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Review

Multi-Soil-Layering, the Emerging Technology for Wastewater Treatment: Review, Bibliometric Analysis, and Future Directions

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Abstract: Due to its unique structure and excellent purification efficiency (e.g., 98% for organic matter and between 94 and 100% for nutrients), multi-soil-layering (MSL) has emerged as an efficient eco-friendly solution for wastewater treatment and environmental protection. Through infiltration-percolation, this soil-based technology allows pollutants to move from the MSL upper layers to the outlet while maintaining direct contact with its media, which helps in their removal via a variety of physical and biochemical mechanisms. This paper attempts to comprehensively evaluate the application of MSL technology and investigate its progress and efficacy since its emergence. Thus, it will attempt via a bibliometric analysis using the Web of Science database (from 1993 to 01/06/2022) related to MSL technology, to give a clear picture of the number of publications (70 studies), the most active academics, and countries (China with 27 studies), as well as collaborations and related topics. Furthermore, through hybrid combinations, pollutant removal processes, MSL effective media, and the key efficiency parameters, this paper review will seek to provide an overview of research that has developed and examined MSL since its inception. On the other hand, the current review will evaluate the modeling approaches used to explore MSL behavior in terms of pollutant removal and simulation of its performance ($R^2 > 90\%$). However, despite the increase in MSL publications in the past years (e.g., 13 studies in 2021), many studies are still needed to fill the knowledge gaps and urging challenges regarding this emerging technology. Thus, recommendations on improving the stability and sustainability of MSLs are highlighted.

Keywords: multi-soil-layering; wastewater treatment; bibliometric analysis; literature review; future directions

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1. Introduction

Adequate sewers and treatment plants are still lacking in many parts of the world, especially in the rural areas of economically developing countries where wastewater treatment infrastructure is limited or inadequate [1,2]. Furthermore, implementation and maintenance of centralized wastewater treatment systems in these areas are often challenging and costly [3]. On the other hand, inappropriate sanitation systems contribute to a variety of parasitic infections and negatively affect population health as well as socio-economic development [3]. Since wastewater management is a major issue and given the increase in the amount of wastewater discharged in rural areas, researchers have begun to consider more environmentally friendly, cost-effective, and long-term treatment solutions [4].

In this regard, multi-soil-layering (MSL) is an innovative and eco-friendly wastewater treatment system [5]. MSL is based on the infiltration-percolation of wastewater and involves alternating layers of soil mixture with permeable layers (e.g., zeolite and gravel). It offers many benefits, including small-scale implementation, low cost, ease of maintenance, and the possibility of reusing its effluents in the agricultural field [6,7]. Furthermore, several studies have acknowledged its effectiveness in removing pollutants from wastewater through combined physical, chemical, and biological mechanisms [7,8].

Although, recent studies have been concerned with the bacterial community in the MSL system and its sanitary efficiency [5,6,9–11]. Thus, some concerns about the MSL's performance are still unclear [12,13]. For instance, the removal of fecal indicator bacteria has moved from 1.01 to 1.28 log units using a single-stage MSL system [7,14]. However, given the necessity to reuse the MSL effluent in agriculture, this percentage still falls short of the standard level [6]. Therefore, the vital challenge with MSL is removing fecal indicator bacteria and pathogens, whose level in treated water is a sign of good sanitary efficiency.

The current work sheds light on a number of subjects that MSL's earlier research did not address. For instance, most of the studies are still locked in laboratories and at the experimental level [15–17], whereas the full-scale experiment still has a weakness [18]. Regarding MSL efficiency, although the removal of organic matter and phosphorus is very promising [19,20], total nitrogen abatement efficiency has not yet achieved this level [13,21]. Moreover, despite using a two-stage MSL system with a vertical flow, the high removal rate of coliform bacteria recorded did not exceed 3.15 log units [7], requiring the development of additional methods to improve MSL sanitary efficiency. Similarly, there is a weakness in research on viruses, pathogens, emerging pollutants, and their removal mechanisms [14,22]. As for combinations, several hybrid configurations are still under experimentation [23–27]. However, in this literature review, it was observed that there is a lack of studies investigating two-stage MSL with vertical and horizontal flow [18]. Regarding modeling approaches, although their results were encouraging [6,10,24], the application of other powerful methods and hybrid models may help to investigate pollutant removal in the MSL system [28,29].

Previous studies have mainly focused on the removal of organic matter and nutrients [30–32], whereas recent research has focused more on coliform bacteria and microbial activity [5,7,9,11,33,34]. In this regard, this paper summarized and discussed MSL performances and highlighted the most studied pollutants and those receiving the least attention. In addition, this review tries to describe the pollutant removal mechanisms based on the latest studies, especially with regard to coliform bacteria, which represents one of the shortcomings of the MSL system. In the same sense, both prior and recent studies agree that aeration, hydraulic loading rate (HLR), and clogging are the key MSL parameters [10,12,16,35,36]. Thus, the current paper attempts to examine their relationships in the MSL field using keyword co-occurrence analysis. Regarding MSL application, most prior studies were carried out at the laboratory or pilot scale [6,15,21,37]. Nowadays, researchers have turned to combining MSL with other treatment technologies, such as constructed wetlands and trickling filters, at full scale [20,23]. Thus, this paper compares and evaluates their efficacy to determine which hybrid configuration is most effective in removing pollutants. Regarding MSL modeling, this topic is still emerging, and the applied nonlinear methods have accurately simulated MSL performance [6,10,16]. Thus, this paper attempts to quantify and discuss the types of applied models, compare their accuracies, and investigate the most targeted parameters.

On the other hand, for the first time, this paper attempts to investigate and explore the evolution of the MSL technology through bibliometric analysis, which has expanded in recent years due to the urgent demand for these types of studies based on quantitative methodologies, especially in the area of wastewater treatment [38]. In addition, bibliometric analysis has evolved into a useful tool for assessing the influence of scientific publications in a given research field and has become extremely important in assessing the quality of studies [39]. Subsequently, a comprehensive investigation and a detailed description of various aspects of MSL technology (e.g., efficiency, design, operating conditions, modeling approaches, etc.) were carried out to offer an overview and identify knowledge gaps and potential future challenges.

Based on the literature and limitations, the main focus of this bibliometric and review paper is to find out the effective working of multi-soil-layering eco-technology, considering the key efficiency parameters, modeling approaches, and key knowledge gaps.

The main objectives of this paper are:

(i) to conduct a bibliometric analysis in the field of MSL technology;
(ii) to provide a comprehensive summary of MSL aspects (e.g., performance, removal mechanisms, etc.);
(iii) to issue a comparative profile of the MSL with other eco-friendly technologies;
(iv) to evaluate models applied to simulate MSL performance;
(v) to highlight the MSL challenges and provide a road map for future research.

2. Materials and Methods

To define the MSL field, the first approach used in this study consists of analyzing the visibility of scientific publications on the MSL system using the library of Web of Science (WoS) (published by Thomson Reuters) between 1993 and 01/06/2022. This catalog of bibliographic references provides access to a wide range of scientific databases and information services and contributes to the advancement of bibliometric analysis. Due to its reliance on the quantitative and statistical method by which scientific production is analyzed and characterized, authors' productivity determined, and scientific production evaluated, bibliometric analysis is currently regarded as a self-contained scientific research approach [40,41]. Subsequently, we have applied a progressive research process to determine the relevant keywords that encompass the publications of this technology, while eliminating those that took us away from the term "multi-soil-layering".

On the other hand, the most commonly used words in the MSL literature were studied. Thus, links between pollutant removal and these extracted words were discussed to understand the MSL system's treatment behavior. Therefore, we have chosen the following keywords: ("multi-soil-layering") or ("vertical multilevel soil") or ("multi-soil layer" and "MSL") or ("multiple-soil-layer" and "wastewater" or "multi-media-layering" and "mixture"). Thus, only English-language documents were considered. Regarding co-occurrence analysis, bibliometric maps were created using VOSviewer software (version 1.6.17). In addition, R software (version 3.5.2) was used to show statistics related to MSL publications (e.g., researchers, countries, journals) and collaborative networks between countries in the MSL field.

3. Results

3.1. Bibliometric Analysis

3.1.1. MSL Published Papers

The application of MSL eco-technology to rural sanitation has been studied worldwide. In this sense, a total of 70 publications were found in the WoS database from 1993 to 01/06/2022. First of all, only 21 papers are freely accessible (open access), and Figure 1a presents the annual MSL publications. Scholars and academics were initially uninterested in this technology when it was first introduced in the early 1990s, until two peer-reviewed scientific papers were published in 2002. Furthermore, the number of publications has increased considerably in recent years, reaching a high of 13 in 2021 (Figure 1a). This result demonstrates an increasing interest in investigating the MSL over the years.

Figure 1b displays data on the number of papers published in each journal. According to the WoS database, seven papers were published as proceeding papers. Thus, Soil

Science and Plant Nutrition was the scientific journal that published the highest number of documents regarding this technology, with 11 articles, followed by the Ecological Engineering and Bioresource Technology journals with seven and four articles, respectively. Refereed journals that have published two articles in this regard were also mentioned, among them Environmental Technology.

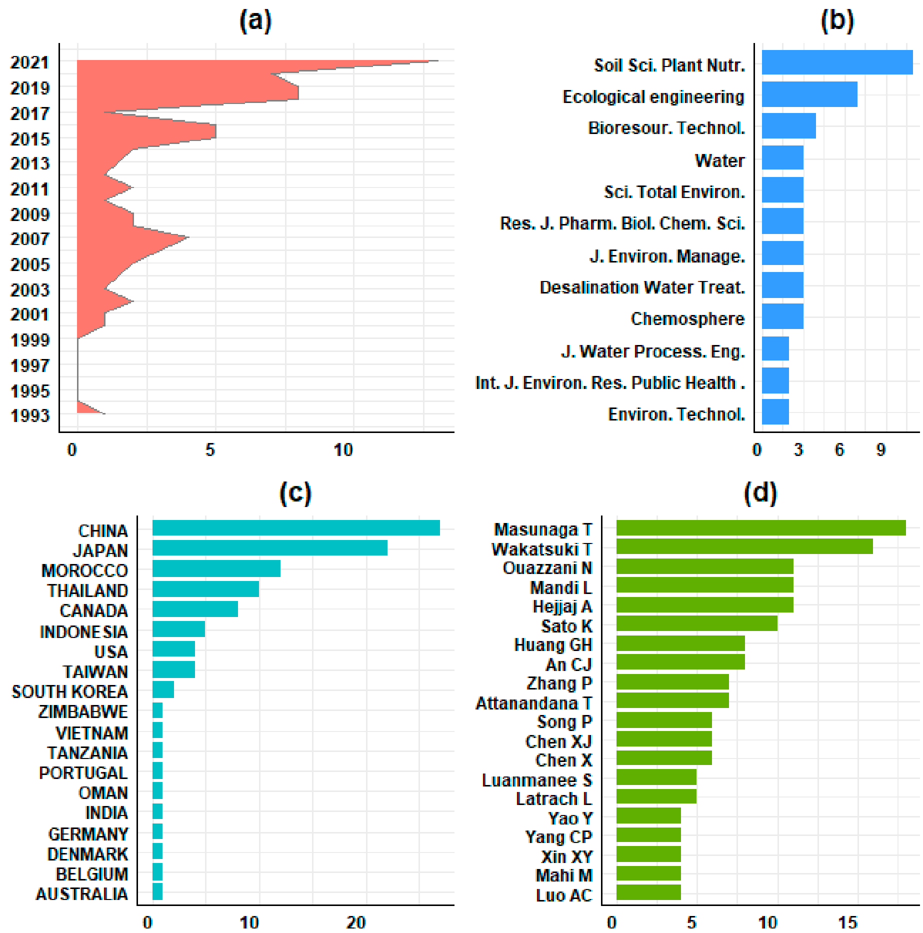

Figure 1. Quantitative analysis of MSL (Multi-Soil-Layering) publications from 1993 to 01/06/2022. (**a**) Evolution of published papers, (**b**) ranking of journals by the number of published papers, (**c**) most productive countries, (**d**) most productive researchers.

Although MSL technology is still being increasingly researched in different countries around the world, China is considered the most significant contributor to the development of this technology with 27 studies, followed by Japan with 22 studies. It was also noted that other countries outside of Asia are interested in studying this technology, as Morocco ranked third in terms of the number of published documents with 12 research papers (Figure 1c). In the same context, related to the authors' publications, Figure 1d displays the number of papers for each author during the period (1993–2022). As it can be observed, Masunaga T, Wakatsuki T, and Sato K are the researchers who have contributed the most to the development of MSL technology, with a total of 18, 16, and 10 papers, respectively. Furthermore, these authors have jointly published numerous articles on different aspects of the MSL system since 2005. Thus, a vivid illustration of this collaboration is the newly released paper on MSL's long-term efficiency [1].

3.1.2. MSL World Collaboration

The countries that produce scientific papers about MSL technology are limited to certain regions and are distributed unevenly around the world, as the geographical distribution of scientific publications shows that they are mostly concentrated in East Asia, North America, and North Africa (Figure 2a). In addition, nearly 70% of all MSL publications come from Asia. As it can be observed in Figure 2b, the collaborative analysis of countries and institutes highlights the primacy of Japan (total collaboration = 15). The cause is probably twofold: Japan was the first country to study the MSL system, and the second reason is due to the strong presence of Japanese researchers in collaborative projects. As a result, even some neighboring countries, such as China and Thailand, collaborate with Japan but not with each other. Additionally, five regions revolve around Japan, represented by countries from Asia, North Africa, North America, and Europe. For instance, an important cooperative network with Thailand is shown by the seven contributions in green (Figure 2). The Japanese researchers also shared their knowledge about MSL technology and collaborated with Morocco through four publications (orange) and the USA through two publications (purple). China, as the first producer of scientific articles on the MSL system, has also invested in collaborations (total collaborations = 14), alongside Canada and the USA with ten publications.

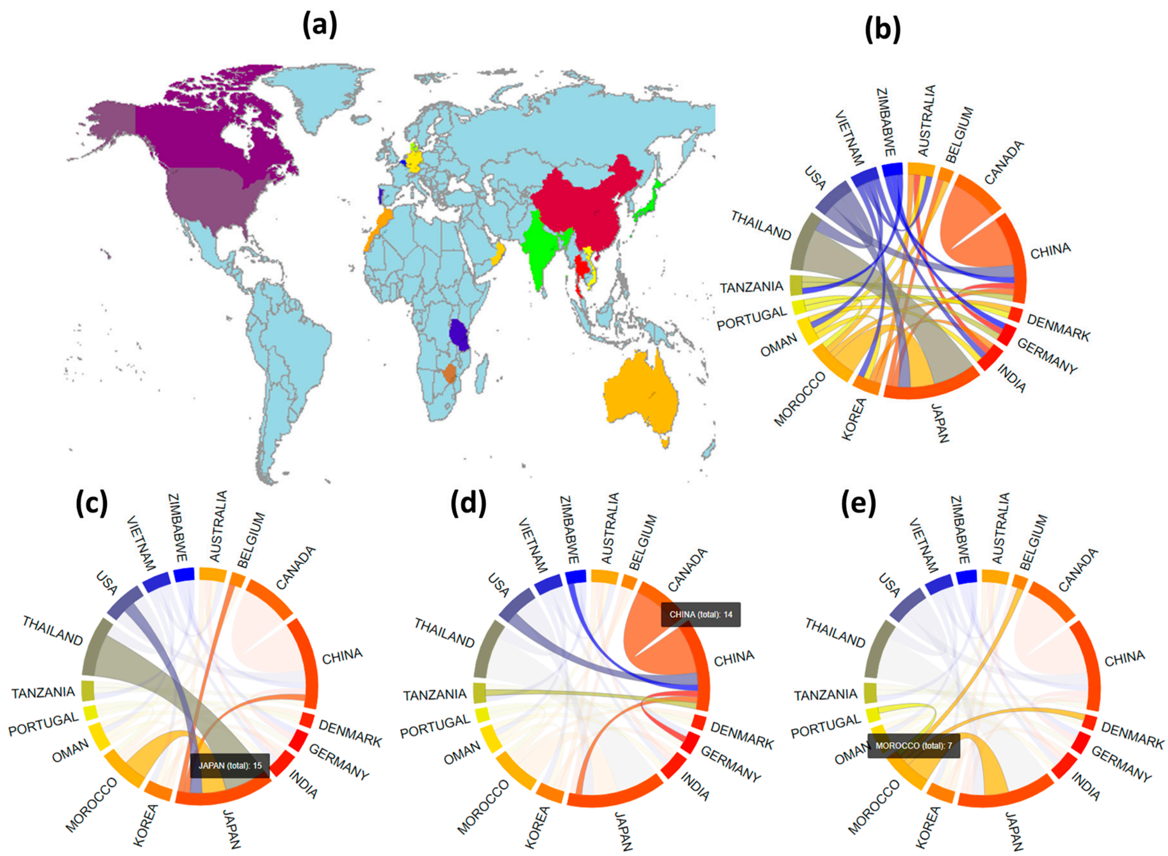

Figure 2. Spatial distribution map of collaborated countries in the MSL field; (**a**) country collaboration map, (**b**) country collaboration diagram, (**c**) Japan collaboration network, (**d**) China collaboration network, (**e**) Morocco collaboration network; each collaborative relationship is indicated by a specific color and its importance increases with the thickness of lines connecting two countries.

Recently, the collaborations with China are extensive and have also reached countries in Africa (Tanzania and Zimbabwe) and Europe (Germany) each with a single collaboration. In addition, Morocco, which ranked as the third country in terms of the number of articles published on MSL technology, has collaborated nearly seven times with four countries scattered all over the world, and this is for the entire period from 2014 to 2021 (Figure 2e).

3.1.3. Co-Occurrences Analysis

Through the search for the most relevant co-occurring items, defined by their relative frequency, we try to make the most repeated items appear. Thus, a bibliometric map of co-occurring terms will be useful in determining which ones best characterize the MSL field. Using density visualization in VOSviewer software (Figure 3), the extracted items shown in the map are exhibited by a label, where the color of each circle indicates its frequency of co-occurrence (density). Colors from the rainbow palette were used (red, orange, yellow, green, and blue); the closer the circles are to red, the more important the element is within the network map. Conversely, the closer the color of the circle is to green or blue, the lower the occurrence of items and the lower their frequency [42].

It was feasible to verify that the hotspots of multi-soil-layering systems, efficiency, performance, nitrogen removal, phosphorus, organic matter, mechanisms, constructed wetlands, and wastewater treatment were the frequently prominent items. It is obvious from the bibliometric map that the frequency of co-occurrence items suggests that researchers are still working on developing and upgrading MSL technology by looking at the removal of conventional contaminants that are known to affect water quality (organic matter and nutrients). However, there is a weakness and an absence of words related to pathogens and coliform removal as a critical indicator of water quality and their accompanying removal mechanisms. Constructed wetlands' inclusion in this bibliometric map of co-occurrence analysis might be due to researchers identifying them as an alternative technology to the MSL on the one side or comparing their efficacy to the MSL system on the other. Furthermore, recent research has integrated these two systems into a combined system to investigate their efficacy in treating wastewater.

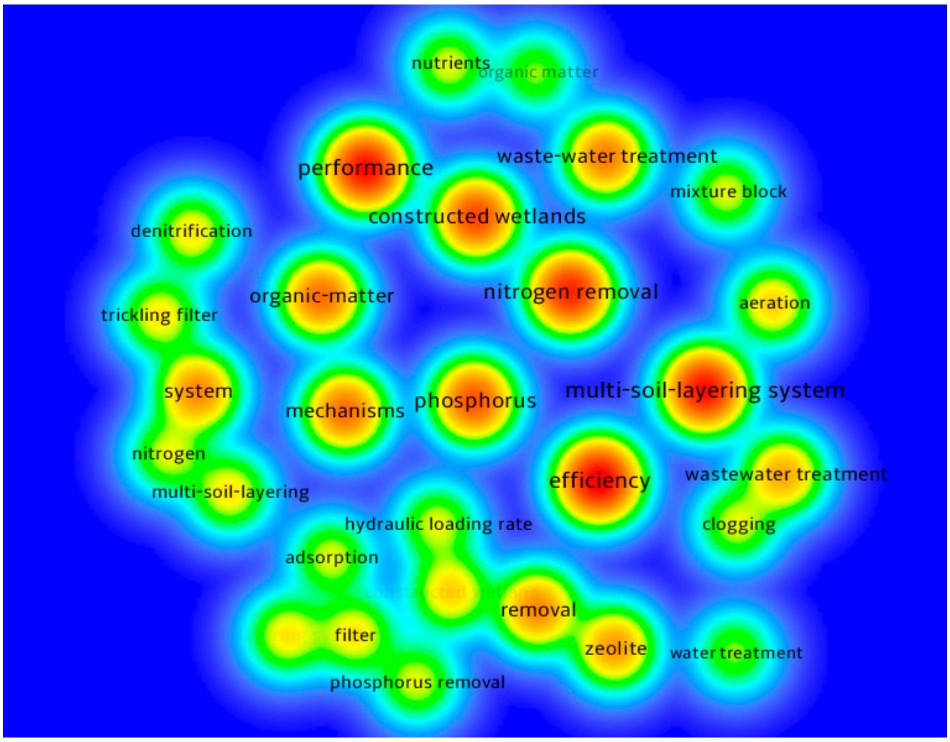

Figure 3. Co-occurrence analysis map using density visualization. Red circles (hotspots) with large labels reflect the most often occurring items compared to those represented by colored circles ranging from green to blue with small labels. In the co-occurrence map, some extracted items are hidden to avoid overlapping.

3.2. Main Pollutant Removal Mechanisms in MSL

The operation of the MSL system is based on infiltration-percolation processes, with the soil mixture serving as the main purification media [43]. The MSL configuration design and method of arranging its components play (Figure 4) a critical role in the distribution of effluent to the MSL layer's surface and help to reduce the risk of clogging [32]. In addition, the soil is a vital ecosystem comprising water, air, organic matter (e.g., animals, plants, and microbes), and inorganic material (e.g., minerals) [44]. It may play a significant role in pollution control by attracting contaminants in wastewater that travels through it, due to its absorption capacities.

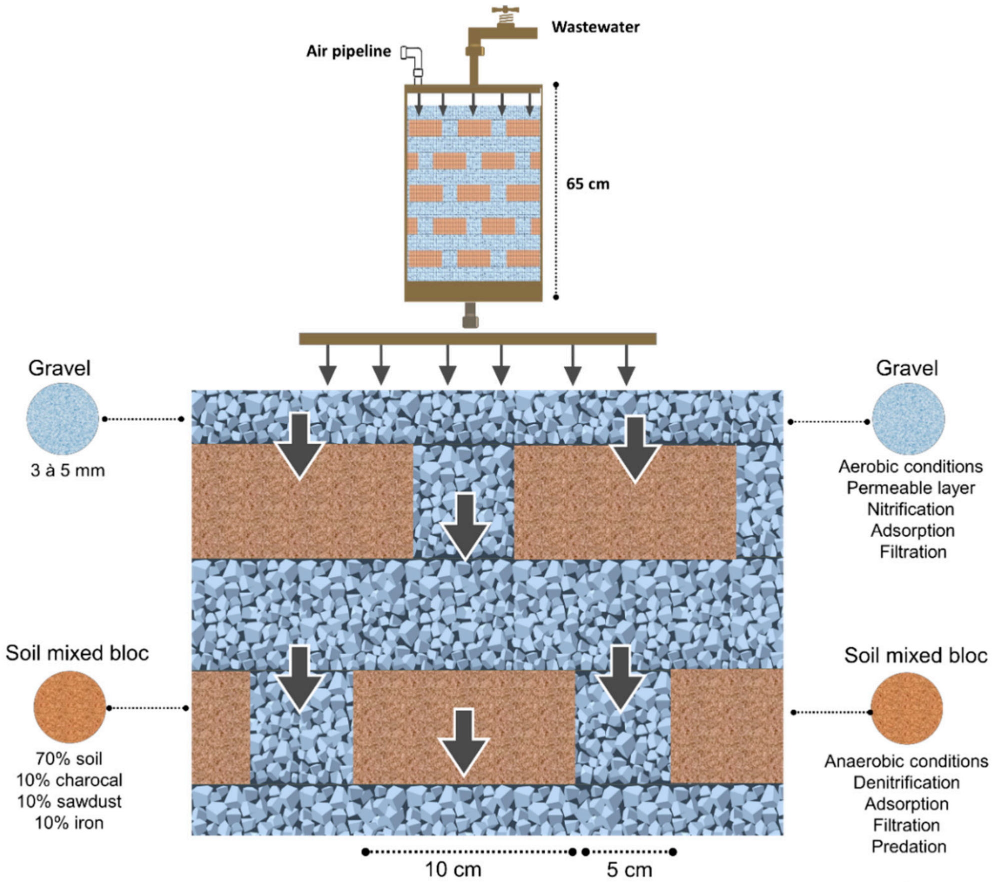

Figure 4. Illustration of an experimental model of a multi-soil-layering system with the major removal mechanisms.

3.2.1. Suspended Solids

Suspended solid (SS) removal was mostly accomplished by filtration as a physical process at the MSL upper layers, and their buildup in these surface layers increases the hydraulic residence time of wastewater within the MSL system [37]. Furthermore, the size of the SS and the MSL media porosity are important factors in SS removal. According to Ho and Wang [30], under the HLR of 1000 L/m^2/day, permeable layer (PL) materials with pore sizes between 3 and 6 mm had an SS removal rate of more than 80%. Despite the MSL system's ability to remove fine particles, Ho and Wang [30] recommended that the HLR be increased to decrease the risk of clogging. However, while investigating the performance of MSL systems under various HLRs.

Masunaga et al. [32] discovered that the removal of SS is not appreciably affected by changes in the HLR. Furthermore, to reduce the risk of clogging, it may be recommended that the MSL system be given a periodic rest time and that the removal of SS discharges into the MSL be preceded by a pre-treatment of wastewater [12].

3.2.2. Organic Matter

Regarding the organic matter, the aerobic and anaerobic biological decomposition of contaminants is based on the microbial biomass that makes up the MSL biofilm [9]. When wastewater is released into the MSL system (Figure 5), organic contaminants are first removed from MSL systems by physicochemical absorption by soil mixture particles and the surface area of the PL, and subsequently broken down and metabolized by heterotrophic aerobic microorganisms [9,12,19]. Thus, its decomposition leads to the emission of carbon dioxide (CO_2) and methane (CH_4) [45]. Furthermore, organic matter is removed mainly at the upper layers of the MSL system, where aeration is more favorable and provides a suitable environment for aerobic heterotrophic bacteria [9,12,19]. Song et al. [5] and Zhou et al. [9], in turn, found that temperature has a role in the removal of organic matter in the MSL system, with low temperatures being unfavorable for bacterial growth and metabolism.

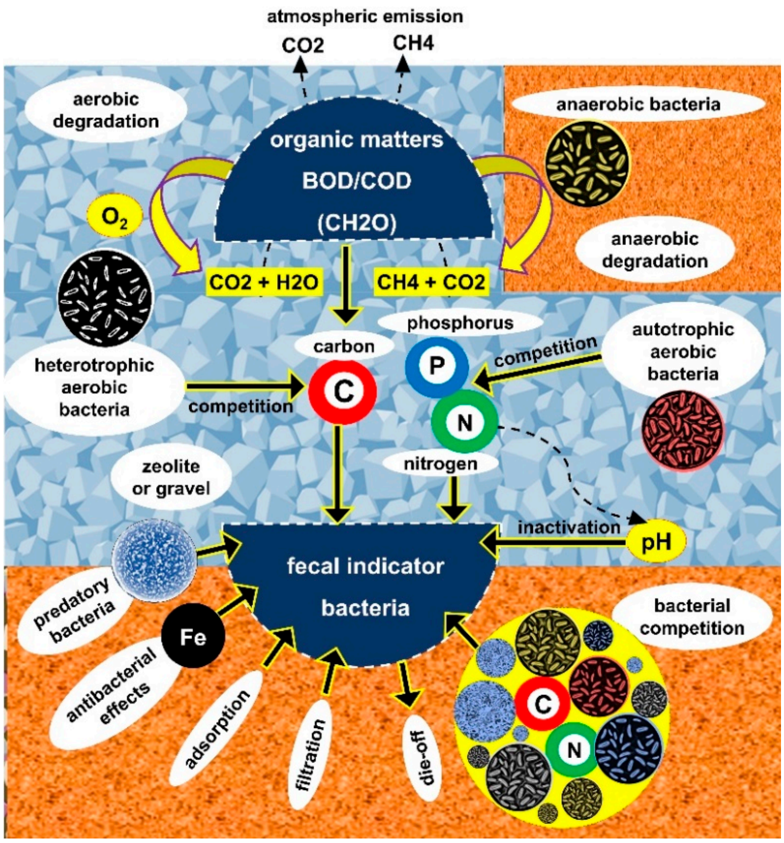

Figure 5. MSL layers design associated with the removal mechanisms of organic matter and fecal indicator bacteria.

3.2.3. Fecal Indicator Bacteria and Pathogens

Regarding microorganism removal efficiencies, the mechanisms involved in fecal bacteria indicator (FIB) and pathogen removal in the MSL system are filtration, adsorption, predation, inactivation, and die-off [7,37]. Thus, both permeable layers and soil mixture layers contribute to reducing their level through filtration (Figure 5), while adsorption is expected to occur in particular at the soil mixture layers [37]. As for microbial degradation, the influence of inhibitory compounds released by other bacteria in soil [46] or predatory populations (protozoa, worms), as reported by Kadam et al. [47], might play a significant role. Furthermore, the MSL system is an ecosystem that includes many species of bacteria [9,17,48] competing to survive and gain an advantage in terms of space and resources, including organic carbon and nutrients (nitrogen and phosphorus). Therefore, interactions within MSL and between microbial species may lead to decreasing these advantages for coliforms, which will negatively affect their level in the MSL system. In the same vein, Latrach et al. [7] claim that natural indicator bacteria die-off is induced by several inactivation mechanisms, including exposure to physicochemical stressors such as pH, oxygen, and temperature. Thus, the critical role of pH in removing FIB has been confirmed recently by Sbahi et al. [11], who also stated that pH action is reinforced by the denitrification mechanism and alkaline properties of soil, while iron metal contributes to decreasing fecal pollution level as an antibacterial element (Figure 5).

3.2.4. Nitrogen

The soil mixture layer and PL alternately contribute to the removal of nitrogen as wastewater passes within the MSL system. Thus, as reported by several authors [12,35,49], PL filled with zeolite can adsorb ammonium (NH_4^+) due to its strong cation exchange capacity. In the MSL system, after the transformation of total Kjeldahl nitrogen (TKN) to NH_4^+ through ammonification, the latter oxidizes in the combined presence of oxygen and nitrifying bacteria into nitrites (NO_2^-) which in turn are transformed into nitrates (NO_3^-) in the same conditions (Figure 6).

This biological process (nitrification) is localized in the MSL upper layer, where the number of nitrifying bacteria is higher due to an increase in oxygen and nutrient availability [50]. Furthermore, these wastewaters flow due to gravity, percolate through the PL, and then drain into the soil mixture layers (anaerobic zone), where they will be reduced in the presence of both organic carbon and denitrifying bacteria to nitrogen gas (N_2, N_2O) [7]. Soil organic matter, sawdust, and charcoal as carbon sources help to promote the denitrification process, which is controlled by degradable organic matter, NO_3^-, and oxygen [49].

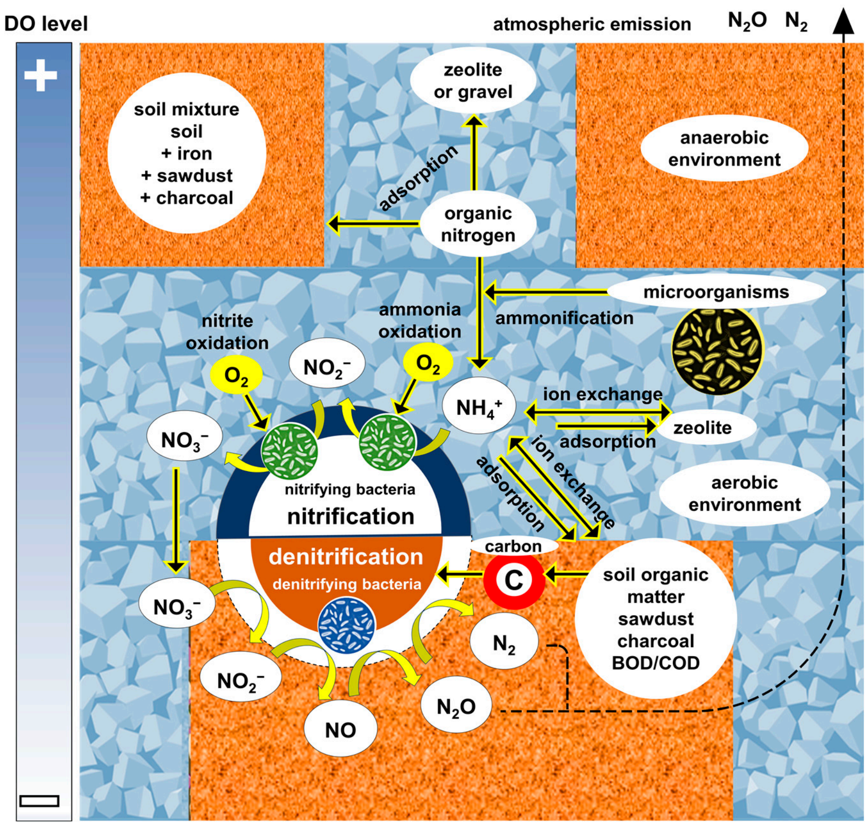

Figure 6. MSL layers design associated with the removal of nitrogen.

Furthermore, Epsilonbacteraeotra was discovered to be a crucial species in nitrogen removal by promoting denitrification at the oligotrophic level, whereas organic might improve the energy metabolism of microorganisms and enzyme activity (e.g., kinase, glycogen phosphorylase), strengthening the denitrification process [9]. In addition to adsorption, nitrification and denitrification are the main mechanisms of nitrogen removal in the MSL system. Thus, the coexistence of aerobic/anaerobic environments is one of the most essential factors influencing the effectiveness of the MSL system in removing nitrogen [7,12,51].

3.2.5. Phosphorus

Regarding phosphorus removal, it can be adsorbed on Fe and Al hydroxide contained in soil and zeolite [12,49], whereas ferrous ion (Fe^{2+}) and ferric ions (Fe^{3+}), as well as other cations present in the soil mixture, can co-precipitate with this pollutant [9]. Indeed, during the percolation of wastewater within the MSL layers, the iron added in the soil mixture layers is transformed into Fe^{2+}, which is then transported to the PL and oxidized to Fe^{3+}, allowing the removal of phosphorus (Figure 7). Zhou et al. [9] also claimed that soil mixture fillers with high surface areas, such as charcoal, have many micropores that contribute to phosphorus adsorption, while Sato et al. [19] indicated that the flow rate and permeability of the soil mixture had a significant impact on phosphorus removal efficiency in the MSL system. Regarding PL, it assumed greater responsibility for its removal than the soil mixture media in the case of high HLR [52] (Figure 7).

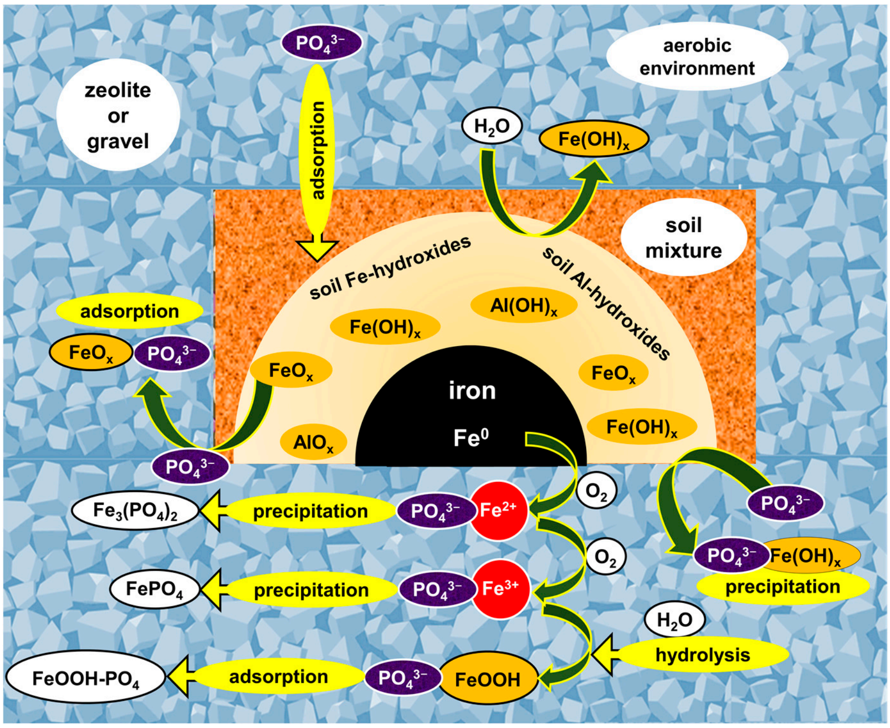

Figure 7. MSL layers design associated with the removal mechanisms of phosphorus.

3.3. *Key Efficiency Parameters*

The effectiveness of the MSL system, like the majority of soil-based wastewater treatment systems, is influenced by a variety of parameters.

3.3.1. Temperature

For instance, Sbahi et al. [6,11] have reported that temperature fluctuations are among the most important parameters that influence coliform removal in the MSL system. Similarly, Guan et al. [36] stated that temperature is a limiting factor for bacterial growth in the MSL system and that this system can remove more than 95% of the five-day biochemical oxygen demand (BOD_5) in the temperature range (25–35 °C) in a humid environment. Zhou et al. [9], in turn, have reported that biological processes within the MSL system, including the removal of nitrogen and organic matter, are sensitive to temperature. However, Latrach et al. [7] have claimed that seasonal temperature fluctuations did not influence MSL performance for both physicochemical and bacterial indicators under arid conditions.

3.3.2. Aeration

Regarding aeration, Song et al. [20] found that, while bottom submersion had the most negative effect, aeration was the most dominant beneficial factor for pollutant removal. Sato et al. [1] reported that anaerobic conditions have decreased the presence of ferric hydroxides, and as a result, phosphorus adsorption has decreased. Luanmanee et al. [35] also reported that aeration is an important factor in the operation of the MSL and recommended varying the duration of aeration depending on the quality of the wastewater and the components of the system. Zein et al. [53] also observed that aeration contributes to the removal of nutrients, oil, and grease in the MSL system.

However, excessive aeration could intensify nitrification and harm microorganisms' metabolism [54], which may, in turn, inhibit the denitrification process and consequently reduce nitrogen removal [55]. In the same context, Luanmanee et al. [31] have declared that continuous aeration was successful in increasing the removal of BOD_5 and total phosphorus (TP) inversely to total nitrogen (TN) removal (dropped to 31%). As a result, regulating the aeration of the system is necessary for maintaining the capacity of the MSL to remove organic matter and nutrients and to prevent clogging. In addition, Sato et al. [19] proposed that improving the MSL's upper layers' aeration and addition of organic matter in its lower layers of soil mixture were effective in simultaneously removing organic matter and nutrients.

3.3.3. pH

On the other hand, the effectiveness of the MSL system is related to the pH value of influent wastewater. For instance, Sbahi et al. [6,11] have reported that the pH of the influent was the most important variable that contributed to coliform removal in the MSL system. Similarly, Latrach et al. [7,37] reported that pH value is a critical factor controlling the survival of bacteria in alkaline water and would aid in their inactivation in the MSL system. In the same context, Song et al. [5] stated that pH could affect bacterial abundance and the nitrification process. In addition, they found that an acidic influent (pH = 3) was suitable for removing sulfamethoxazole through increasing its sorption affinity with the micropores of MSL media.

Regarding nutrient removal, Luanmanee et al. [35] found a significant ($p < 0.05$) positive relationship between TN and TP removal and the pH value of MSL effluent, which is also related to MSL aeration. Furthermore, they recommended that the pH of the MSL system's effluent be kept between 6.5 and 7.0 to maintain its effectiveness in wastewater treatment. On the other hand, changes in the pH of the MSL effluents may be utilized to regulate the aeration rate and its duration in the MSL system [35,56] and consequently enhance the biological nitrification/denitrification processes.

3.3.4. Hydraulic Loading Rate and Clogging

Regarding the HLR and flow pathways, Sato et al. [1] have noticed that shortcut flow can cause a decrease in the decomposition of organic matter and the capacity for oxidation-reduction potential (ORP) of treated water. Guo et al. [57] and Sato et al. [19] have suggested that flow rate is a critical operational parameter for organic matter and nutrient removal and that its regulation can prevent clogging [58]. Guan et al. [36] have stated, in turn, that HLR strongly affects the distribution of anaerobic and aerobic zones by changing the depth of water. Guo et al. [57,59] concluded that the MSL system demonstrated strong adaptability with the variation of HLR.

However, Masunaga et al. [60] observed that HLR contributes to MSL clogging, especially at 4000 L/m²/day. In the same sense, Guan et al. [61] reported that HLR and hydraulic residence time are related factors and concluded that the residence time of flow inside the MSL system was highly correlated to HLR. As a result, a high inflow rate would favor short-circuiting flow, increase the volume of dead space, and consequently decrease MSL efficiency.

Regarding clogging, this factor has already been discussed by Guan et al. [36] as a crucial parameter in MSL efficiency. Thus, Figure 8 presents the bibliometric map when the key efficiency parameters "HLR (Figure 8a)", "Clogging (Figure 8b)", and "aeration (Figure 8c)" are selected. Through these network maps, the selected terms are related to each other and also affect the efficiency of the system through some of the relevant links (relationships with "multi-soil-layering system", "efficiency", and "performance"). In addition, they are directly linked to the mechanisms responsible for removing pollutants in the MSL system. Thus, selecting the item "hydraulic loading rate" highlighted some related terms, including "organic matter", "nitrogen removal", "denitrification", and "performance". In this context, increasing the HLR inversely reduces the contact time of nitrogen within the MSL media and consequently reduces its removal through limiting the denitrification process. In general, decreasing the HLR increases the removal of pollutants in the MSL system.

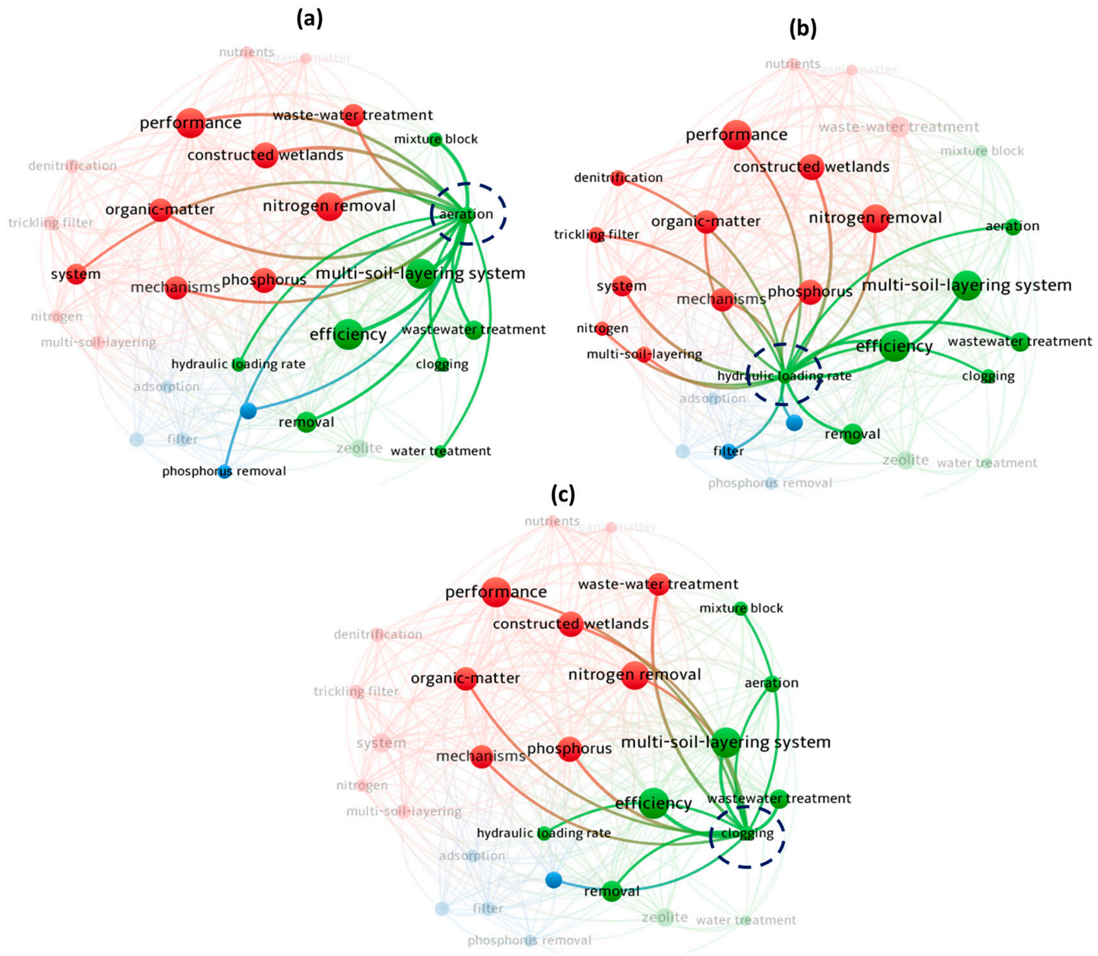

Figure 8. Selections of items in the network map. (**a**) Aeration, (**b**) HLR, (**c**) clogging. The distance between two items reflects the strength of the association, while the lines show the relationships

between the items. Each color indicates a cluster that groups the more related terms; aeration, HLR, and clogging belong to the same cluster. To avoid overlapping labels, some extracted items are not presented on the network view.

3.4. Filter Media and Structure

The lack of sufficient knowledge of the MSL system can lead to environmental effects on public health [36]. Sato et al. [19] stated that the effect of used materials and their structure within the MSL on the removal efficiency is not entirely understood. Thus, for the effective operation of the MSL system, researchers have extensively tested different kinds of materials. The soil mixture consists of soil (around 70%), while supplementary purification materials (iron, jute, sawdust, charcoal, and activated charcoal) depend on the type of wastewater and differ according to the research purpose [12,60].

The PL material consisted mainly of zeolite due to its high capacity of adsorption and affinity with NH_4^+ [31,60,62,63], whereas many studies confirmed the high purification capabilities of other materials such as gravel, perlite, and pozzolan [1,11,15,33]. In the same context, Maeng et al. [22] have reported that the introduction of zeolite/slag into the MSL system could improve the removal of traces of organic pollutants as well as the growth of bacterial biomass, resulting in better dissolved organic matter reduction via biodegradation. Song et al. [50], while treating turtle aquaculture effluent by an MSL system, found that adding sludge (20%) to the MSL could improve the NH_4^+ removal efficiency by promoting the number of nitrifying bacteria. Ait-Hmane et al. [64] have discovered, in turn, that MSL combined with activated carbon as an adsorbent was a suitable alternative for purifying wastewater from olive mills by improving the adsorption process. Wang et al. [65] have found that the purifying capacity of sludge-based biochar material outperforms that of charcoal in eliminating organic matter and nutrients.

Regarding the number of layers and configuration design, Sy et al. [66] discovered that the more MSL layers, the greater the decrease of contaminants, while Sato et al. [21] observed that six layers were found to be required for a high removal rate of organic matter. Moreover, Sato et al. [58] also indicated that reducing the width of soil-mixed blocks helped to improve the dispersion of water flow inside the MSL system. Chen et al. [43] reported that a larger soil mixture surface area increases the removal of SS, organic matter, and TP due to increased interaction and contact between the soil mixture layers and wastewater. Similar results were reported by Sato et al. [1]. In the same context, Wei and Wu [49] and Guan et al. [36] have stated that effluent recirculation is recommended to remove even more nitrogen in the MSL system.

Regarding soil mixture fillers, Xiao et al. [67] reported that combining granular Fe^0 with an iron sulfide mineral improves the efficiency of conventional Fe^0 systems, including MSL technology. In addition, sulfide minerals increase Fe^0 dissolution by lowering the pH of the system, resulting in the subsequent precipitation of hydroxides coupled with the co-precipitation of contaminants. Chen and Pat [68] observed that iron was the main factor that improved the capability of the MSL in phosphorus removal (more than 83%). The same authors reported that the addition of oyster shells successfully eliminated up to 99% of the iron released from the soil mixture in the effluent after the reaction with phosphorus.

On the other hand, there are recent studies that have used new materials to improve the effectiveness of the system. For instance, Song et al. [48] reported that using polybutylene succinate (PBS) in soil mixture was favorable for species involved in the denitrification process. Hong et al. [13] reported that PBS had some advantages over sawdust as it is a pure carbon source and does not bring nitrogen and phosphorus to the MSL system. Additionally, Liu et al. [69] observed that PBS releases organic matter at a slower rate, which consequently increases the operation time of the MSL system. Zhou et al. [9], adding a blended organic carbon source (BCS) to the MSL system, have found that BCS increases denitrification gene abundance (nirS and nosZ). Guo et al. [57] reported that using a biosurfactant in the MSL was a promising option for enhancing ammonia removal and biological activity. Pattnaik et al. [70] showed that adding a sucrose solution to untreated effluent improved the removal of nutrients in the MSL system.

In general, the MSL system's structure and component arrangement optimize wastewater dispersion and distribution while lowering the risk of clogging. In the permeable zone, zeolite is the most commonly employed filter media because of its high purifying power through adsorption and ion-exchange capacity, as well as its benefit to microorganisms. However, in contrast to sites marked by ancient volcanic activity [71], this material is not abundant in many parts of the world. Therefore, a low-cost and easily accessible alternative natural filter media, such as gravel, that has been proven to be effective is also a suitable choice.

On the other hand, the number of layers in MSL is an important factor in the system's efficiency. In this regard, the more significant it is, the longer pollutants will be retained and the system's efficiency will improve. In the same vein, the MSL's efficiency rises in lockstep with the increase in the pollutants' contact surface with the soil mixture blocks. Furthermore, adding an extra carbon source to the composition of these blocks might help the bacterial population grow and boost its action in the breakdown of organic matter and nitrogen. On the other hand, iron remains a critical parameter in the removal of phosphorus from wastewater, which may be enhanced further with the addition of sulfide minerals.

3.5. MSL Typology and Performance

3.5.1. Single-Stage MSL

The use of eco-friendly technologies, especially in rural areas without suitable purification facilities, is vital for reducing pollution from wastewater released into the natural environment. MSL is a natural technology developed for lowering pollutant levels in discharged effluents. Many researchers have tested the efficacy of this system in the lab and on a pilot scale [7,48]. However, its application at full scale is limited and focused mostly on domestic wastewater purification [1]. Several studies have looked into the effectiveness of the MSL system by experimenting with different configuration designs and purification materials [30,33,72].

Figure 9 depicts various types of wastewater treated by the MSL system at various scales (lab, pilot, and full scale), as well as the highest removal efficiency recorded for each water quality indicator. Across all MSL scales, real and synthetic rural domestic wastewater remain the most investigated kinds of water [6,17]. In addition, the MSL's performance in treating other types of wastewater, such as textile and livestock effluent, is also being investigated [66,73].

Recently, on a laboratory scale, MSL has been demonstrated to be successful in removing a variety of contaminants, such as sulfamethoxazole in poultry wastewater and cyanotoxins in contaminated freshwater [5,15]. In terms of removal efficiency, MSL has demonstrated remarkable results in the removal of a wide range of pollutants. Regarding SS, in several investigations, its removal has exceeded 97%, both in the lab and at full scale [17,43,53]. In the case of organic matter, the chemical oxygen demand (COD) parameter was more thoroughly investigated than BOD_5 (Figure 9). Thus, Sato et al. [19] have found that MSL removed almost 98% of BOD_5 from domestic wastewater under an HLR of 1000 $L/m^2/day$. Similar results were found for COD removal at HLRs of 400 and 500 $L/m^2/day$, respectively [10,13]. However, Attanandana et al. [74] have found that MSL removes an average of 57% under a hydraulic head of 850 $L/m^2/day$. This might be because the MSL system is still in its early stages, and that the findings of subsequent research have enhanced its efficiency. Concerning nitrogen removal, in the study conducted by Song et al. [20], the removal of NH_4^+ from domestic wastewater has reached 100%. Close results were recorded by Guo et al. [57] when treating swine wastewater, with a removal rate going up to 94% for TN under an HLR of 160 $L/m^2/day$. In terms of TP, many studies have reached a removal rate of 100% [5,10,13].

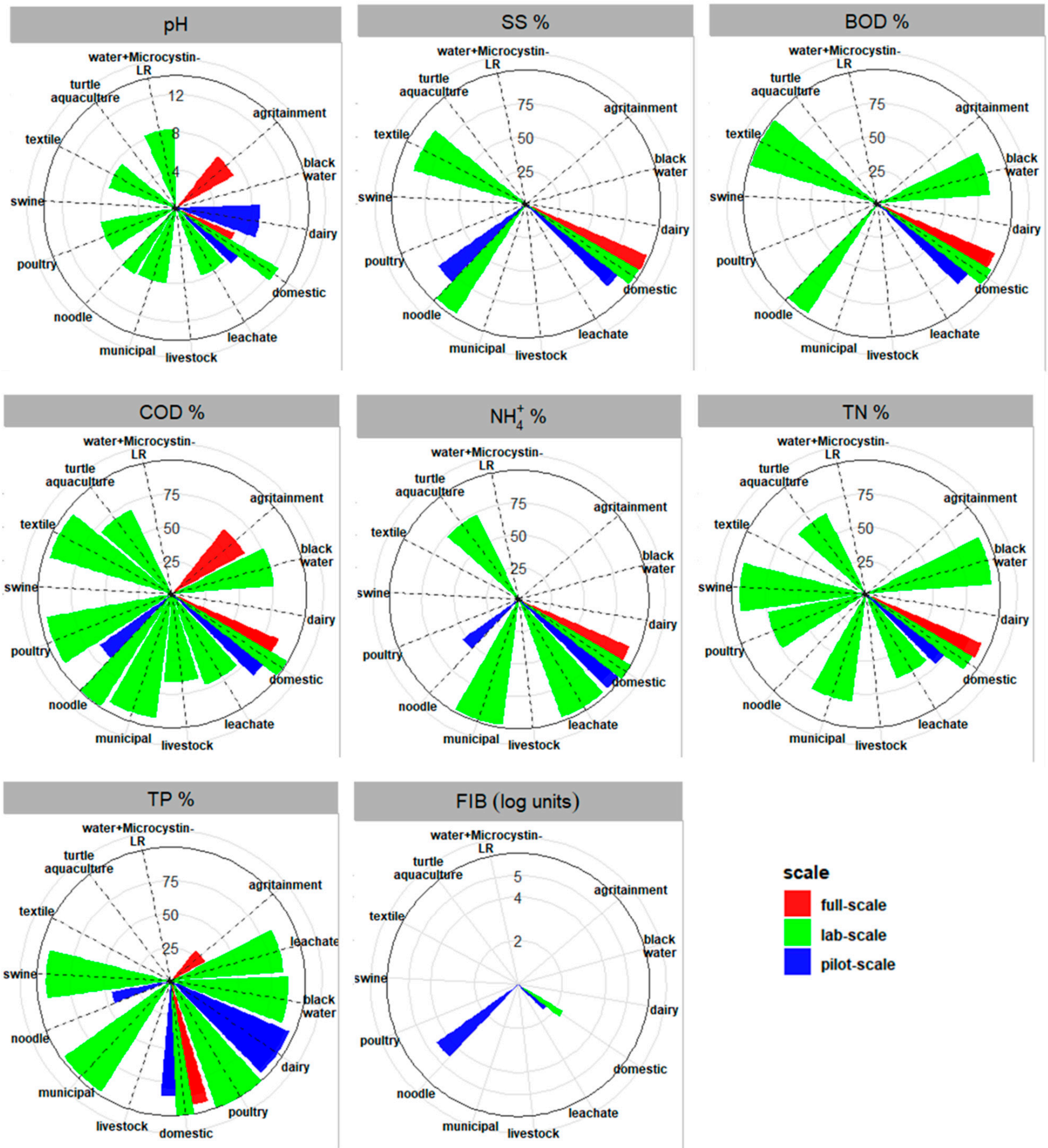

Figure 9. Performance of single-stage MSL systems while treating a variety of wastewaters at different configurations; scale inside plots indicates the removal efficiency.

Although these findings are encouraging, more research on the removal of FIB from wastewater is needed to increase the MSL's sanitary efficiency, particularly at the full-scale level (Figure 9). Overall, the MSL system was able to remove 2.26 log units from domestic wastewater [33], whereas Sbahi et al. [11] discovered that the MSL system could remove 1.62 log units from rural domestic wastewater.

In terms of pH, the literature analysis revealed that it is about 8 in the MSL effluent (Figure 9). This suggests that the MSL system's chemical activity has tended to be alkaline, which aids in the removal of contaminants [6,53,75]. Within the same context, Latrach et al. [7] and Masunaga et al. [32] observed that pollutant removal seems to not be largely influenced by seasonality. However, Sbahi et al. [6,11] found that the removal efficiency of the MSL system was sensitive to seasonal variations in semi-arid climates.

3.5.2. Combined Systems

It has been noted that the combination of the MSL with other treatment technologies in sanitation is not frequent around the world. Among the 70 papers considered, 13 studies investigated the combination of the MSL with other treatment plants. In order to efficiently treat different types of wastewater, the researchers have attempted to combine the MSL system with different other technologies, such as sand filters, trickling filters, constructed wetlands (CW), as well as MSL on a two-stage level. Table 1 shows a summary of the combined typologies' performance. In addition, Figure 10 shows a schematization of these configurations based on the literature review.

- Two-stage MSL

In this combination of two MSL systems, domestic wastewater flows under the influence of gravity (Figure 10a). Thus, it has shown a high potential for eliminating SS (97%), organic matter (≥91%), and nutrients (≥95%) from domestic wastewater in a small rural community in Morocco [7]. In addition, this configuration was shown to be efficient in fecal coliform bacteria removal (>3 log units) (Table 1). For the treatment of polluted river water, Wei and Wu [49] also developed a hybrid two-stage MSL system with vertical flow (Figure 10b). As a result, the authors discovered that a 50% bypass combined with the addition of an organic carbon source was able to accomplish the full nitrification process (NH_4^+removal = 99%). Furthermore, the study revealed a significant removal efficiency of COD (>70%) and TP (82%) (Table 1). Thus, in contrast to the system proposed by Latrach et al. [7], which uses gravel as a purification material, this configuration uses zeolite and ceramsite as purifying materials. In addition, the first unit had a ryegrass-planted topsoil layer.

- MSL with constructed wetland

Gravity is used to move wastewater in these configurations. Furthermore, some research coupled MSL and CW on a two-stage system (Figure 10c), while others integrated the two technologies into a single unit (Figure 10d–f). For instance, Song et al. [20] have examined the performance of a full-scale configuration consisting of an MSL system and a CW unit to treat domestic wastewater (Figure 10c). Similarly, Zhang et al. [23] have used the same configuration to treat wastewater produced by agritainment activities (Figure 10c). In terms of design and components (soil, sand, clay, zeolite, and gravel), the two typologies are comparable, but there are some differences, mainly in terms of the size and types of plants used. In addition, both have demonstrated good performance in the removal of pollutants, particularly from domestic wastewater [20], where organic matter and phosphorus removal rates were both about 92%, while nitrogen removal rates were around 76% (Table 1). Furthermore, these eco-friendly combinations have proven to be efficient in mitigating greenhouse gas emissions and required low economic costs.

Koottatep et al. [62], while treating solar septic tank effluent utilizing a pilot plant scale in Thailand (Figure 10d), discovered that this combination was able to remove SS (>70%), organic matter (72–80%), nutrients (>70%), and coliforms (2 log units) (Table 1). In the same context, to treat real rice noodle wastewater in Vietnam, the study conducted by Nguyen et al. [24] using an integrated hybrid system (MSL combined with vertical flow CW) has demonstrated close results for SS (>70%) and organic matter (72–80%) compared to nutrients (54–60%) (Figure 10e). Similarly, in Thailand, Koottatep et al. [25] have investigated the efficacy of a lab-scale system consisting of a vertical flow MSL and CW for treating septic tank wastewater (Figure 10f). The findings showed that this arrangement exceeds 84% in terms of SS and organic matter removal (Table 1). Overall, these three configurations also differ in terms of materials used in the permeable layers (e.g., zeolite, sand, and gravel), the number of soil mixture layers, and the types of plants grown on their surface.

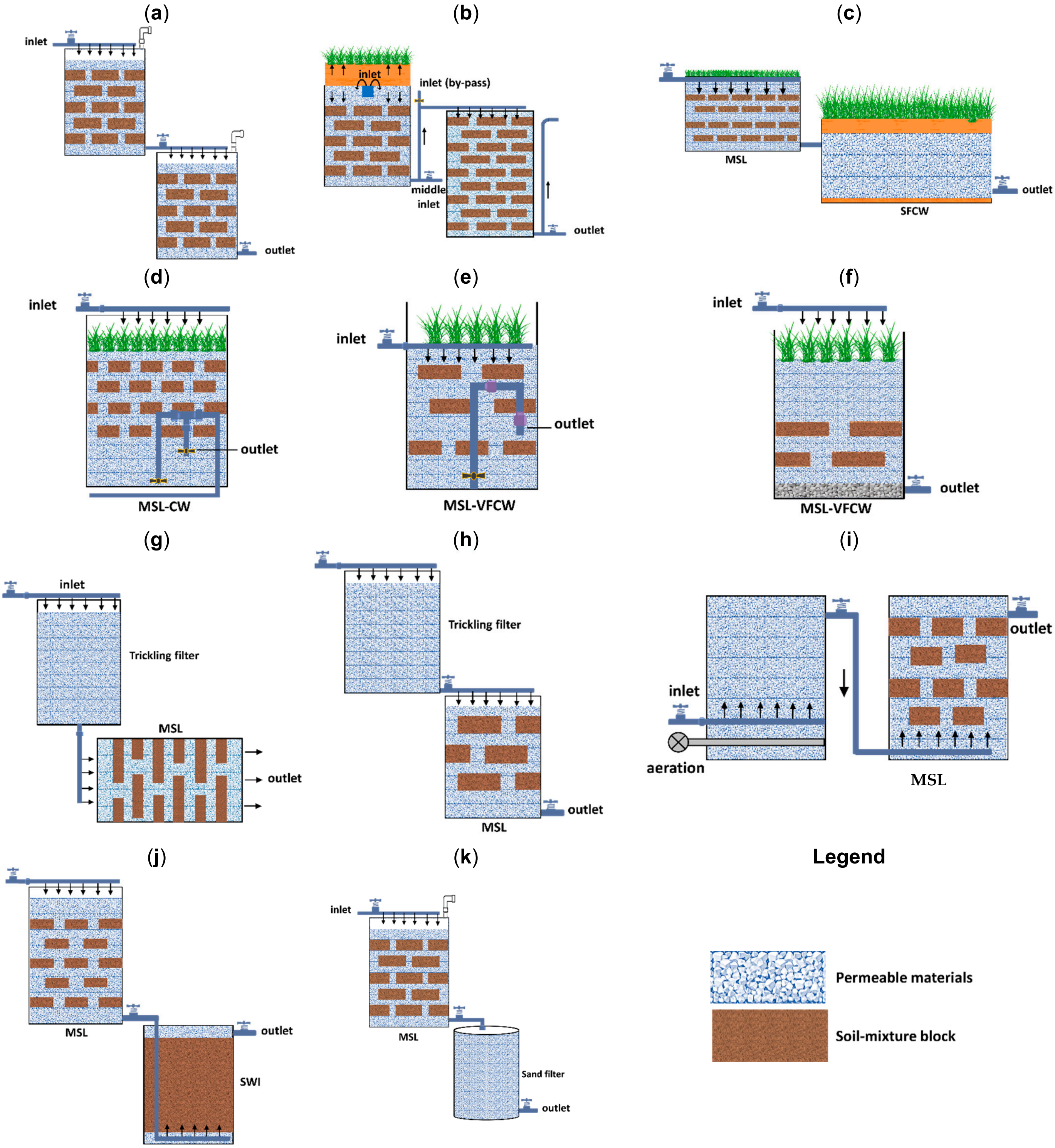

Figure 10. The simplified schematization of the multi-soil-layering (MSL) system combined with other technologies (VFCW = vertical flow constructed wetland; SFCW = subsurface flow constructed wetland; SWI = subsurface wastewater infiltration): (**a**) two-stage vertical flow MSL, (**b**) topsoil planted MSL with vertical flow MSL, (**c**) planted vertical flow MSL with SFCW, (**d**) integrated vertical flow MSL and VFCW, (**e**) integrated VFCW and MSL with two soil-mixture layers, (**f**) integrated VFCW and MSL with three soil-mixture layers, (**g**) trickling filter with horizontal flow MSL, (**h**) trickling filter with vertical flow MSL, (**i**) blended carbon sources preceded by aeration system with vertical flow MSL, (**j**) vertical flow MSL with infiltration section based mixed soil and gravel, (**k**) vertical flow MSL with sand filter.

Zhang et al. [51] have previously combined a trickling filter with a horizontal flow MSL to treat domestic wastewater at the lab scale (Figure 10g), and it has demonstrated outstanding efficacy in the elimination of organic matter (≥94%) and nutrients (92–96%) (Table 1). Likewise, Tang et al. [63] have found close results and discovered that this combination (Figure 10g) can process a high content of organic matter (960 mg/L) at varying concentrations of sodium dodecyl benzene sulfonate. Using the same design, Tang et al. [76] have investigated its efficacy in treating mariculture effluent in China. Thus, the authors found that this configuration was also efficient in removing COD and NH_4^+ (> 80%) (Table 1). In addition, they concluded that extracellular polymer substances could enhance the organic matter removal and mitigate cytotoxicity from salinity.

Luo et al. [26] also designed a two-stage system consisting of a trickling filter and a vertical flow MSL system to treat domestic wastewater in China (Figure 10h). This novel design provides better dispersion of the influent inside the MSL system. Furthermore, the removal efficiencies of COD, TP, NH_4^+, and TN were 93%, 93%, 86%, and 61%, respectively, at a mean HLR of 920 L/m^2/day (Table 1). Although these configurations are comparable in terms of efficiency, they differ in terms of the flow regime, which is vertical in the MSL system operated by Luo et al. [26], compared to the MSL with horizontal flow operated by Zhang et al. [51] and Tang et al. [63,76]. In addition, iron was also used by Luo et al. [26] to support the trickling filter system's efficiency.

- Novel hybrid combinations

In the same regard, other studies have examined the efficiency of the MSL combined with other treatment systems. For instance, to treat rural non-point source wastewater, Zhou et al. [9] have developed a novel combination at pilot scale that consists of two stage MSL with blended carbon sources (Figure 10i). This combination also uses ceramsite as a purification material. However, unlike the reviewed combinations, this system is characterized by an upward flow in the two combined units (Figure 10i). In addition, this hybrid system effectively reduced NH_4^+ (> 50%), TN (64%), and TP (60%) (Table 1). Furthermore, the author concluded that this pilot plant could promote the denitrification process.

Li et al. [21] have developed a novel system consisting of an integrated MSL system and a subsurface wastewater infiltration unit (SWI) that consists of mixed soil and gravel (Figure 10j). Thus, the flow in this combination is in the opposite direction (gravity-flow in the MSL and upward flow in the SWI unit). In addition, this combination recorded a removal rate of 93%, 98%, 74%, and 74% for COD, TP, NH_4^+, and TN, respectively (Table 1). Latrach et al. [27] have investigated the efficiency of a lab-scale plant consisting of the MSL system followed by a sand filter (Figure 10k). The study findings indicated that the novel conception showed very high efficiency in removing SS (94%), organic matter (80–90%), NH_4^+ (93%), and TP (78%). In addition, this hybrid combination was effective in removing helminth eggs (100%) at the HLR of 100 L/m^2/day (Table 1). Although this system also enhances coliforms and pathogen elimination, the risk of clogging has emerged in this combination.

Table 1. Various combinations of the MSL technology with other systems according to the literature review.

Combination Units	Scale	Type of Wastewater	Flow (L/day)	SS (%)	BOD_5 (%)	COD (%)	NH_4^+ (%)	TN (%)	TP (%)	Coliforms (log Units)	References
Two stage MSL											
two vertical flow MSL in series	pilot-scale	domestic	1000	97	96	91	95	96	95	3.15	[7]
		polluted river	1000	-	-	>71	99	70	82	-	[49]
MSL with CW											
MSL + Constructed wetland	pilot scale	solar septic tank effluent	743	>70	80	72	>70	>70	>70	2.00	[62]
MSL + subsurface flow CW	full scale	agritainment	30000	-	-	78	-	-	70	-	[23]
MSL + subsurface flow CW	full scale	domestic	5000	-	93	92	-	76	92	-	[20]
Integrated hybrid system	pilot scale	rice noodle	50	80.5	-	73.2	60.6	-	54	4.80	[24]
MSL+ vertical flow CW	lab scale	academic building effluent	-	84.7	85.5	84	-	-	-	-	[25]
MSL with trickling filter											
vertical flow trickling filter + horizontal flow MSL	lab scale	mariculture	660	-	-	84	83	-	-	-	[76]
		domestic		-	-	92	82	-	96	-	[63]
				-	-	94	96	93	92	-	[51]
MSL + iron modified zeolite trickling filter		domestic	920	-	-	93	86	61	93	-	[26]
Other combinations											
MSL + blended carbon sources	pilot scale	rural non-point source	800	-	-	30.3	>50	64	60	-	[9]
MSL + subsurface wastewater infiltration		domestic	300	-	-	93	-	74	98	-	[21]
MSL + sand filters	lab scale	black water	100	94	80	90	93	54	78	4.50	[27]

Overall, the hybrid systems developed, including the MSL system, have been found to be effective in removing pollutants from a variety of wastewater, whether on a lab, pilot, or full scale. This improvement is mostly observed in the reduction of coliform levels (Table 1). For instance, the reduction of coliform content in domestic wastewater has improved from 1.62 log units in single-stage MSL to 3.15 log units in a two-stage MSL system [7]. In addition, it reached 4.80 log units while treating rice noodle wastewater using MSL combined with a CW system [24].

Likewise, the removal of organic matter and phosphorus from domestic wastewater by these reviewed combinations is comparable (Figure 11). However, when it comes to nitrogen removal, this convergence in effectiveness differs, since the two configurations (two-stage MSL and MSL with trickling filter) have high efficiency in eliminating TN when compared to the two systems, MSL-CW and MSL-SWI (Figure 11). In addition, this finding can also be seen in the case of NH_4^+ removal in the MSL-CW system, suggesting that aeration in these combinations (MSL-CW and MSL-SWI) should be monitored as well as the denitrification process to improve their efficiency in removing nitrogen.

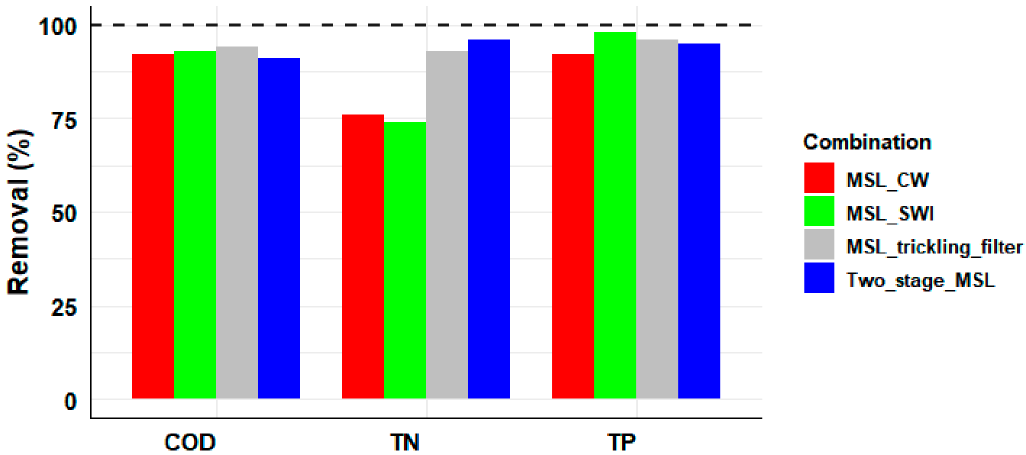

Figure 11. Pollutant removal efficiency by the reviewed combinations using bar charts.

3.6. Multi-Soil-Layering and Alternative Treatment Technologies

This paper also aimed to investigate potential alternative wastewater technologies for MSL through a comprehensive literature analysis. The findings reveal that constructed wetland, lagoon, and sand filter technologies are widely used as rural sewage treatment technologies. Table 2 provides a summary of the comparison's findings. These alternative methods can be used to treat water in rural regions, according to preliminary comparisons. Additionally, they have the trait of being low-cost and friendly technologies. Thus, the techno-economic evaluation shows that MSL is a suitable option since it can withstand high organic loading rates and only requires a small area for operation. Additionally, MSL can withstand the negative effects of odor or insects. However, MSL's sanitary efficiency falls short of expectations. Additionally, MSL is an emerging technology and shows a sensitivity to clogging at high HLR. Therefore, conducting more studies in this field has become an urgent necessity to improve MSL's performance.

Table 2. Main advantages and disadvantages of various rural sewage treatment technologies.

Methods	Basic Substrates	Principle	Advantages	Disadvantages	Reference
MSL	Soil Iron Charcoal Sawdust Zeolite (Gravel)	Exert soil filtration, adsorption, and biodegradation functions supported by adequate aeration and HLR	Small land requirement Low-cost Low energy No odors, no insects Easy operation and maintenance Adaptation to high pollutant loads Support high HLR	Moderate sanitary efficiency Risk of clogging at high HLR	[12,18]
CW	Soil Sand Clay Gravel Plants	Benefiting from the combined effect of the physical and biochemical properties of soil, artificial media, and microorganisms	Low-cost Low energy Simple operation	High land requirement Plants are subject to the effects of the seasons Low denitrification rates Periodic maintenance Odor and insects	[12,77]
Lagoon	Microorganisms Plants	Transformation of organic matter into mineral elements that can be assimilated by plants	Low-cost Minimal energy Simple operation Resistance to HLR variations High sanitary efficiency	High land requirement Risk of evaporation High residence time Odor and insect	[12,78,79]
Sand filter	Rocks Gravel Sand	Infiltration and purification of wastewater by sand-attached microorganisms	Low-cost Small land requirement Easy operation and maintenance High sanitary efficiency	Risk of clogging Low denitrification rates Odor and insect	[80–82]

3.7. Modeling Approaches Used

Many authors have recently concentrated on simulating the performance of the MSL technology and analyzing linear and non-linear interactions between water quality indicators and MSL efficiencies through modeling approaches. This research axis is considered nowadays as an emerging topic in the MSL field, and researchers have employed a variety of data-driven approaches as well as conventional methods to simulate the performance of the MSL system. Thus, after a thorough analysis of the literature review, regression models and machine learning models were identified as two data-driven models [83] employed to describe MSL behavior, followed by kinetic models. Table 3 presents the number of studies that have targeted modeling water quality indicators in MSL systems, including hybrid systems.

3.7.1. Data-Driven Models

For instance, Sbahi et al. [16] were the first to use neural networks (NN) to predict nitrogen removal in the MSL system (Table 3). Thus, through two hidden layers, the NN model has accurately predicted NH_4^+, TKN, and TN removal ($R^2 > 0.93$). Furthermore, HLR was proved to be the most significant predictor for all the output variables ($p < 0.05$). Similarly, for predicting fecal coliform (FC) concentration at a two-stage MSL system's outlet, other research [6] revealed that the NN model had higher accuracy ($R^2 \geq 0.95$) compared to the Cubist and multiple linear regression (MLR) methods ($R^2 = 0.48$) (Table 3).

In the same context, the potential of NN in predicting the sanitary efficiency of MSL systems has been previously demonstrated by [11]. Thus, both studies [6,11] revealed that SS and pH were found to be the most important factors in removing coliform bacteria in the MSL system.

For modeling sulfamethoxazole removal, Song et al. [5] compared a stepwise-cluster analysis (SCA) approach with the MLR method. Time and the removal of COD, TP, NH_3 (ammonia), NO_3^-, TN, DO (dissolved oxygen), ORP, and pH were all used as input variables in both models. Furthermore, the evaluation of accuracy shows that the MLR model was inaccurate (R^2 = 0.62) compared to the SCA model (R^2 = 0.82, α < 0.001). In the same context, Hong et al. [13] have used the same approach (SCA) to simulate TN removal in the MSL system (Table 3). The R^2 of the best model was greater than 0.93, with a significance level (α = 0.03). Similarly, to investigate the non-linear relationship between pollutant removal and input data in the MSL system, Song et al. [20] have built an SCA model for each output variable (Table 3). The removal rates of COD, BOD_5, TP, TN, NH_4^+, and NO_3^- were used as input and output data; with time being the only fixed predictor in the proposed input variables. In addition, except for TP (R^2 = 0.85) and NO_3^- (R^2 = 0.88), the model precision for the remaining output variables exceeds 0.95 to estimate BOD_5 concentrations at the MSL system's outlet.

On the other hand, data-driven methods were also used for investigating other factors related to wastewater treatment in the MSL system. For instance, Hong et al. [13] have also developed accurate quadratic polynomial functions (Table 3) using PBS, activated sludge, and submerged height as input data, but in this case, to describe the variation of water quality indexes (DO, pH, ORP, removal rates of COD, TP, NH_4^+, NO_3^-, and TN). In the same vein, through a simple linear model, Nguyen et al. [24] have found that the level of COD and NH_4^+ at the outlet of the MSL system was expressed with acceptable accuracy (Table 3). However, for the integrated hybrid system (combination of MSL and CW systems), these linear models were more accurate (R^2 = 0.92) for both COD removal and COD effluent compared to those for the output variables NH_4^+ removal and NH_4^+ effluent (R^2 (NH_4^+effluent) = 0.49, R^2 (NH_4^+removal) = 0.58), respectively.

3.7.2. Kinetic Models

Regarding kinetic models, Tang et al. [76] have proposed two logistic kinetic functions to calculate the removal of COD and NH_4^+ in the combination that consisted of a vertical flow trickling filter associated with a horizontal flow MSL system. For the final effluent of COD, the model input variable was only salinity as an external environmental factor, while the concentration of NH_4^+ in the effluent was related to BOD_5 load, media surface area, and filter effluent temperature, respectively. Both models had a high level of accuracy (R^2 = 0.94). Koottatep et al. [25], in turn, investigated both the completely mixed flow and plug flow models based on COD, BOD_5, and NH_3 concentrations (Table 3). Thus, the suitable kinetic model and coefficients were based on the highest accuracy. The findings indicate that the first-order completely mixed model was proposed as the best fit model for the MSL-vertical flow CW system for the three output variables ($0.98 \leq R^2 \leq 0.98$) as indicated in Table 3.

Table 3. Modeling approaches used for water quality indicators in the MSL system.

References	Modeling Approach	Input Variables	Output Variables	R^2	Conditions	Limitations
Data-driven models						
[16]	Neural network (NN)	HLR, NH_4^+, DO, BOD_5, and EC (influent)	NH_4^+ (removal)	>0.93	NN = Large data, input and output variables, activation function, hidden layers and neurons, weight decay, optimizer [84]. Cubist = Large data, input and output variables, committees, instance, pruning, or combining operations [84]. SCA = Large data, input and output variables, continuous and/or discrete variables, nodes, leaf nodes, cutting or merging operations [13,85,86]. QPF = ≥2 input variables, continuous output variable, no multicollinearity [87,88]. MLR = ≥2 input variables, continuous output variable, no multicollinearity [87–89].	NN = Difficult to describe connection weights; subjectivity in determining optimal parameters; time consuming; high computational complexity [90]. Cubist = Sensitive to a small dataset; sensitive to the fitness of the dataset; overfitted condition often occurred; high computation time [91]. SCA = High requirements for the predictor; high computational requirements; sensitive to its inputs and internal parameters; usually not well described [92–95]. QPF = Sensitive to outlier data points; difficulty in interpreting its coefficients; Perform poorly on the predictor's extremes [96,97]. MLR = Sensitive to outliers data points; fails to capture nonlinear relationship; low performance in large datasets; cannot be used to model data with numerous
		HLR, TKN, TC, DO, and NH_4^+ (influent)	TKN (removal)			
		HLR, TN, TC, BOD_5, and DO (influent)	TN (removal)			
[5]	Stepwise cluster analysis (SCA)	Time, DO, ORP, pH, removal of COD, NH_3, NO_3^-, and TN	sulfamethoxazole removal	0.82 (SCA)		
	Multiple linear regression (MLR)			0.62 (MLR)		
[6]	Neural network (NN)	SS, pH, EC, DO, and BOD_5	FC (effluent)	0.95 (NN)		
	Cubist			0.94 (Cubist)		
	Multiple linear regression (MLR)			0.48 (MLR)		
[11]	Neural network (NN)	HLR, pH, SS, orthophosphates, TC, TN, TKN of the influent	TC (total coliform effluent)	0.97 (NN)		
	Multiple linear regression (MLR)			0.58 (MLR)		
[24]	Linear model	COD (influent loading rates)	COD (removal/MSL)	0.88		
			COD (effluent/MSL)	0.88		
		NH_4^+ (influent loading rates)	NH_4^+ (removal/MSL)	0.75		
			NH_4^+ (effluent/MSL)	0.59		
[13]	Stepwise cluster analysis (SCA)	Time, DO, pH, ORP, removal of NH_4^+, NO_3^-, and TN	TN (removal)	0.94		
	Quadratic polynomial function (QPF)	PBS, activated sludge, and submerged height	DO, pH, ORP, removal of COD, TP, NH_4^+, NO_3^-, and TN	0.89–0.99		
[10]	Quadratic polynomial function (QPF)	bottom submersion, microbial amendment, aeration	removal of COD, BOD_5, TP, TN, NH_4^+ and NO_3^-	0.77–0.99		
[10]	Stepwise cluster analysis (SCA)	Time, removal of BOD_5, TP, TN, NH_4^+, and NO_3^-	COD (removal)	0.98		
		Time, removal of COD, TP, TN, NH_4^+, and NO_3^-	BOD_5 (removal)	0.95		
		Time, removal of BOD_5, COD, TP, TN, and NO_3^-	NH_4^+ (removal)	0.95		
		Time, removal of BOD_5, COD, NH_4^+, TN, and NO_3^-	TP (removal)	0.85		
		Time, removal of BOD_5, COD, TP, NH_4^+, and NO_3^-	TN (removal)	0.98		

		Time, removal of BOD_5, COD, TP, TN, and NH_4^+	NO_3^-(removal)	0.89		inputs and outputs; requires numerical values; sensitive to a large number of input variables [84,90,98].
[72]	Linear regression	pH (effluent)	TN (removal)	0.32		
			Kinetic Model			
[76]	Logistic kinetic model (LKM)	Q (salinity)	COD (effluent)	0.98	Kinetic = Kinetic constant, input and output variables, reaction rate coefficient, temperature coefficient [25].	Kinetic = Large models result in computational intractability; cannot be used to model data with numerous inputs and outputs; non-linearity; computational tractability; parameter identifiability [99,100].
		BOD load, NH_4^+ load, Iv (media surface area), and T (filter effluent temperature)	NH_4^+ (effluent)	0.94		
[25]	Kinetic Model	Influent concentration, kinetic coefficients	COD, BOD_5, and NH_3 removal	≥0.94		

In this study, the methods with regression structures are allocated to the regression model category, whereas approaches involving undefined model structures are given to the machine learning model category [83]. Figure 12 also shows the distribution of the three common modeling approaches among the various modeled water quality indicators in the MSL systems. Thus, nitrogen was the most modeled parameter in seven studies with 18 models (nine using regression, seven using machine learning, and two using kinetic models), followed by COD with seven models using the three approaches, while phosphorus modeling using regression and machine learning has been the subject of two studies (Figure 12). This significant attention might be due to the large amount of research effort spent on nitrogen removal in decentralized wastewater treatment systems [41]. Models for coliform bacteria have also been developed recently, as illustrated in Figure 12, although with less applicability than the other parameters discussed above.

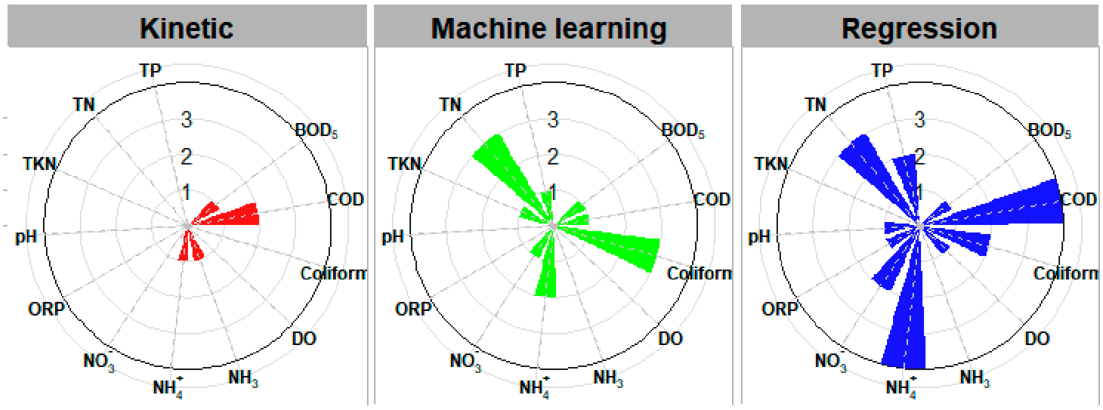

Figure 12. Modeling approaches associated with water quality indicators in the MSL systems with scale inside plot indicates how many times the modeling approach has been utilized.

In summary, NN and SCA dominate machine learning models in MSL performance modeling. Thus, the models have been used to predict MSL performance, investigate its behavior, and analyze non-linear relationships between water quality indicators and operational variables such as time and HLR. Furthermore, these models have demonstrated moderate to high prediction accuracy when it comes to simulating real MSL performance. Although this literature review considers machine learning models to be credible approaches for simulating MSL system performance, their application in the MSL field is still relatively new, with only 11 research papers among 70. However, the results are still encouraging and might be useful to the MSL system in the future. Similarly, while kinetic models are crucial in the research of treatment systems as well as the management and control of their efficacy, they are not up to the task. Future research in this area is also needed to better understand MSL behavior and increase its efficacy.

4. Recommendations and Future Consideration

For three decades, various research studies have been carried out in the field of multi-soil-Layering (MSL) technology, but still further research is required as per the review's outcome. Although the MSL system has shown its effectiveness as a nature-based technology to treat wastewater under different operating conditions, its use is still very limited on a large scale. Further research is still needed to enhance the treatment efficiency of MSL and optimize its design criteria. Therefore, through this bibliometric analysis and review, we will try to evaluate this technology in comparison with similar treatment technologies, point out certain knowledge gaps and challenges, and suggest some recommendations to help researchers gain a better understanding of MSL behavior.

4.1. MSL Treatment Efficiency

In this literature review, the majority of studies focused on investigating contaminant removal in the MSL system. However, there is some gap in knowledge about MSL behavior and its sanitation efficiency. Thus, there are urgent challenges in improving MSL's performance against pathogens and viral indicators in wastewater. Thus, this review urges investigators to investigate predatory activities and microbial flora within the MSL system biofilm responsible for removal and transformation mechanisms. In addition, the findings of this review also encouraged researchers to address other topics that are not covered, such as highlighting factors that influence nitrification and denitrification processes as well as phosphorus sorption dynamics; evaluating the reuse of MSL effluents on irrigation and soil properties; studying the kinetics of contaminant removal in the MSL technology; investigating the effect of MSL characteristic media and residence time on microorganism removal; and evaluating the MSL effectiveness under variation of the hydraulic and organic regime, aeration conditions and type of substrate. In the same context, further research regarding the long-term pollution removal performance of this system is needed. Future research by MSLs should also consider the mechanisms involved in the removal of certain pollutants, such as emerging pollutants, heavy metals, and toxins.

4.2. Design and Costing

The authors have extensive expertise in MSL technology and have several papers in peer-reviewed scientific journals. However, the MSL system is still considered an emerging solution for wastewater treatment, which calls for continuous improvements. This paper recommends developing a new composition of soil mixture to improve MSL purification performance by adding mineral apatite and smectite clays as high purifying materials [101,102]. Furthermore, the majority of papers investigated in this review tested MSL systems with vertical flow. Thus, additional studies on MSL purification efficiencies under horizontal flow and with a hybrid system are recommended. In addition, there is a lack of sufficient knowledge about the effect of used substrates and their structures within the MSL on the removal efficiency.

On the other hand, although a recent study [68] attempted to estimate the cost of soil mixture blocks in the lab and in the field, which is between USD 0.35 and USD 3 per packet, as well as the cost of zeolite (about USD 20 per kg). However, more research into this aspect of the MSL system is needed, especially because material prices are still fluctuating all around the world, and per capita income is low, particularly in rural parts of developing countries. In addition, estimating the MSL's initial investment (including sizing), water quality enhancement, operation, and maintenance are required for a full-scale MSL.

4.3. MSL Modeling

Regarding modeling approaches to simulate the performance of the MSL system; most of the models developed recently are constrained and cannot describe the non-linear interactions between the water indicators within the MSL system. Thus, the use of more complex models (e.g., random forest, support vector machine) is recommended, especially with the advent of artificial intelligence techniques. Moreover, the majority of the models have mainly investigated input/output datasets rather than MSL internal processes datasets. Nevertheless, kinetic models are also important to understand pollutant removal in this system. In addition, determining the MSL's kinetic constant may aid in the optimization of the MSL system's investment cost. Regarding numerical solutions, models that describe the growth and death of bacterial species (e.g., autotrophs and heterotrophs) might potentially aid in understanding MSL behavior in terms of the removal mechanisms. On the other hand, it is suggested that the authors use mechanistic models to investigate the MSL system's physical (dispersion-advection), chemical, and biological processes.

Another issue to be developed in the future is the environmental impact assessment of different applications involving MSLs in wastewater treatment to find solutions to improve their environmental performances. Thus, elaborating guidelines providing useful information on how to implement, operate, and maintain MSL nature-based technology is actually needed.

5. Conclusions

The multi-soil-layering (MSL) system is considered an emerging ecotechnology that has proven its efficiency in the treatment of a wide range of wastewater across the world (97% for SS, 98% for BOD_5, and 100% for NH_4^+ and TP). This technology is characterized by several advantages, such as low investment costs, small area occupation, simple maintenance, and no energy requirements, which make it an interesting option to be integrated with other technologies to improve its performance. However, among 70 publications, only 14 research papers were found in this literature review combining MSL with other wastewater treatment methods (e.g., constructed wetlands, trickling filter, sand filter, etc.). Although numerous scientific studies have looked into and monitored the MSL system, the majority of these studies have been done on a lab or pilot scale. Thus, full-scale MSL systems should be an area for future research to evaluate their behavior in a real environment rather than on a lab scale. Thus, this will allow for a better understanding of the challenges the system may face and an increase in its sanitary efficiency particularly (1.62 log units in single-stage MSL). Other aspects of the research that must be investigated include the reuse of the MSL effluents in the agricultural field and the irrigation of green space, as many countries that have implemented this technology suffer from water scarcity, especially with the lack of precipitation and consideration of climate change. Furthermore, it is important to investigate the kinetic of the MSL systems and further explore non-linear relationships between water quality parameters in the MSL, mainly fecal indicators bacteria and pathogens, to better understand their removal process. On the other hand, the addition of a carbon source within the soil mixture can hasten the growth and diversity of the microbial community, hence improving the MSL system's efficiency. Published studies on the potential financial cost of the MSL system are still limited, and they have not allowed for the development of first sizing rules for vertical and/or horizontal flow MSL systems used as secondary or tertiary treatment (admissible pollutant load, surface occupation, investment cost/inhabitant). Therefore, attention to the challenges and recommendations proposed in this review will inevitably contribute to the improvement of MSL sanitation efficiency, cost estimation, and simulation of its behavior with high accuracy ($R^2 > 90\%$).

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Nomenclature

Al	aluminium
BCS	blended organic carbon source
BOD_5	five-day biochemical oxygen demand
CH_4	methane
CO_2	carbon dioxide
COD	chemical oxygen demand

CW	constructed wetland
DO	dissolved oxygen
EC	electrical conductivity
FC	fecal coliform
Fe^0	metallic iron
Fe^{2+}	ferrous ions
Fe^{3+}	ferric ions
FIB	fecal bacteria indicator
HLR	hydraulic loading rate
MLR	multiple linear regression
MSL	multi-soil-layering
N_2	diazote
N_2O	nitrous oxide
NH_3	ammonia
NH_4^+	ammonium
NN	neural networks
NO_3^-	nitrates
NO_2^-	nitrites
ORP	oxidation-reduction potential
PBS	polybutylene succinate
PL	permeable layer
Q	salinity
SCA	stepwise-cluster analysis
SFCW	subsurface flow constructed wetland
SS	suspended solids
SWI	subsurface wastewater infiltration
TC	total coliform
TN	total nitrogen
TKN	total kjeldahl nitrogen
TP	total phosphorus
VFCW	vertical flow constructed wetland
WoS	Web of Science

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