which show that the GDMBR system can efficiently remove COD and ammonia nitrogen. This membrane is negligible in the treatment of total nitrogen and total phosphorus [15], remaining at almost the same concentration as at the time of entry, so that other methods of removal and resource recovery can be considered or this type of treated effluent can also be used for agricultural irrigation [15].

Table 4: Experimental data of GDMBR [15]

Parameter	Influent (mg/L)	Effluent (mg/L)	Removal Efficiency
Chemical Oxygen Demand (COD)	55-370, average 22	39.5(UGDMBR) 52.23(0.22GDMBR) 53.59(0.45GDMBR)	60-80%
Dissolved Organic Carbon (DOC)	20-90, average 38.82	10.20(UGDMBR) 11.71(0.22GDMBR) 11.19(0.45GDMBR)	70.88%(UGDMBR) 66.39%(0.22GDMBR) 68.62%(0.45GDMBR)

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Table 4: (continued)

NH_4^+-N	30-55	12.16(UGDMBR) 11.66(0.22GDMBR) 11.37(0.45GDMBR)	70%
Total Nitrogen (TN)	20-70	Up to 50	15.93%(UGDMBR) 17.26%(0.22GDMBR) 17.71%(0.45GDMBR)
Total Phosphorus (TP)	2.5-7.5	Almost the same concentration as the influent water	About 17% (initially), followed by virtually no removal

2.6. Solar-driven interfacial evaporation [17]

Solar-powered interfacial evaporation technology is a method of recovering potable water directly from household wastewater using solar energy. The basic principle of the technology is to convert solar energy into thermal energy through a solar absorber, which promotes evaporation of water and condensation to obtain clean drinking water [17].

Solar-powered interfacial evaporation technology relies on the use of solar energy to reduce conventional energy consumption and carbon emissions, and also offers high photothermal conversion and evaporation efficiencies [17].

A significant advantage of solar-powered interfacial evaporation technology is its low cost and high efficiency [17]. While conventional direct potable reuse technologies are high in energy consumption and carbon emissions, solar-powered interfacial evaporation systems enable cost-effective, high-efficiency water treatment through efficient thermal management and photo- and heat-converting materials [18]. According to a life cycle analysis, the cost per kilogram of produced water is approximately \$0.027, with a carbon footprint of approximately 0.085 kg CO_2 equivalent/kg of water [17]. Under actual sunlight conditions, 2-3 people can have their daily drinking water needs met by the system's average daily water production rate [17]. Additionally, the experiments demonstrated that the produced water quality complies with Chinese drinking water standards [17], and most of the pollutants are removed.

However, the data for this experiment was obtained under laboratory conditions [17], so the processing efficiency and speed of the system may be significantly reduced under low sunlight or cloudy conditions, resulting in longer processing time. This requires further adjustment and optimization.

3. Analysis

3.1. Constructed wetland treatment [4]

Constructed wetlands perform well in sewage treatment;[19] And it can create a small ecological environment that can improve the urban environment; In addition, its lower construction and maintenance costs make it cost-effective; [5] However, the treatment efficiency of constructed wetlands is closely related to environmental conditions, and rapid changes in non-natural temperature and humidity in cities may affect the treatment effectiveness of constructed wetlands; [20] And the construction of constructed wetlands requires a large amount of land resources [5], which may be difficult to achieve in urban areas.[19]

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3.2. iHydroMET [8]

iHydroMET can provide important support for urban agriculture and greening; However, this technology only performs well in small-scale, decentralized applications and is suitable for small-scale applications such as households or small communities;[8] In addition, the installation and operation of the iHydroMET system require a certain amount of space, and how to deploy the system reasonably to avoid encroaching on urban infrastructure is an important consideration for its feasibility [21].

3.3. Solar-powered electrochemical treatment [10]

At present, many cities' environmental policies encourage to use renewable energy, which has facilitated the implementation and promotion of solar powered electrochemical technology, and its lower operating costs make it more sustainable; However, the height, density, and air pollution of buildings in cities may lead to low efficiency of solar power generation, and the limited space in cities may hinder the installation of solar panels, especially in densely populated areas; In addition, installing photovoltaic cells, especially in large quantities, brings high initial investment; Furthermore, this technology only performs well in small-scale domestic sewage treatment, and the efficiency of a single system may not be sufficient to support too many populations.

3.4. RAF-HRBC [13]

RAF-HRBC has high efficiency in treating organic matter and nutrients, and can meet strict emission standards; And the space requirement of this technology is not high, it can complete efficient processing in a relatively small space; In addition, the biological treatment method used in this process reduces the use of chemicals, which is of great significance for environmental protection;[22] The only drawback is that its initial investment is relatively high, but the lower operating costs and energy consumption in the later stage still make it highly practical.

3.5. GDMBR [15]

GDMBR technology replaces mechanical pumps with gravity as the driving force, reducing energy consumption and maintenance complexity; In addition, its high efficiency and adaptability in treating sewage make its service range from small-scale households to large-scale communities; Moreover, due to its compact design, the GDMBR system does not require high space requirements and only needs to maintain a certain height difference; Its only drawback is the high initial installation cost, especially in large facilities.

3.6. Solar-driven interfacial evaporation [17]

Solar-Driven interfacial evaporation does not rely on chemical agents and has significant environmental advantages; In addition, its operating costs are relatively low and it has the advantage of long-term operation; However, the current achievements are still limited to laboratory and small-scale applications, with limited maturity and potential differences in practical applications; In addition, the installation location must have sufficient lighting conditions, which may be difficult to achieve in urban areas, especially densely populated cities; And the initial equipment and installation costs of this technology are relatively high, which may increase the financial burden if the payback period is slow.

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4. Discussion

In summary, the RAF-HRBC progress, because of its high treatment efficiency, low space occupancy rate, and environmental protection benefits, can be integrated into urban infrastructure or deployed in underground buildings or other underutilized spaces to replace centralized domestic sewage treatment systems and alleviate their pressure; GDMBR technology, as a result of its high processing efficiency, low space occupancy, and low operating costs, can be applied to small-scale households to large-scale communities. Both have high initial investment costs, but they still have high economic benefits by shortening the investment return period through methods such as reducing operating costs. The treatment efficiency of both can cope with the domestic sewage generated by urban population, but they can also be combined to achieve higher treatment efficiency and reduce the burden on a single system.

However, iHydroMET technology, solar driven electrochemical technology, and solar driven interface evaporation technology is suitable for setting up in less densely populated urban areas due to their good treatment effect on small-scale domestic sewage and large space requirements. They can be placed on rooftops and other areas to avoid occupying too much space resources, and these technologies can be combined to achieve high efficiency in domestic sewage treatment.

Finally, constructed wetlands can only be deployed in rural or remote areas due to their high demand for land resources. Some urban domestic sewage can be transported to the area for purification through pipeline laying, sharing the pressure of urban domestic sewage treatment systems.

However, from the several technologies proposed in this paper, none of them, except for the solar powered interfacial evaporation technology, can satisfy the point of reaching drinking water from wastewater. These technologies do not seem to be effective in getting rid of nitrogen and phosphorus, and the effluent after treatment can only be transported to rural areas for irrigation. Therefore, if these technologies are to be utilized and wastewater is to be converted into potable water, other ancillary technologies need to be considered to eliminate these pollutants to match the water requirements of the urban citizens.

5. Conslusion

This review examines in detail six technologies for decentralized domestic wastewater treatment, understands their principles, advantages and disadvantages, and considers whether decentralized domestic wastewater treatment systems can replace centralized domestic wastewater treatment systems. The article concludes that the RAF-HRBC process and GDMBR technology are most suitable for MSW treatment; iHydroMET, solar-driven electrochemical technology and solar-driven interfacial evaporation technology are suitable for low population density's urban areas and should be used in combination to achieve the highest treatment efficiencies; but constructed wetlands are not suitable for MSW treatment. When using technologies other than solar-driven interfacial evaporation, it is necessary to combine them with other auxiliary technologies to remove total nitrogen and total phosphorus, which are pollutants so as to match the needs of urban drinking water.

However, most of the conclusions drawn in the article are based on reading and summarizing various literatures, without practical experience, which may have effects on the final practical results; in addition, the article does not include all the known technologies, this paper only includes the analysis and comparison of technologies; and this paper does not take into account the cost of the various options, which has become a part of the concern in the actual choice for the aspect. In future work, more research and even practice should be carried out to address these shortcomings to achieve the desired results.

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