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Review

Challenges of Urban Artificial Landscape Water Bodies: Treatment Techniques and Restoration Strategies towards Ecosystem Services Enhancement

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Abstract: With the rapid adoption of green infrastructure and nature-based solutions for a low-impact development, much consideration is given to ecosystem services and the ecological enhancement in modern planning of urban spaces. Artificial landscape water bodies have, in recent years, been utilized to enhance the ecological quality of urban environments. As an environmentally friendly measure, the water source of these waters has predominantly been adopting reclaimed water (treated wastewater). As a result, landscape water bodies are often eutrophic, exhibiting poor hydrodynamics, with lengthy water change cycles, creating the ideal environment for algal blooms that negatively impact the aesthetic appeal of these landscape waters. Based on the existing literature, this paper summarizes the treatment techniques and strategies employed in enhancing the quality of urban artificial landscape water bodies and providing integrated design solutions in the urban environment.

Keywords: artificial landscape water; reclaimed water; eutrophic landscape water; treatment; restoration

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1. Introduction

Through sustainable practices, the adoption of green technology and nature-based solutions, i.e., bioretention areas, green walls and roofs, permeable paving, urban forests etc., and the adoption of low-impact development across the globe has increased in recent years to lessen the impact of urban development on the environment and climate [1,2]. The vast majority of urban developments tended to favor concepts and designs with low environmental impact [3], while promoting a new circular approach or urban infrastructure and development [4]. One such practice is seen in the integration of artificial water bodies in the form of ponds, water parks, and scenic waterfronts in various parts of urban spaces such as residential and commercial areas and parks. Throughout the literature, terminologies such as "urban artificial water bodies", "landscape water bodies", "scenic water bodies", and "landscape water" are all used to refer to any body of water that is created artificially or organically to enhance the aesthetic of towns, cities, and tourist destinations [5]. However, for the purposes of this paper, they are referred to as artificial landscape water bodies (ALWs).

In addition to controlling climate, preserving water resources, enhancing ecological diversity, promoting a circular use of urban water, and enhancing environmental comfort, ALWs can also discharge floodwaters and control soil erosion in some situations [6,7]. In order to address the recent water shortage, cities and suburbs have begun to use water reclaimed from the enhanced treatment of wastewater as an additional water source for ALWs [8]. However, the high concentrations of pollutants such as carbon, nitrogen, and phosphorus present in reclaimed water have unquestionably made eutrophication of these ALWs worse [9]. Other factors such as the influx of surface runoff, sewage, and rainwater, as well as the hydraulic characteristics (i.e., low flow rate), further contribute to the degradation of the water quality, resulting in eutrophication [10], algae bloom [11], and odor problems [12]. In the most extreme scenario, these conditions can potentially increase the emissions of toxic gases, and create dead zones that deplete diverse aquatic life forms, thereby endangering the safety of the environment and that of the entire aquatic ecosystem [9].

In a quest to resolve the challenges and maintain serene aesthetically appealing ALWs while minimizing their public health risks, several techniques have been applied over the years in restoring and mitigating these threats. These techniques can be categorized mainly into physical, chemical, and biological–ecological [13]. This paper seeks to assess the current available techniques for controlling and treating various water quality challenges that exist in ALWs. It also aims to overview the advantages and shortcoming of these techniques and the potential of hybrid and integrated approaches, as well as the future perspectives of this area of scientific interest.

2. Treatment Techniques

2.1. Physical Techniques

The treatment and remediation of polluted water bodies have seen the application of mechanical or physical interventions, some of which include water diversion, sediment dredging, filtration, and construction of hydraulic structures, just to name a few. These techniques yielded positive results in reducing eutrophication and limiting algae growth in water bodies.

2.1.1. Water Diversion and Dilution

Water diversion and dilution, which is also termed pollution flushing, is among the physical methods of mitigating pollution in ALWs. This technique moves vast amounts of treated water into polluted waters to dilute pollutants [14]. Incoming treated water typically contains sufficient dissolved oxygen and increases the flow of the existing water body. The introduction of dissolved oxygen also further promotes biological degradation of organic pollutants to obviously reduce the concentration of contaminants by self-purification function/process [15]. This technique has been successfully utilized in small-sized water bodies with the need for rapid remediation. This technique, however, causes the reintroduction of sediments into the water body during the flushing process, leading to secondary pollution in the downstream basins of the water body. Consequently, the water body is likely to divert as a result of the injection of a substantial volume of water and solids. Also, the typically enormous expense of water diversion projects illustrates that this strategy is incapable of addressing the core cause of the problem [16]. According to Yang et al. [15], the amount and quality of fresh water and water left to be diluted, the flow rate, the relative position to the freshwater inlet, and the direction of the flow field's circulation are crucial to the efficiency of water diversion technique in ALWs.

2.1.2. Sediment Dredging

This approach uses the necessary mechanical equipment to remove the mud from the bottom of the water body, and the mud removal process aims at lowering the concentrations of hazardous chemicals and precipitated contaminants [11]. This approach has effectively been used to enhance the quality of rivers and lakes, as well as the surrounding ecosystem. However, this technique has many downsides. It requires the installation of specialized equipment and also critical consideration of the excavation depth and the extent of evacuation. This results in high cost of construction and maintenance and room for further challenges [17].

2.1.3. Aeration

Aeration is simply the introduction of oxygen into the water basin, thereby increasing the dissolved oxygen content of the water body and boosting the purifying capacity of the polluted water body and the surrounding ecological circle. The principle of aeration lies in the microbial activity promotion with oxygen-enhanced respiration. This results in a positive impact on the decrease in COD or BOD_5, total nitrogen via nitrification, and even total phosphorus concentrations via biological phosphorus removal [18]. Additionally, the impact helps to tighten the loose bottom silt and keep pollutants in the bottom of the water and prevent sludge from contaminating the top of the water body [19]. Aeration broadens and multiplies the microbial communities that break down organic chemicals in wastewater and river water [20]. This technique yielded efficient results in pollutant removal efficiencies in water bodies, especially when adopted in combination with other techniques. The major drawback of this treatment is the high cost of maintaining the aeration pumps/machines in the water column. The higher energy consumption of this technique, however, makes it unsuitable for the pollution treatment of additional water bodies. Although aeration as a technique is straightforward, simple to use, sustainable, and broadly applicable, the aeration pumps are often costly to install. More significantly, aeration can also be passively achieved via waterfall, weir, cascade aerator, or water surface renewal, provided the gravity grade permits this, in order to save energy input (Figure 1), thereby presenting a cost reduction option to aeration. This makes it possible to obtain the benefits of aeration at comparatively minimized cost. The adoption of the moderately affordable aeration strategies will successfully eliminate one major drawback of this technique [21,22].

Figure 1. Aeration via river bubbling (**a**), pond water spreading (**b**), and canal waterfall (**c**).

2.1.4. Mechanical Algal Removal

This technology employs a variety of mechanical approaches to control water contamination caused by algal growth. Mechanical methods, processes, and equipment have successfully been applied in mitigating eutrophication in rivers and lakes vary widely. Popular among the mechanical techniques are the air flotation technology, the mixed method, the ultrasonic method, and artificial arching, ultrasonic method. These have proven potent in combating excessive algae growth. The application of mechanical processes for algal removal can successfully avoid secondary pollution by eliminating the growth of algae caused by nutritional temples. Though effective, the need for heavy machinery and equipment in mechanical processes makes them expensive and is only recommended for use in remediating limited quantities of polluted water. Mechanical intervention alone is deficient in addressing eutrophication of water bodies produced by algae outbreaks. They are only suitable for emergency removal, due to its limitations [23].

2.2. Chemical Techniques

Among the commonly used chemical treatment techniques are flocculation, photocatalytic degradation, oxidative disinfection, chemical alga-killing, stabilization, and solidification [24]. Using flocculation, oxidation, precipitation, and algaecides, polluted water can be chemically treated to remove suspended solids (SS) and algae [11]. Chemical methods can quickly remove SS from contaminated river water, but they only provide a temporary fix, and are also highly likely to also generate secondary pollutants that pose further risks. In addition, the precipitated/flocculated solids accumulate as sludge at the bottom of the ALWs, gradually reducing the effective volume of the water body and eventually requiring the costly procedure of mechanically removing the bottom sludge. Therefore, the primary focus of flocculation or precipitation operations should be on the use of environmentally friendly chemicals for chemical treatment of algae and suspended particles under controlled conditions. Chemicals such as poly aluminum chloride have been used in several experiments as non-polluting flocculation foam that can successfully remove algae from water [25]. Also, the introduction of calcium peroxide (CaO_2) can control the pollutants released from the sediment, lower the N and P concentrations in the surrounding water by increasing dissolved oxygen and oxidation-reduction potential in the eutrophic water and, to a lesser extent, changing the microbial community in the sediment. Wang et al. [26] reported the use of CaO_2 in purification and restoration of a severely eutrophic scenic water body. Overall, chemical techniques can significantly improve the water quality of eutrophic landscapes in a short amount of time. However, these methods frequently have the drawbacks of high costs, short durations, secondary contamination, and potential dangers to the environment.

2.3. Biological-Ecological Techniques

There are several biological–ecological treatment technologies available in the literature, including microbial bioremediation, biofilm technology, contact oxidation, membrane bioreactor technology, ecological ponds, ecological floating beds, and constructed wetlands. Each technique has its strengths and most suitable application. Ding et al. [27] compared various ecological techniques to highlight their advantages and drawbacks in ALWs. Generally, these techniques have gained much acceptance, since they are considered to be more environmentally friendly.

2.3.1. Constructed Wetlands

These are artificial engineered wetland systems, designed and built to utilize natural wetland functions in purifying wastewater through multi-processes, within a controlled environment [28,29]. The major pollutant removal processes that occur in constructed wetlands include plant assimilation, precipitation, sedimentation, adsorption, and microbial degradation [30]. One of the major advantages of this nature-based technique is the low cost of operation and maintenance. Constructed wetlands have an added ecological advantage with numerous environmental benefits [31]. This technique can be employed in small and large scales (Figure 2) [32]; however, it requires large amounts of space. In recent years, innovative scientific studies developed novel constructed wetland designs (modular constructed wetlands, artificially aerated wetlands), which have led to comparatively less required space and yet have proven effective in improving water quality standards in water bodies [29]. The integration of constructed wetlands at the construction phase of ALWs can serve as long-term pollution control measure. The efficiency of this strategy was comprehensively analyzed in Zhou [33] and a successful application was reported by Li et al. [23]. Various modifications to various components of constructed wetlands (plants, substrate, microbes) are constantly being studied by researchers to improve their pollutant removal efficiencies. Aside from laboratory success, constructed wetlands have been successfully employed for the construction of several multi-beneficial wetland parks that provide water treatment and landscape enhancement advantages [34,35].

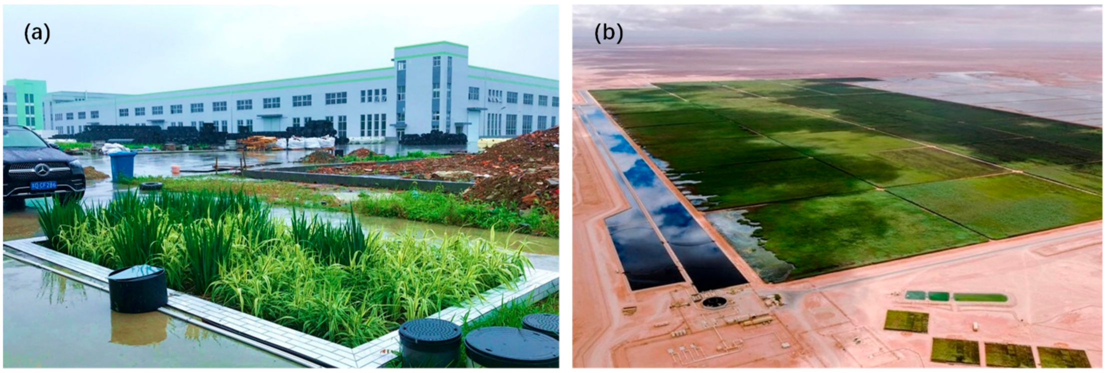

Figure 2. Small-scale constructed wetland in a water body near to a factory (**a**) and large-scale constructed wetland in the Middle East [36] (**b**).

2.3.2. Floatation Beds

Floatation beds are another nature-based treatment technology that employ flotation structures to grow surface vegetative plants in water bodies [37]. Their application, which previously targeted nutrient polishing, algae, and mosquito control, has, in recent years, broadened due to novel technological advances aimed at improving their pollutant removal efficiencies (Figure 3). These include the introduction of artificial biofilm carriers [38,39], artificial aeration [40], incorporating microbes [41], and the addition of material to increase buoyancy of floatation mats [42]. For urban artificial landscape water bodies, limited studies have been conducted into their efficiencies. Wang et al. [6] studied their potential in the removal of algae and recommended that for their effective performance, the flotation bed's water depth should be between 60 and 110 cm, and the relationship between plant size and plant density should be inverse. Bed coverage should be between 5% and 38%. Gaballah, et al. [43] even suggested a 70% required coverage using a native aquatic species in Egypt (water hyacinth or *E. crassipes*) combined with 25 cm water depth, and a contact time of 3–5 days to effectively remediate the polluted water of an urban lake. This implies that the bed coverage should be increased as much as is feasible for landscape waters with severe eutrophication. For landscape waters with mild eutrophication, the bed coverage should be reduced suitably. The overall results show a considerable removal of nitrogen and phosphorus levels, which is mainly attributed to plant uptake, microbial assimilation, and sedimentation. However, it should be pointed out that the floatation bed should try to introduce lightweight substrates to support more microbial communities, rather than solely depending on the plant roots.

2.3.3. Microbial and Biofilm Bioremediation

The introduction of specific pre-grown microbial co-cultures medium into polluted water ecosystems (bioaugmentation) has also proven efficient in the control of algal growth and eutrophication [19]. It relies on the metabolic activity of microorganisms in order to fulfill the goal of environmental governance by degrading and transforming toxic compounds while restoring ecological integrity. Throughout the cycle of bioaugmentation, bacteria are the most prevalent species [44]. Biofilm has also proven itself as a rather effective component of ecological wastewater treatment technology. Yang et al. [45] successfully applied plastic carbon fiber-biofilm technology in ALWs eutrophication control, with results showing high removal efficiencies for COD, TN, and TP. Biofilm technologies utilized in the restoration of polluted water bodies include substrate contact oxidation, contact oxidation, aerated bio-filter biological fluidized bed, thin-layer flow method, suspended carrier biofilm reactors, and underground steam purification method [46]. Moving bed biofilm reactors have a number of benefits, including simple operation, minimal biomass loss, less temperature dependence, stable biofilm thickness, and a low likelihood of clogging [38]. The extremely polluted river water and wastewater can be remedied using a biological contact oxidation method, which has a number of advantages, including the ability to facilitate sludge thickening and the absence of bed clogging. However, its efficacy fluctuates with seasonal temperature. This technique is an environmentally benign and economically viable method for increasing pollutant degradation [19].

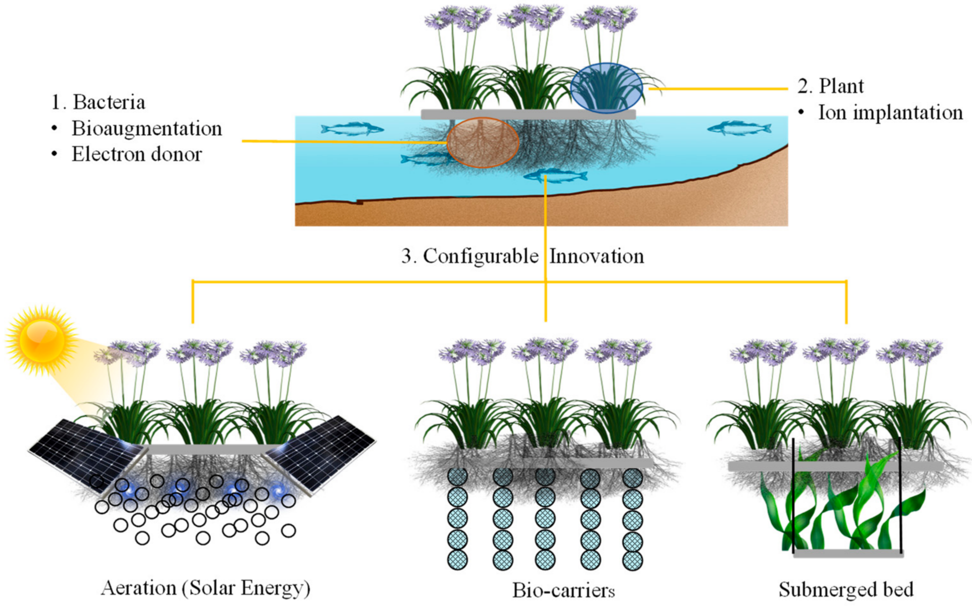

Figure 3. Strategies of enhanced floatation beds for improved treatment efficiency.

2.4. Hybrid–Integrated–Novel Approaches/Techniques and Prospects

2.4.1. Hybrid–Integrated Approaches

Scientific interest in water and wastewater treatment has peaked in the past decade and there are several studies that have analyzed the potential in leveraging the benefits of a combination of conventional techniques with other methods in order to derive the optimum treatment technology with high pollutant removal and limited environmental risks. The various methods of ALWs treatment and their respective treatment mechanisms, as well as the benefits and drawbacks associated with each method, are outlined in Table 1.

One interesting study was conducted by Huang et al. [47], in which surface flow constructed wetlands, aeration, ecological gravel beds, and wetland multi-pond systems were integrated. The final results show ammonia nitrogen (NH_3-N) levels to be less than 1.0 mg/L, TP levels as less than 0.2 mg/L, COD levels as less than 20 mg/L, dissolved oxygen levels as greater than 5 mg/L, and transparency levels as greater than 60 cm. In addition, the river's reclassification from class V to class III of the China Surface Water Environmental Quality Standard (GB3838-2002) is achieved, demonstrating the efficacy of the integrated approach. Another study was also conducted into the potential of a combination of aeration and algae-eating fish to control algal bloom and eutrophication in ALWs [18]. In addition, He et al. [48] utilized a novel alum-sludge-based floating treatment wetland, which was developed to improve the quality of natural water bodies. In this study, polyurethane in combination with alum sludge was used to develop the polyurethane–alum-sludge-based lightweight substrate (PU–AL), which was used in a floatation bed. Compared to the conventional floatation beds, the results show higher TN and TP removal efficiencies, with average pollutant removal of 53.31 ± 4.65% for TN and 45.39 ± 4.69% for TP, while their removal rate in the blank trial is 27.35 ± 5.97% for TN and 12.87 ± 3.81% for TP. The study, therefore, concludes that the integration of substrates with floatation beds could improve the pollutant removal as well as the plants' growth environment.

Table 1. Comparison of advantages and drawbacks of each type in categories.

Treatment Techniques	Treatment Process	Advantage	Disadvantage	Reference
Water dilution	Introducing clean water into polluted waterbody thereby diluting contamination.	Enhance quality of water, water supply, controls pollution, and stimulates self-purification abilities of ALW	Cost and labor intensive and also could pose a risk to the entire water ecosystem.	[14,15]
Aeration	Introducing air into water bodies enhances microbial diversity and destroys organic substances.	Improves water quality efficiently, is simple and quick to use, is stable and broadly applicable	High cost of installation and maintenance	[21,35]
Flocculation	The adding of chemical agents to water in order to transform particles into larger clusters, or flocs, so that they can be removed.	Relatively simple, fast, and efficient process	Production of secondary pollutants, environmental toxicity	[13,25]
Chemical precipitation (sponge iron and calcium nitrate)	Transfer of phosphorus from eutrophic water to the sediments	Rapid restoration of eutrophic waterbody with high P levels eutrophic	Possible toxicity to aquatic life	[49]
Phytoremediation	Plants remove nutrients through nutrient absorption, retention, and breakdown of pollutants.	The method is inexpensive and well-accepted by the public, regardless of region.	Slightly ineffective performance for eutrophic waterbodies; less resistant to natural disasters	[50,51]
Constructed wetlands	Employs the principal pollutant removal methods including plant assimilation, precipitation, sedimentation, adsorption, and microbial decomposition.	Ecologically beneficial, low cost and easy to maintain, nature-based solution.	Requires larger land area, low hydraulic load, and inefficient for heavy pollutant loading rates, prone to clogging over time	[34,35]
Flotation beds	Synthetic buoyant mats, which act as substrates for the growth of plants and roots extending into the water body for pollutant removal	Cost effective, aesthetically appealing, environmentally friendly, nature-based solution.	Slow process and time consuming, suitable for only low to moderately polluted waterbodies	[6,52,53]
Biofilm remediation	Solid media are added to suspended growth reactors to create attachment surfaces for biofilms in order to boost microbial population and pollutant decomposition	It requires limited land /space compared to traditional treatment techniques and also cost effective	Extensive construction work required	[45,54]
Microbial remediation	Microorganisms introduced into water to help the breakdown of organic pollutants and accumulation of nutrients and heavy metal	Effective in removal of pollutants of both organic and inorganic nature, cost effective with little to no toxicity to aquatic life	Need an extended time, affected by several environmental factors (rainfall, temperature)	[13]

2.4.2. Prospects

With the vast development in scientific research, many techniques are indeed available for the health and long-term success of the ALWs. However, in line with the nature of ALWs, it is wiser to adopt environmentally friendly or green technologies under the concept of nature-based solutions (Figure 4). Most of the green strategies have an added advantage of improving the scenic value of ALWs while combating the growth of unpleasant looking algae and eutrophication that threatens the very life of the ALW ecosystems.

Though most chemical and physical techniques are efficient and fast in remediation in some critical instances, prioritizing the implementation of bio–eco remediation techniques, while adopting physico-chemical remedies as a backup, is a secure way to mitigate the harmful consequences and secondary pollution from their application. The adoption of hybrid and integrated strategies, consequently, harnesses the advantages of the techniques combined while compensating for their limitations. Furthermore, to enhance bioremediation technology and its efficiency in addressing the challenges of ALWs, bioremediation materials should be adjusted, and the bioremediation process should be explored from various viewpoints and hierarchies. The general operating conditions of numerous technologies, such as aeration, bio-film, and microbial preparation and dosage, need careful examination.

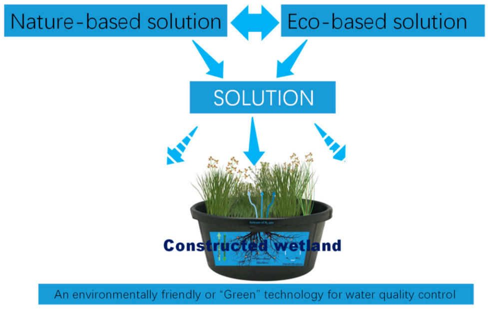

Figure 4. Constructed wetland is the core technique of nature-based solutions in water pollution control.

An examination of the literature reveals that chemical procedures pose an environmental concern and may cause secondary pollution such as sludge. Furthermore, in terms of mechanical techniques, the high cost of implementation, as well as the long-term environmental repercussions as observed in the case of water diversion, render these strategies ineffective in offering a complete solution to ALW contamination. Biological and ecological treatments are more environmentally friendly, but they take a longer time to provide the intended results. In the long term, further studies should be conducted into finding faster eutrophication control and resolution by exploring more biotechnologically advanced, less expensive, and more practical methods, which can substitute the existing fast yet unsafe techniques, providing a wholistically greener, safer, more efficient, and rapid remedy for polluted ALWs

3. Conclusions

ALWs are among the many green strategies adopted to improve the biodiversity, aesthetics, and general environmental health of urban environments. The challenge of pollution control in ALWs has seen the implementation of physical, chemical, and bio-ecological techniques. Generally, chemical techniques have been credited with providing rapid and effective solution to ALWs eutrophication and algae bloom, however their use may result in secondary pollution and harm to the ecological integrity of these water bodies. Physical techniques have also achieved some success in the control and remedy of ALWs. However, their major drawback lies in the high cost of implementation, while potential environmental degradation has raised questions about their adoption in recent years. Bio-ecological techniques, though highly desired due to their environmental safety, require much advancement to improve their rate of remediation. Green technologies, and in particular nature-based solutions, appear as an attractive and promising toolbox that can provide effective treatment with the simultaneous provision of multiple environmental benefits and ecosystem services. A number of studies were conducted into novel strategies of ALWs pollution treatment, the majority of which yielded much potential for efficient pollution control. The analysis conducted in this review on treatment technologies for ALWs reveals that studies that employ an integrated approach, utilizing a combination of two or more conventional techniques, display a great deal of potential, since it permits maximizing the strengths of each technique while offsetting any possible limitations each singular technique could possess. This review examines the efficacy, benefits, and drawbacks of the numerous single and hybrid strategies used for the clean-up of polluted ALWs, as well as their application. It also highlights the prospects for these techniques to be made more efficient, cost-effective, and sustainable through various integrated and optimization strategies in the near future.

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