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Technologies with greater efficiency in domestic wastewater treatment: a review of the literature

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***Abstract*– Increasing urbanization and demand for water resources have intensified the need for efficient technologies for domestic wastewater treatment. The present literature review evaluated the most efficient technologies in wastewater treatment, aligning with Sustainable Development Goal 6: Clean Water and Sanitation. Two hundred scientific articles in English from Scopus and Web of Science databases were analyzed, selecting 72 that met the established criteria. The results showed that vertical flow wetlands, using the filtration method, and biochar, using the adsorption method, are the most efficient technologies for domestic wastewater treatment. Vertical flow wetlands achieved COD, BOD and TSS removals of 97.5%, 99% and 94%, respectively, while biochar showed removal percentages in color, turbidity, phosphates and E. coli of 97.06%, 97.50%, 82.67% and 73.06%, respectively. Natural materials such as Moringa oleifera, Eichhornia crassipes and coconut shell activated carbon were identified as sustainable low-cost options. Performance varied depending on implementation scale and climatological conditions. It was concluded that these technologies offer solutions adapted to various contexts, such as decentralized systems, rural communities, and urban areas with limited sanitation infrastructure, significantly improving water quality and contributing to environmental protection.**

***Keywords*-- water treatment, remediation, efficiency, technology, domestic wastewater.**

I. Introduction

Freshwater scarcity has become a critical global issue due to population growth and the effects of climate change. This situation has intensified the need to reuse treated wastewater, driving the search for innovative treatment methods [1,2]. According to Ref. [3], 90% of drinking water is wasted and discharged as wastewater, an alarming figure considering that basic consumption for hydration and sanitation is approximately 20 liters per person per day (l/p/d), while water use for activities such as personal hygiene, food preparation, laundry, and bathing reaches 100 l/d [4,5].

Wastewater treatment is crucial for preserving the environment, public health, and ecosystems[6,7]. However, there is considerable disparity in the management of these effluents globally. In high-income countries, approximately 70% of wastewater generated undergoes treatment processes before being discharged, while in low-income countries, only 8% of this water receives any kind of treatment [8]. This large difference highlights the need to develop and implement treatment methods that are both economically viable and effective, particularly in areas where resources are scarce.

One of the critical challenges for wastewater treatment is the impact of seasonal changes on the composition and removal of fluorescent dissolved organic matter (FDOM) and dissolved organic matter (DOM), as seasonal variations affect microbial activity and, therefore, the production, degradation, and transformation of organic compounds throughout the treatment process. These changes not only complicate treatment, but also require continuous and precise adjustments to treatment plant operations to maintain efficiency in contaminant removal. In addition, the development of advanced photocatalysts is crucial to address the removal of refractory organic contaminants present in wastewater [9].

In response to these challenges, various studies have explored innovative solutions for wastewater treatment. In their research, Ref. [10] studied the use of perfluorotetracarboxylic acid (PTA) nanosheets obtained through a simple method, highlighting them as a highly efficient photocatalyst with a high monopotassium persulfate (PMS) activation capacity for the removal of bisphenol A (BPA). Likewise, thermochemical conversion technologies offer an opportunity to transform wastewater biosolids management operations from costly and energy-intensive processes to centers for the extraction of economic and energy resources [11]. On the other hand, the implementation of three-dimensional electrodialysis (3D ED) systems with graphite as the third electrode has demonstrated significantly higher efficiency in the simultaneous removal of nickel (Ni), phosphorus (P), and chemical oxygen demand (COD) from non-electrolytic nickel plating (ENP) wastewater, compared to conventional two-dimensional electrodialysis (2D ED) systems [12]. These technological advances represent progress toward improving the efficiency and sustainability of wastewater treatment, although substantial challenges remain to be addressed for large-scale implementation.

The process of removing contaminants from wastewater is a major challenge for many countries due to the high cost of current technologies, increased water consumption, and constant population growth [13,14], with rural communities being the most affected due to the difficulties they face in providing a centralized wastewater treatment system [15,16]. Furthermore, water consumption is expected to increase significantly in the future, with global demand for all uses expected to rise by 20% to 30% by 2050, with significant differences between regions of the world [17,18].

In this regard, wastewater treatment could contribute significantly to reducing the domestic water footprint by between 40% and 80%. To this end, Goal 6 of the Sustainable Development Goals (SDGs) established by the United Nations recognizes that the main challenges facing humanity are sanitation and access to drinking water [19]. However, this goal is hampered by concerns about the health and hygiene risks that the use of this treated water could entail, as well as by negative perceptions regarding the quality of recycled water [20–22].

Therefore, considering the growing need for sustainable solutions for domestic wastewater treatment and minimizing its environmental impact, this literature review article posed the following general question: What are the most efficient technologies for domestic wastewater treatment?

The discharge of untreated domestic effluents contaminates water sources and damages ecosystems, exacerbating water scarcity in many countries [12,23,24]. Faced with this challenge, the recovery and reuse of treated wastewater is a viable alternative to mitigate this scarcity, improving sanitation and preserving water resources [25–27]. This reuse not only saves this resource, but also allows the by-products of the treatment process to be exploited, creating a more efficient and sustainable system [28]. Various energy-saving and cost-effective physical, chemical, and biological treatment methods have been investigated [29,30], whose efficiency varies but all aim to safely eliminate wastewater [14]. On the other hand, gray water reuse can help make local water systems more resilient to shortages, but it is crucial to monitor quality to protect public and environmental health [31].

To this end, this research is justified from an environmental perspective, as the most effective technologies for addressing sanitation issues related to domestic wastewater can contribute to reducing water pollution, preserving aquatic ecosystems, and mitigating the impact of climate change. In the social sphere, these technologies can benefit communities by reducing public health risks and improving water quality for more sustainable development. Economically, the adoption of these efficient technologies can lower long-term operating costs, stimulate innovation in the water treatment sector, and generate employment opportunities in the water and sanitation industry, contributing to sustainable development and the circular economy.

In view of the above, the objective was to determine the most efficient technologies for domestic wastewater treatment. In addition, to compare the performance of domestic wastewater treatment technologies, as well as to identify the types of materials used in domestic wastewater treatment technologies, and to assess the environmental impacts of domestic wastewater treatment technologies.

II. Methodology

A. *Type and design of the research*

The research was qualitative and applied in nature, as it sought to explore in depth the knowledge acquired on the most efficient technologies for domestic wastewater treatment.

This study adopted a non-experimental design because it was based on the observation and analysis of existing bibliographic information without involving experiments such as the manipulation of variables and the collection of primary data.

B. *Sources of information*

For the literature review of this research, scientific articles were consulted from the Scopus and Web of Science databases.

C. *Search strategy*

A systematic search was conducted using keywords and Boolean operators such as "AND" and "OR". The search string applied was: (technologies OR methodology) AND (remediat* OR treatment OR recover* OR repair* OR remediation OR control) AND ("domestic wastewater" OR "wastewater domestic" OR greywater).

D. *Information selection*

Once the information search was established, the article selection process was carried out due to the volume of scientific literature, taking into account the range of years from 2019 to 2024, the type of document selected, and the English language.

III. Results and Discussion

A. *Information search*

This literature review analyzed various technologies applied to domestic wastewater treatment, with the aim of identifying those that are most efficient.

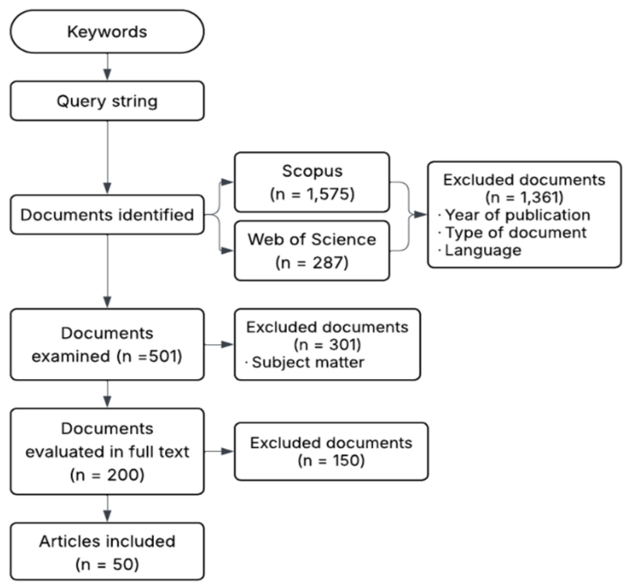

Fig. 1. PRISMA flow diagram of study selection.

The initial search yielded a total of 1,862 documents, which were reduced to 501 after applying specific filtering criteria, such as publication period, document type, and language. Subsequently, 301 studies were excluded for not fitting the theme, and 200 complete documents were evaluated in detail to determine their eligibility through a thorough review. As a result, 50 relevant papers were finally selected, as shown in Figure 1. This systematic and rigorous process minimized potential biases and excluded irrelevant information, strengthening the credibility of the study and ensuring a solid and reliable compilation of data [32,33].

B. Technologies used in domestic wastewater treatment

Table 1 presents 33 articles from the Scopus database and 17 from Web of Science referring to efficient technologies for domestic wastewater treatment. The selected studies are relevant because they include ecological methods, such as plants and biochar, as well as technological innovations such as bioreactors and electrocoagulation.

TABLE 1
SCIENTIFIC RESEARCH SELECTED FROM DATABASES

No.	Technology		Technology	Author(s)
	Scopus	Web of Science		
1	X		Biochar and *Moringa oleifera* seeds	[34]
2		X	Green wall	[35]
3		X	Green wall	[36]
4		X	Phytoremediation with climbing plants (*Trachelospermum jasminoides, Lonicera japonica, Callistemon laevis*)	[37]
5	X		Date palm fiber (DPF) filter	[38]
6		X	Phytoremediation	[39]
7		X	Biochar	[40]
8	X	X	Artificial wetland with horizontal surface flow	[41]
9		X	Activated carbon from coconut shells	[42]
10		X	Phytoremediation	[43]
11		X	Activated carbon biological filter	[44]
12		X	Green wall	[45]
13		X	Activated carbon	[46]
14	X	X	Green wall	[47]
15	X		Horizontal surface flow constructed wetland	[48]
16		X	Coagulant	[49]
17		X	Filter	[50]
18		X	Phytoremediation	[20]
19		X	Horizontal surface flow constructed wetland	[51]
20		X	Filter	[52]
21	X		Upflow anaerobic sludge blanket reactor and vertical flow wetlands without plants	[22]
22		X	Hybrid multi-hydrocarbon stratification system	[53]
23	X	X	Microalgae	[54]
24		X	Biological reactor	[55]
25	X	X	Microalgae	[28]

26	X	X	Vertical constructed wetland	[56]
27	X	X	Biochar	[57]
28	X	X	Iron and steel electrodes	[58]
29	X	X	Horizontal surface flow constructed wetland	[59]
30	X		Coagulant	[60]
31	X	X	Phytoremediation	[61]
32	X	X	Horizontal surface flow constructed wetland	[62]
33	X	X	Green wall	[63]
34	X		Phytoremediation	[64]
35	X	X	Horizontal surface flow constructed wetland	[65]
36	X		Membrane bioreactor	[66]
37	X	X	Phytoremediation	[67]
38	X	X	Horizontal surface flow constructed wetland	[68]
39	X	X	Phytoremediation	[69]
40	X	X	Artificial floating islands	[70]
41	X		Filter	[71]
42	X	X	Horizontal subsurface flow constructed wetland	[72]
43	X	X	Microalgae	[73]
44	X	X	Vertical constructed wetland	[74]
45	X	X	Conventional membrane bioreactors	[75]
46	X	X	Horizontal subsurface flow constructed wetland	[76]
47	X	X	Phytoremediation	[77]
48	X		Vertical constructed wetland	[78]
49	X		Adsorbent	[79]
50	X	X	Phytoremediation	[80]

For Ref. [36,63], graywater treatment using green walls represents an innovative ecological solution that combines various physical filtration, adsorption, and biological processes, using layers of growing media and plant roots to remove contaminants. On the other hand, the incorporation of materials such as biochar and activated carbon facilitates the adsorption of contaminants in wastewater through absorption techniques demonstrated by Ref. [46], [42] and [40]. Meanwhile, constructed wetlands using phytoremediation techniques through plants contribute to reducing the volume of graywater, according to research conducted by Ref. [41]. Thus, most studies show a trend toward combining biological and physicochemical methods to improve treatment efficiency and promote graywater reuse.

C. *Efficiency performance of domestic wastewater treatment technologies*

Table 2 details the efficiency performance of various technologies used in wastewater treatment, highlighting 10 studies that obtained the best results in contributing to the reduction of pollutants, as well as the versatility and effectiveness of the different technologies available, allowing for an informed selection according to the specific needs of wastewater treatment in different environments.

TABLE 2
EFFICIENCY PERFORMANCE OF DOMESTIC WASTEWATER TREATMENT TECHNOLOGIES

No.	Technology	Method	Efficiency	Author(s)
1	Upflow anaerobic sludge blanket reactor and vertical flow wetlands without plants	Anaerobic decomposition (UASB reactor)	UASB reactor: COD: 53%, BOD5: 26%, TSS: 82%, TSS: 69% Vertical flow wetland without plants: COD: 97.5%, BOD5: 99%, and TSS: 94%	[22]
2	Horizontal free surface flow wetlands	Phytoremediation and filtration	Ammonia: 60%, Oil and grease: 78.46%, COD: 85% Total phosphorus: 37.04% Total coliforms: 75%, Fecal coliforms: 79.59%	[41]
3	Biochar	Adsorption	Color: 97.06% Turbidity: 97.50% Phosphates: 82.67% E. coli: 73.06%	[57]
4	Iron and steel electrodes	Electrocoagulation	COD: 86.5 %	[58]
5	Bioflocculant using *Corchorus olitorius* L.	Biocoagulation	BOD: 89.78% TSS: 88.50% Turbidity: 83.47%	[60]
6	Surface flow constructed wetlands using *Eichhornia crassipe*	Phytoremediation	SST: 82.25% Color: 82.31% Orthophosphates: 86.59% DB5: 56.06% Fecal streptococci: 100% Fecal coliforms: 43.80%	[64]
7	Green wall	Biofiltration	BOD: 96% Total nitrogen: 58% Total phosphorus: 61%	[36]
8	Activated carbon (BAC filter)	Adsorption	Total organic carbon: 31%	[46]
9	Filter (date palm fiber)	Filtration	Turbidity: 90% TDS: 15% Conductivity: 15%	[38]
10	Absorbent (wood apple shell)	Adsorption	Turbidity: 96.67% Conductivity: 92% Total suspended solids: 95% Hardness: 31.25% Phosphates: 6.41% Nitrates: 5% COD: 84.74% BOD: 80.56%	[79]

The results indicate that the efficiency of contaminant removal in wastewater treatment varies significantly depending on the method and technology used. The upflow anaerobic sludge blanket (UASB) reactor combined with vertical flow wetlands without plants uses anaerobic decomposition to efficiently treat organic matter, achieving removal efficiencies of up to 99% in BOD_5, 97.5% in COD, and 94% in TSS [22]. Horizontal free-flow wetlands, through phytoremediation and filtration processes using *Typha domingensis* and *Eichhornia crassipes*, achieved removal efficiencies of 85% in COD, 79.59% in total coliforms (TC), 75% in fecal coliforms (FC), 37.04% in total phosphorus (TP), 60% in ammonia, and 78.46% in oils and fats [41]. Biochar as an adsorbent material demonstrated high efficiency in the removal of color, turbidity, phosphates, and *Escherichia coli*, with rates of 97.06%, 97.50%, 82.67%, and 73.06%, respectively [57]. Electrocoagulation with electrodes achieved 86.5% in COD removal [58]. Natural coagulants using *Corchorus olitorius L.* reached efficiencies of 89.78% for BOD and 88.50% for TSS [60]. Phytoremediation using *Eichhornia crassipes* showed effective removal of orthophosphates (86.59%) and TSS (82.25%) during the rainy season [64]. Green walls through biofiltration achieved 96% BOD removal, 58% total nitrogen, and 61% total phosphorus [36]. Activated carbon through adsorption reached 31% removal of total organic carbon [46]. Date palm fiber filters achieved 90% turbidity reduction, with 15% reduction in both TDS and conductivity [38]. Finally, wood apple shell adsorbents demonstrated 96.67% turbidity removal, 95% TSS removal, 84.74% COD removal, and 80.56% BOD removal [79].

The studies in Table II were conducted at different scales. Ref. [22] implemented a full-scale system in a real household in Jordan, while Ref. [64] and [38] conducted pilot-scale studies.

Climatological conditions can significantly influence the performance of technologies such as wetlands and green walls. Ref. [64] reported markedly different results between seasons: during the rainy season, removal of color (82.31%), orthophosphates (86.59%), and TSS (82.25%) was considerably higher, while fecal streptococci elimination was more effective in the dry season (100% vs. 74.89%). These differences are attributed to variations in temperature, solar radiation, and hydraulic loading, which directly affect microbial activity and plant performance. Therefore, seasonal and climatic context must be considered when interpreting the efficiencies reported for these technologies.

D. *Types of materials used in domestic wastewater treatment technologies*

In selecting relevant articles on the consumption of materials in domestic wastewater treatment technologies, key criteria were taken into account to ensure the relevance and quality of the information synthesis, such as articles presenting innovative technologies, the use of sustainable and low-cost materials, and better results in terms of contaminant removal efficiency.

Table 3 presents a compilation of the types of materials used in domestic wastewater treatment along with the technologies employed in each method, reflecting the innovation and multifaceted approach in the field of graywater treatment, adapting to different contexts and needs to effectively address the variety of pollutants and improve water quality.

TABLE 3
TYPES OF MATERIALS USED IN DOMESTIC WASTEWATER TREATMENT TECHNOLOGIES

No.	Technology	Type of material	Author(s)
1	Biochar	*Moringa oleifera*	[34]
2	Green wall	Pumice stone, hemp fiber, coffee grounds, and composted fiber, *Juncus compressus, Carex nigra, and Myosotis scorpioides*	[36]
3	Vertical flow constructed wetlands	*Trachelospermum jasminoides, Lonicera japonica, Callistemon laevis*	[37]
4	Horizontal free-flow constructed wetlands	*Typha domingensis, water hyacinth (Eichhornia crassipes)*	[41]
5	Activated carbon	Coconut husk	[42]
6	Coagulant	*Moringa oleifera*	[49]
7	Upflow anaerobic sludge blanket reactor and vertical flow wetlands without plants	Zeolite tuff	[22]
8	Electrodes	Iron and steel	[58]
9	Coagulant	*Corchuros olitorius* L.	[60]
10	Plant	*Eichhornia crassipes*	[64]

Among the various technologies used in wastewater treatment, along with specific materials, the use of *Moringa oleifera* seeds as the main material for removing contaminants stands out, demonstrating their effectiveness in adsorbing impurities [34,40]. Likewise, green walls are being extensively researched, using a variety of materials such as coconut fiber, zeolite, perlite, pumice, hemp fiber, coffee beans, and plants such as Adiantum fragans and Davallia tyermanii [35,36,45].

On the other hand, vertical and horizontal flow constructed wetlands use plants such as *Trachelospermum jasminoides* and *Typha domingensis* for phytoremediation [37,41], while activated carbon derived from coconut shells is used in several studies for its high adsorption capacity [42,44,46]. Other methods include the use of natural coagulants such as *Moringa oleifera* and *Corchuros olitorius* L., and technologies based on electrocoagulation with iron and steel electrodes [49,58,60].

E. *Environmental impacts of domestic wastewater treatment technologies*

Technologies applied to domestic wastewater treatment demonstrate various innovative solutions aimed at improving water quality and reducing environmental impacts, especially in contexts with infrastructure limitations.

In this context, constructed wetlands stand out as sustainable and widely applicable alternatives. The vertical flow constructed wetlands proposed by Ref. [22] help mitigate water scarcity and significantly reduce pollution, providing an ecological and efficient option for areas with limited infrastructure. Complementarily, Ref. [72] propose the use of horizontal subsurface flow constructed wetlands as an economical and flexible solution to reduce wastewater infiltration into groundwater. Similarly, Ref. [78] developed artificial wetlands with vertical subsurface flow as a sustainable alternative for the disposal of untreated wastewater, highlighting their smaller footprint and economic and ecological viability.

To address the problem of eutrophication and nutrient loading, Ref. [70] implemented artificial floating islands capable of removing nitrogen and phosphorus pollutants, promoting ecological balance and significantly improving water quality in eutrophic water bodies. Along the same lines, Ref. [73] investigated the use of microalgae as an effective strategy for reducing the nutrient load in effluents, contributing both to water conservation and to the mitigation of water scarcity. Likewise, Ref. [69] analyze phytoremediation as a strategy aimed at reducing demand on public water supplies, raising the water table, and optimizing the use of environmental resources through the application of the 3R principles (reduce, reuse, and recycle).

In the field of biological processes and filtration systems, Ref. [57] evaluated the use of biochar in portable handwashing systems, demonstrating its effectiveness in capturing and retaining contaminants and nutrients, which improves the quality of treated water and offers a sustainable solution for temporary facilities. For their part, Ref. [71] highlight biofiltration as an effective alternative for the degradation of recalcitrant substances and the reduction of microbial proliferation in wastewater with a high bacterial load, generating safer effluents. In addition, vermi-biofilters are presented as a low-cost and highly flexible option for the treatment of eutrophic waters [77]. Finally, conventional filtration systems stand out for their low energy demand, economic viability, and high biomass retention capacity, establishing themselves as efficient alternatives for wastewater treatment [79].

IV. Conclusions

Various efficient technologies were identified for domestic wastewater treatment, including constructed wetlands, biochar, and phytoremediation, due to their high contaminant removal capacity and contribution to environmental sustainability.

Vertical flow constructed wetlands, using the filtration method, and biochar, using the adsorption method, demonstrated the highest overall removal efficiencies, achieving up to 99% for BOD, 97.5% for COD and 94% for TSS; and 97.50% for turbidity, 97.06% for color, 82.67% for phosphates and 73.06% for *Escherichia co*li, respectively.

Natural materials such as *Moringa oleifera*, *Corchorus olitorius* L., coconut shell activated carbon, and plants such as *Typha domingensis* and *Eichhornia crassipes* stood out as sustainable and low-cost options, determining the efficiency of each technology.

The studies were conducted at laboratory, pilot, and full-scale levels, and climatological conditions, particularly temperature and seasonal variations, significantly influenced the performance of wetlands and green walls, factors that must be considered when selecting the most appropriate technology for each context.

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