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A state-of-the-art review (2019–2023) on constructed wetlands for greywater treatment and reuse

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ABSTRACT

Faced with increasing water scarcity, the potential of greywater reuse stands out, but requires effective treatment of to remove organic matter, pathogens, surfactants, and suspended solids. Constructed Wetlands (CW) are sustainable and decentralized technologies gaining increasing prominence for this propose. They are recognized for their low-cost, simplicity, and effectiveness in wastewater treatment, producing effluents that meet quality standards for reuse. Despite their advantages, there is a need for a deeper understanding of the factors that influence their performance and efficiency. This review aims to fill this gap by systematically analyzing the current research on CW technology, identifying key variables that affect its application and potential for improvement. A systematic review considering the period 2019–2023 was carried out using Methodi Ordinatio, a multicriteria decision-making methodology. The search databases were Science direct, Web of science and Scopus. This approach involves structures process for selecting scientific articles, resulting in a bibliographic portfolio of recent studies,. The initial search yielded 291 retrieved titles, and through multicriteria selection, 48 studies were chosen for in-depth analysis. Existing studies allowed to evaluate the ways in which CW systems are applied. The review highlights how CW systems are applied, the influence of substrates type, plants, and operational criteria which emerged as the primary factors influencing the technology's performance. This review also highlights the growing use of construction waste and biochar as substrates, which have shown promise in enhancing CW efficiency. Despite the focus on greywater "reuse", for articles selection, it was observed that the topic was scarcely addressed, thus suggesting that studies on CW application for greywater water reuse remains underexplored. This review provides a state-of-the-art synthesis of CW technology, offering valuable insights into how specific design and operational choices impact system effectiveness. It serves as a worthwhile resource for enhancing the efficiency and application of CW in sustainable wastewater management.

1. Introduction

The demand of water reuse from wastewater treatment has significantly increased due to population growth and rising of industrial activities (Kataki et al., 2021a). Greywater has the potential for reuse due to its lower risk of contamination. However, the presence of pathogens, surfactants and suspended solids, as well as the organic load generated, limit its reuse, requiring an effective treatment to make it suitable for reuse in various activities (Shereya et al., 2021). On the other hand, wastewater treatment is imperative, since without proper treatment it can contaminate water resources, including drinking and/or irrigation water, posing serious environmental and public health risks. Additionally, the significant increase in the release of micropolutantes into the environment in recent years, which are resistant to conventional wastewater treatment processes, has become a pressing concern (Karthik and Philip, 2021), as most of the micropoluents (e.g. pharmaceuticals) are extremely recalcitrant to conventional wastewater Treatment Plants (WWTP) treatments, as they were not designed to removed these compounds, leading to their released into watercourses or accumulation in sewage sludge (Pereira et al., 2015a; Silva et al., 2020, 2021, 2023). As a result, regulations have become increasingly stringent. In this context, mitigation measures, as well as the development of optimised

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technologies for efficient treatment, whether for water reuse or for discharge into the waterways, is crucial to meeting these challenges. Constructed Wetlands (CW) are sustainable systems, decentralised technologies, that have increasingly investigated and implemented to address these challenges and are gaining increasing prominence (Gorgoglione and Torretta, 2018; Souza et al., 2023).

Constructed Wetlands have been globally applied for the treatment of domestic wastewater, various industrial effluents, agricultural wastewater and polluted watercourses (Bakhshoodeh et al., 2020; Parde et al., 2021; Wu et al., 2015). They were the first nature-based systems applied to greywater treatment (Boano et al., 2020). These systems are one of the *in situ* wastewater treatment technologies that are easy to operate, economical, less-energy consuming, and suitable for both small communities and areas that are not connected to the sewerage system (Avellán and Gremillion, 2019; Kataki et al., 2021b; Ingrao et al., 2019; Vo et al., 2019). The substrate in CW is a critical component, as it can intercept pollutants, support plant growth, provide reactive substances for pollutant transformation, and serve as a support medium for biofilm (Deng et al., 2021; Wei et al., 2024). The use of low-cost adsorbent materials has sparked interest in various research projects aimed at removing these contaminants from wastewater (Karthik and Philip, 2021; Topare and Wadgaonkar, 2023). In addition, their use in the filter bed of CW as a substrate can be interesting, helping to increase treatment efficiency (Wang et al., 2018; Li et al., 2021).

Despite the widespread use of CW technology for the treatment of different wastewaters in countries such as China, Austria, India, Hungary, Brazil, Mexico, Italy, Argentina, among others (Kataki et al., 2021a), there is a need t for more experimental studies to refine design criteria (Boano et al., 2020). While a promising and sustainable tecnology, CW faces several gaps and challenges that need to be addressed to optimize their efficiency and broaden their applicability. Some of key gaps include the lack of standardized design, leading to variability in performance across different installations; scale-up challenges from laboratory or pilot studies to full-scale applications, due to the lack of comprehensive design guidelines that ensure consistent performance; performance variability according to seasonal and climatic variations, different types of pollutants (e.g., nutrients, heavy metals, micropollutants); phatogen removal; operational and maintenance issues; space requirements, and cost-benefit analysis. Addressing these gaps through targeted research, development of standardized guidelines, and promoting awareness can help optimize the use of CWs for sustainable wastewater management. This literature review aims to identify current research trends, advances and methodologies in CW, as well as to identify specific areas where research is lacking or inconsistent, such as design standardization, performance variability, and treatment of emerging contaminants. By enhancing knowledge and expertise, this review helps direct future research efforts towards these critical areas. Additionally, it emphasizes the environmental and public health benefits of CW, thereby increasing awareness and acceptance among communities, industries, and governments.

2. Methodology

2.1. Theoretical-methodological procedure

This systematic literature review was conducted using the Methodi Ordinatio, which is a scientific research approach that sets out specific criteria. The Methodi Ordinatio is a multicriteria decision-making methodology used in the selection of scientific articles for the composition of a bibliographic portfolio. According to Pagani et al. (2018), the application of this method involves nine stages (Fig. 1).

In the first phase, the focus of the research was defined, which

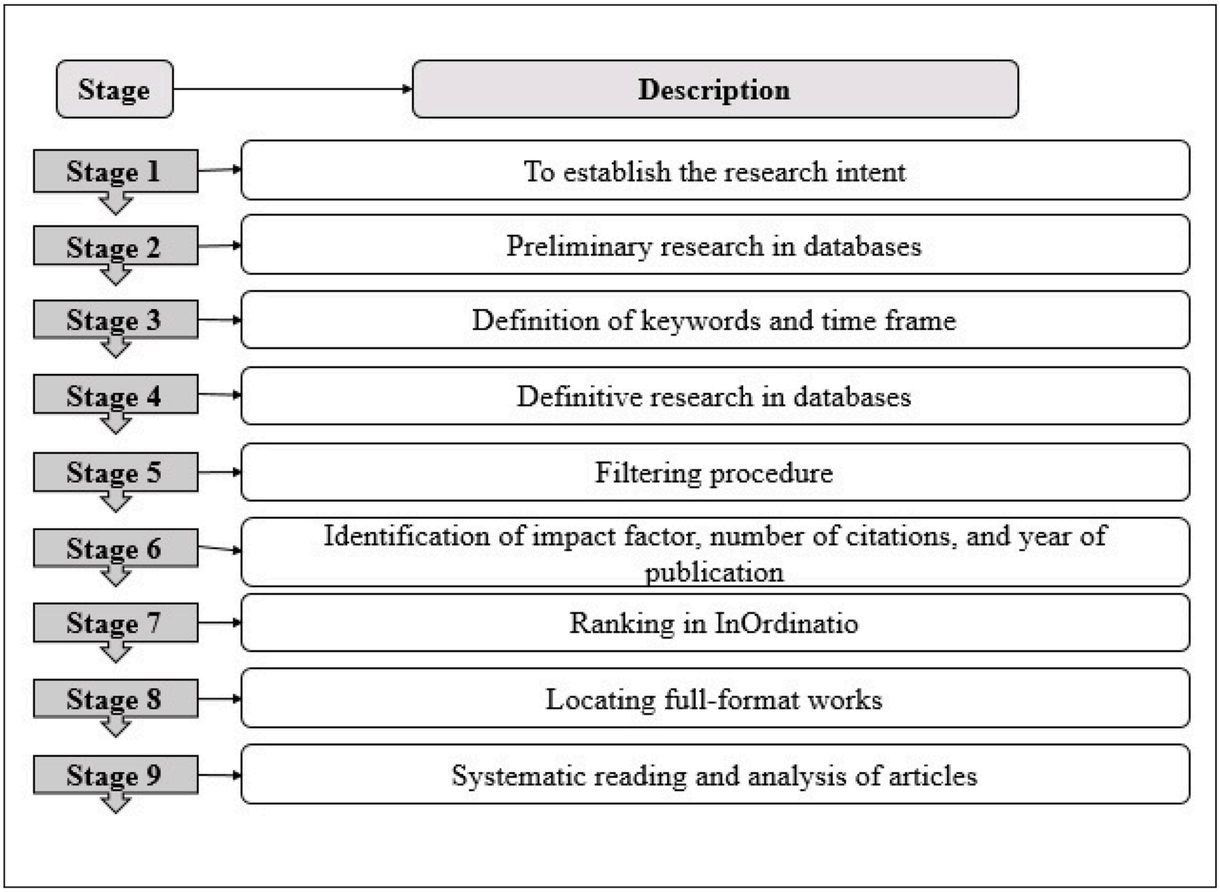

Fig. 1. Definition of portfolio phases by Methodi Ordinatio Source.

consisted of investigating the application of emerging substrates in CW systems for wastewater treatment aiming at its reuse. In the next phase, a preliminary search on the defined topic was carried out using the academic databases ScienceDirect, Web of Science, and Scopus databases. In the third stage, the keywords used to compile previously published works related to this research topic were defined as Wetlands, Greywater, Brick, Shell, Biochar, Macrophytes and Reuse, using the "and" operator. Furthermore, the research focused on publications from 2019 to 2023. This timeframe captures the most recent advancements and innovations in CW technology and emerging substrates, ensuring the inclusion of the latest research findings and methodologies. It provides insights into current priorities and directions, aligning with contemporary challenges like climate change and urbanization. Moreover, it ensures relevance to the latest regulatory frameworks and compliance requirements, and addresses contemporary issues such as emerging contaminants like pharmaceuticals and microplastics.

Subsequently, in the fourth stage, the definitive search was conducted in the databases with the defined keywords and temporal scope for this work. As a result of the considerable number of selected articles, further refinement of the most appropriate documents was accomplished, based on the criteria: relevance to research aim, language (Portuguese or English), availability of full text. This search resulted in 291 documents, 184 from Science direct and 107 from Scopus (Fig. 2). During the fifth stage, the retrieved documents underwent filtering procedures, by going through the titles, abstracts and conclusions, of each work. The following Inclusion criteria were considered: robust study design and methodology, and quality and rigor (e.g. sample size, data collection methods, statistical analyses). So, papers that do not meet specific predefined criteria (e.g., unrelated topics, insufficient methodological rigor, duplication of data) were excluded. This resulted in 121 articles (Fig. 2), and from this, 4 were duplicates, resulting in 117 articles. . Ultimately, after full articles evaluation, 48 well-targeted works related to the research aim were obtained. The portfolio included article and review article types

In stage six, the number of citations, impact factor, and publication year of each article were collected. The database's Impact Factor (IF) was obtained and used as a measure of the journal's relevance. The publication year was extracted from the articles, and the number of Citations (CI) was collected using Google Scholar. Based on this data, stage seven involved calculating the InOrdinatio (*In*) for each work to classify them according to their scientific relevance.

The "*In*" is a mathematical expression that allows weighting the ordering index of selected scientific articles according to their scientific relevance (Pagani et al., 2018) determined by Eq. (1):

$$\mathrm{In} = \left(\frac{\mathrm{IF}}{1000}\right) + 10 \times [10 - (\mathrm{ResearchYear} - \mathrm{PublishYear})] + (\mathrm{CI}) \tag{1}$$

Where IF is the Impact Factor and CI the number of times the article has been cited.

The aforementioned stages aimed to select up-to-date and significant files relevant to the main theme. In the final phase, with the portfolio defined, stages eight and nine were initiated, where full texts were located, and a systematic reading and analysis of the articles were carried out. Other additional bibliographies with theoretical basis were also referenced when relevant and essential to the discussion. Two software tools were used for storing and managing compiled references. The Mendeley Desktop© software was employed for archiving the found works along with titles, authors, scientific journals, publication years, and abstracts. Furthermore, the JabRef software was used to eliminate duplicate works and export the works that would be organized into an Excel spreadsheet. The VOSviewer software aided in developing the relational idea maps.

3. Sistematic literature review

3.1. Data analysis

After the collection of works, a total of 291 documents were obtained. However, with the aim of encompassing only those that would facilitate the aim of this research, filters were applied, resulting in 117 articles for analysis, of which 48 were selected for reading and the construction of the bibliographic portfolio. Fig. 2 presents a detailed flowchart of the document selection stages and Table 1 presents the indexed works for systematic evaluation and reading.

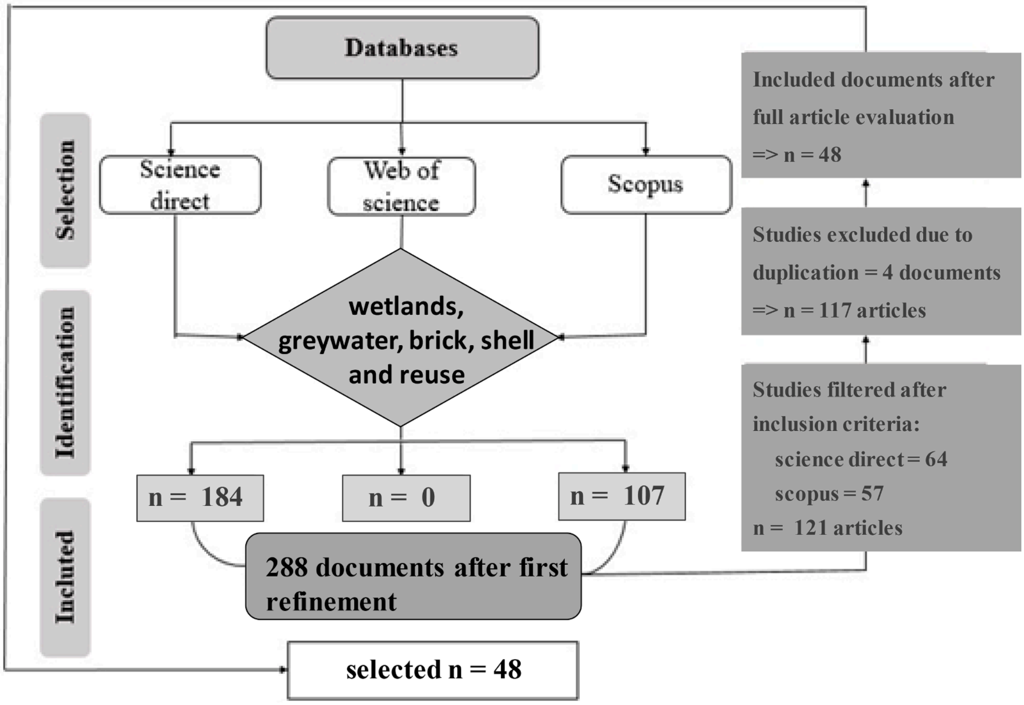

Fig. 2. Flowchart of the article selection process, covering the period 2019–2023.

Table 1
Characteristics of the selected works in terms of Impact factor (IF) and number of times the article was cited (CI), values obtained in 2023, and InOrdinatio weighting ordering index (*In*).

References of the manuscript	IF	CI	*In*
Abedi and Mojiri, 2019	6.700	69	159.01
Avellán and Gremillion, 2019	16.799	87	177.02
Bonnard et al., 2019	3.519	21	81.00
Chaves et al., 2019	2.430	4	64.00
Corzo and Sanabria, 2019	7.340	11	101.01
Hernández and Sanabria, 2019	7.340	10	70.01
Saeed et al., 2019a	5.190	26	86.01
Saeed et al., 2019b	8.910	29	89.01
Saeed and Khan, 2019	7.968	43	133.01
Sanjrani et al., 2019	0.711	9	69.00
Vo et al., 2019	8.400	29	119.01
Yu et al., 2019	9.700	101	191.01
Boano et al., 2020	10.754	130	200.01
Dell'Osbel et al., 2020	2.984	16	86.00
Ismail et al., 2020	9.910	52	142.01
Jehawi et al., 2020	7.758	64	154.01
Karthik and Philip, 2020	7.968	21	101.01
Kochi et al., 2020	3.3	37	127.00
Mateus and Pinho, 2020	11.072	20	90.01
Mlih et al., 2020	4.379	53	123.00
Wu et al., 2020	11.072	43	133.01
Deng et al., 2021	11.072	63	143.01
Hamada et al., 2021	6.796	8	88.01
James and Yadav, 2021	7.758	10	90.01
Ji et al., 2021	8.943	44	134.01
Kataki et al., 2021a	8.910	75	155.01
Kataki et al., 2021b	16.799	106	196.02
Parde et al., 2021	7.758	96	176.01
Shreya et al., 2021	6.137	9	99.01
Vymazal et al., 2021	4.379	68	148.00
Chairopoulou et al., 2022	5.640	1	91.01
Cui et al., 2022	4.379	22	112.00
De et al., 2022	3.900	1	91.00
Hdidou et al., 2022	3.200	15	105.00
Lin et al., 2022	8.910	6	96.01
Negi et al., 2022	16.744	15	105.02
Rahman et al., 2022	4.4200	3	93.00
Waly et al., 2022	3.900	15	105.00
Xu et al., 2022	7.968	7	97.01
Zhang et al., 2022	1.293	0	90.00
Zhuang et al., 2022	7.340	16	106.01
Fahim et al., 2023	8.943	0	90.01
Justino et al., 2023	3.2	2	92.00
Khajah and Ahmed, 2023	1.325	0	90.00
Khajah et al., 2023	2.900	4	94.00
Obeng et al., 2023	7.758	0	90.01
Souza et al., 2023	7.340	1	91.01
Wani et al., 2023	5.190	3	93.01

As can be seen in Table 1, the manuscript IF varies from 0.711 (Sanjrani et al., 2019) to 16.799 (Avellán and Gremillion, 2019; Kataki et al., 2021b), the number of CI diverges from 0 (Zhang et al., 2022; Fahim et al., 2023; Khajah and Ahmed, 2023; Obeng et al., 2023) to 130 (Boano et al., 2020), resulting in In indexes between 64 (Chaves et al., 2019) and 200.01 (Boano et al., 2020).

3.2. Bibliometric review

3.2.1. Production in the research field

Due to the scarcity of natural resources, the scientific community has extensively researched the practice of greywater reuse as a potential alternative to meet the water demands of agriculture. In this regard, CW have been recognized in the literature as an effective treatment system for these liquid residues. As illustrated in Fig. 3, the topic is of relevant interest, with publications having been observed, according to the criteria defined for this study, in all the years of the selected period. In 2019, 10 articles were published, falling to 8 in 2020, but increasing in 2021 to 9, and reaching the highest number in 2022, 11 publications. However, in 2023 less articles were published, 7.

Among the 45 articles, the research on CW for greywater treatment a diverse geographical distribution, structured based on the subject (Fig. 4). In the period of 2019–2023, ten of them (22%) were produced in India and 8 in China (18%), four in Germany (9%), three Brazil (7%), two in Bangladesh, Colombia, Italy, Kuwait, United Kingdom and Portugal (representing 5%) and, in other countries, research is still limited to only one publication (2%). The highest percentages in cowntries like China and India, may be allied with the fact that CW are low-cost, as they only produce a small amount of sludge and do not require much energy, and are easy-to-operate technologies for wastewater treatment not requiring much maintenance by a specialised company, and produce water good enough to reuse, e.g. at home for flushing the toilet (Cui et al., 2022; De et al., 2022). Despite most studies on CW being conducted in China and India, research has also been carried out in countries across the American and European continents, with Germany ranking third. This demonstrates the global relevance of the process and its adaptability to different geographical and climatic conditions, highlighting its versatility.

CW are widely acknowledged as effective and economical methods for treating wastewater. This statement is supported by a global analysis of the technology using VOSviewer software to generate a map displaying the citation frequency and relevance of each country (Fig. 5). The larger circles indicate the frequency of the most cited publications by geographical distribution, highlighting that India and China take the lead in research on the subject. This illustrates their valuable contribution to studies on effluent treatment and showcases their ongoing development of promising technologies in this field. As a result, other nations should allocate more resources towards researching this topic to keep pace with these advancements and refine their own treatment control and monitoring methods for increased efficacy. International cooperation can facilitate this process, especially in researching knowledge and advancements to guide future studies.

The 45 articles selected on greywater treatment through CW were published in 31 journals. The Environmental Technology & Innovation and Journal of Environmental Management had the highest number of publications on the topic with four registered articles each, making up approximately 13 % of the publications. Journal of Cleaner Production, Ecological Engineering and Journal of Environmental Chemical Engineering had 3 publications each (10 %), and Current Opinion on Environmental Science Health and Environmental Science Pollution Research have two publications each. The remaining journals published only one publication each. Within VOSviewer, article sources can be used for analyzing citations, enabling visualization and analysis of citation networks and the occurrence of terms in scientific papers. In relation to wastewater treatment using CW, this analysis highlights a balanced distribution of pertinent scientific documents across several academic journals, indicating a widespread interest and research in this particular field, with notable contributions from various sources. This observation demonstrates a firm grasp of the topic's background knowledge and research. Additionally, the spacing between each journal in the illustration determines the journal's significance in relation to related citation links, whereas the thickness of the line signifies the strength of the link, as illustrated in Fig. 6.

3.3. Results and discussion

3.3.1. Substrates and processes involved in CW systems treatment

The removal of pollutants from wastewater treatment systems relies on a combination of physical, chemical, and biological processes (Deng et al., 2021; Parde et al., 2021; Xu et al., 2022). Concerning biological processes, researchers have emphasised that the selection of the substrate for the treatment system bed is a critical factor that influences treatment efficiency (Gorito et al., 2017; Parde et al., 2021). This is due to the fact that the selected substrate can cause high adsorption of constituents and provide a significant surface area for the growth of

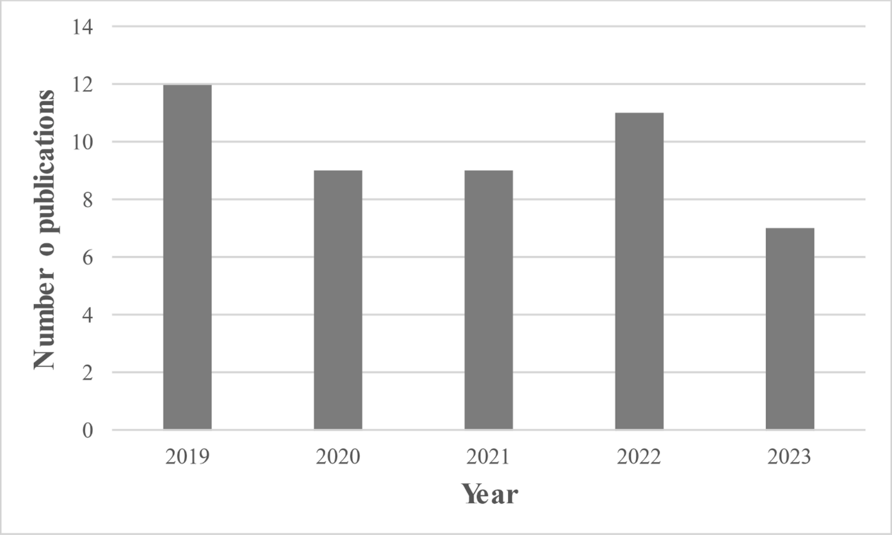

Fig. 3. Evolution of documents published from 2019 to 2023, according to the selection criteria in this study, and the polynomial tendency.

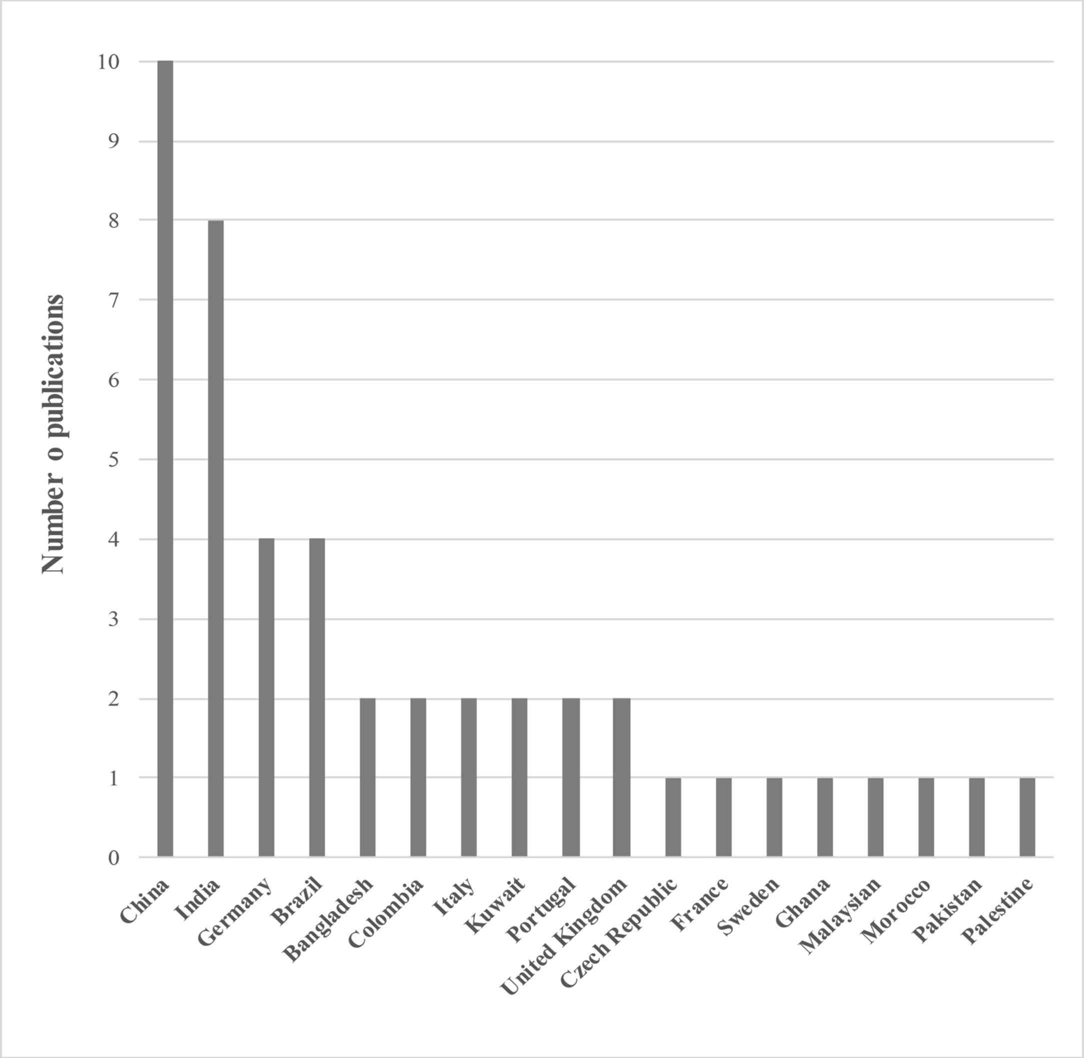

Fig. 4. Number of research articles on CW for greywater treatment published by countries from 2019 to 2023.

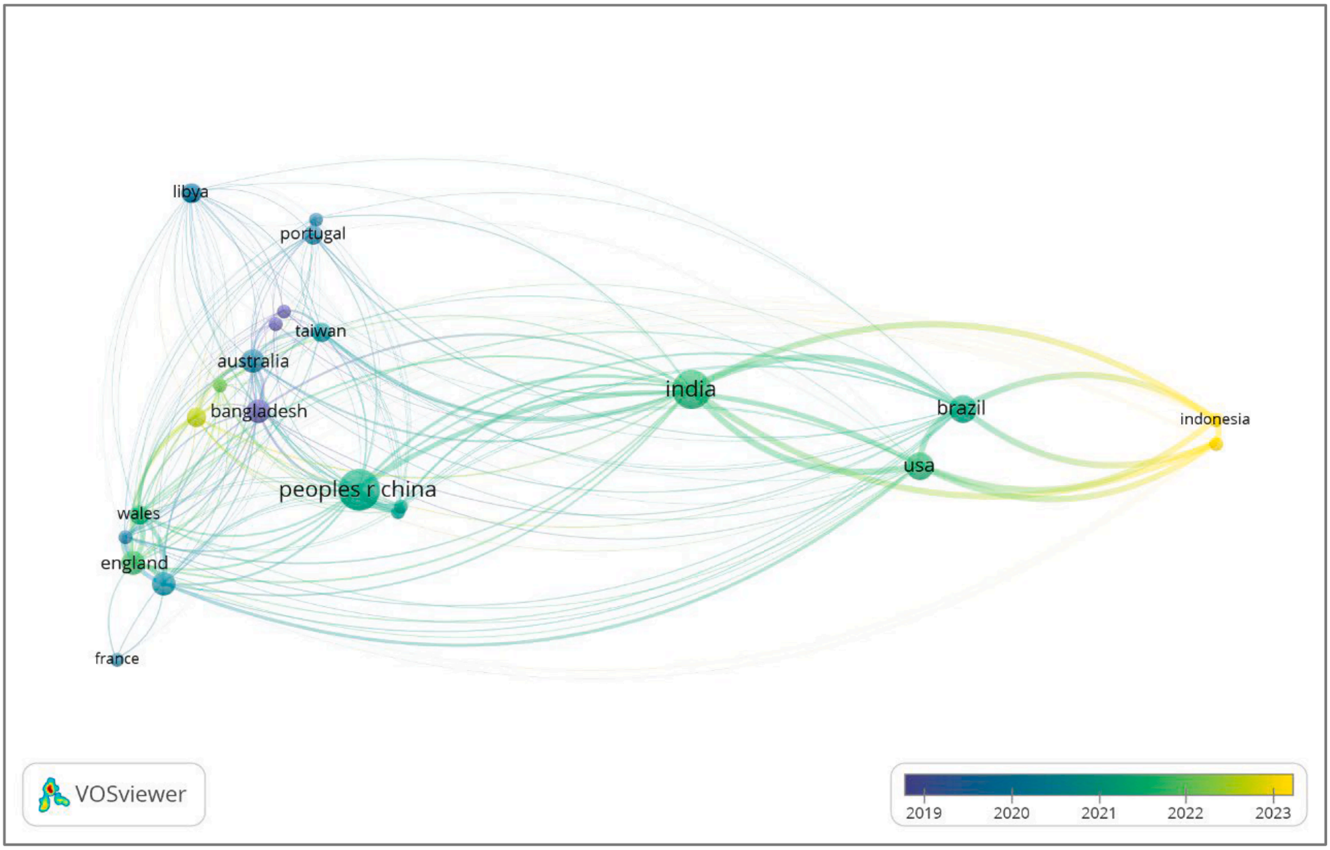

Fig. 5. Countries with the most cited documents about CW for greywater treatment in the Period 2019–2023.

immobilized microbial consortia responsible for decomposing contaminants in wastewater (Gorito et al., 2017; Parde et al., 2021).

The application of inert and conventional materials like sand, unpolluted soil and gravel, as a substrate, has been widely studied in CW, but the low adsorption capacity of these materials and some operating problems such as clogging have been seen as limitations to treatment efficiency (Yang et al., 2018). Therefore, alternative materials, both natural and waste-derived, are the object of increasing interest (Marcelino et al., 2020; Zhong et al., 2022). In a scenario of growing awareness in improving alternatives for wastewater treatment, recent studies have explored various natural and low-cost materials from agricultural and wood residues, such as coconut and rice husks, and also biological sludge from wastewater treatment plants, and highlight the potential of biochar as an effective substrate for the removal of ammoniacal nitrogen, nitrate, and phosphorus (Zhuang et al., 2022). Biochar has gained attention as an effective substrate due to its high surface area, porosity, and ability to adsorb pollutants. Studies have shown that biochar can enhance the removal of heavy metals, nutrients, and organic contaminants from wastewater. For instance, the application of biochar resulted in higher values for the removal of organic matter (98%), ammonia (79%) and phosphorus (60.7%) than those obtained without the use of biochar, 45%, 54.9% and 65% respectively (Zhuang et al., 2022). Deng et al. (2021), conducted a literature review on biochar's efficacy as a substrate in treatment systems. From theirs search, authors observed that N-ammonia and N-nitrate removal achieved efficiencies exceeding 60%, reaching up to 99.6% and 91.3%, respectively. Phosphorus removal efficiency varied considerably, with minimum values of 21.9% and maximums of 100%. However, the most common range for phosphorus removal efficiency was between 60% and 80%. These findings demonstrate the promising potential of biochar in treatment systems. It is a versatile and green carbonaceous biomaterial produced by carbonization of various biomasses including ocally available and renewable waste biomaterials, including locally available agricultural by-products, compost, manure, sludge, shells, among other, and can have different physico-chemical charateristics according to the on the raw materials and the conditions of production (Deng et al., 2021; Amalina et al., 2022). It is a highly biodegradable and porous material, with high specific surface area, and exceptional adsorption capacity, and contains a high amount of organic carbon and some amounts of micro and macro elements as well, exceptional properties for notable its performance (Tomczyk et al., 2020; Deng et al., 2021).

It is important to note that shellfish farming remnants, including oyster shells, have gained significant attention as prospective substrates in multiple applications (Ballantine and Tanner, 2010; Chairopoulou et al., 2022; Wani et al., 2023). As per Chairopoulou et al. (2022), these shells are predominantly composed of anhydrous calcium carbonate, exhibiting an aptitude for eliminating phosphorous in synthetic wetlands. This conversion of new waste could serve as a feasible choice for reasonable social technology applications in the treatment of wastewater. However, it is important to note that further research is needed on using marine shells in combination with water and effluent treatment technologies, indicating a promising area for investigation. The study by Lin et al. (2022), investigated the improvement of the efficiency of a biofilter for water and wastewater treatment using shells as a filter medium. The biofilter was operated with an upward flow, a flow rate of 0.240 m^3/h, and a hydraulic retention time (HRT) of 23 min. The bed material was arranged in layers, with 10 cm of gravel followed by 100 cm of mussels. The results showed that the efficiency of the system increased during the first 30 days of operation. Authors observed that during this initial period, contaminant removal was mainly due to adsorption in the filter layer, with N-NH_4^+ removal efficiency below 10 %. After the 30th day, removal became the result of a combination of adsorption and biological processes, with an N-NH_4^+ removal efficiency of 43.27%. This phenomenon was attributed to the development of the

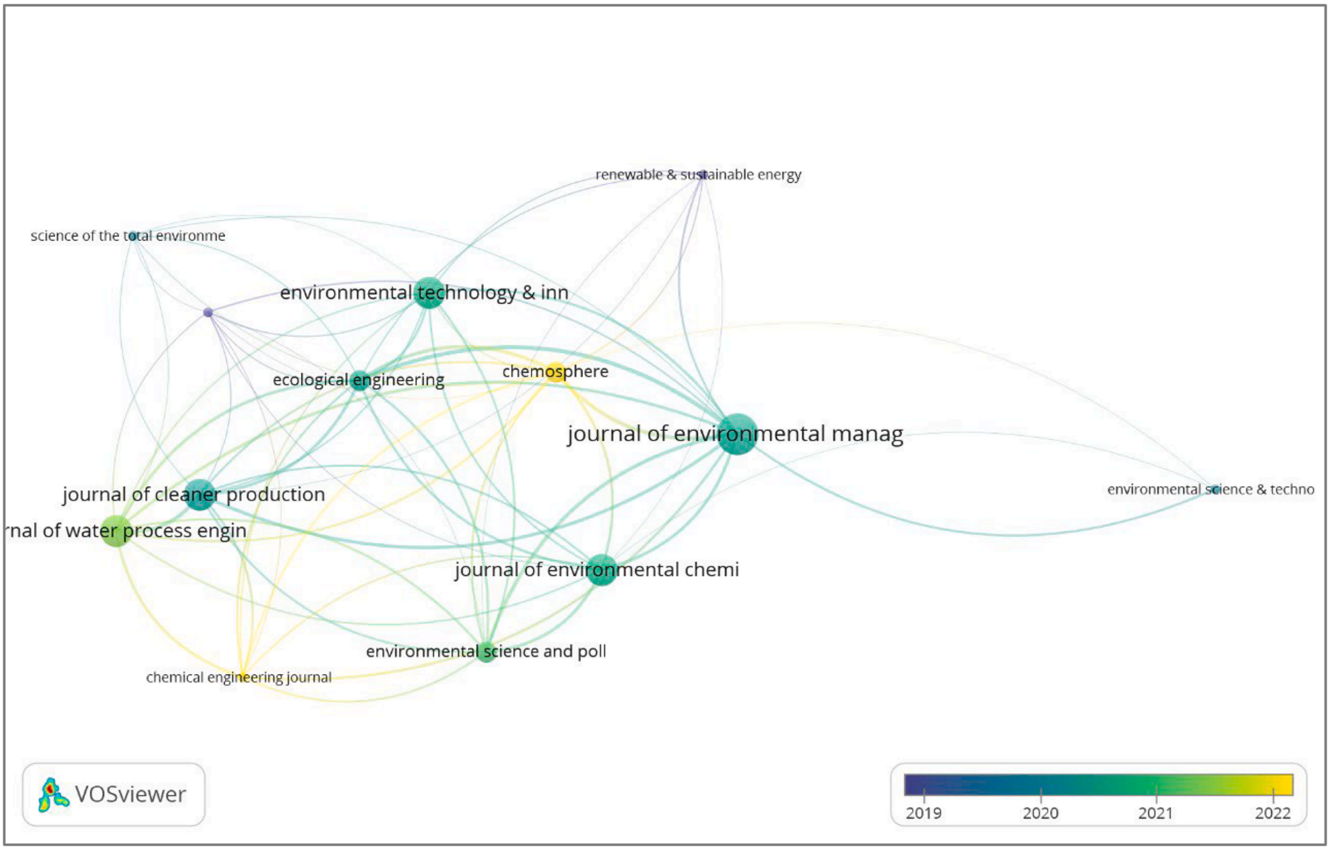

Fig. 6. Journals with the Most Cited Documents on greywater treatment through CW in the Period 2019–2023.

biofilm, which was well established after the 45th day of operation, as reflected in the turbidity removal efficiencies, ranging from 60% to 90%. The study highlighted the effectiveness of using oyster shells as a filtration medium in biofilters to improve pollutant removal over time through the interaction of adsorption and biological processes. These collective research efforts exemplify the ongoing innovation and exploration of alternative materials and provide valuable insights for advancing wastewater treatment towards greater environmental sustainability and efficient resource management. A critical literature review on sustainable solutions for shell reuse was conducted by Bonnard et al. (2019). In this review it is mentioned that natural oyster shells, in combination with biofilm, are relevant for wastewater treatment due to their porous structure and buffering properties. In addition, as oyster shells are composed of calcium carbonate (>95% by weight), shells can alter the pH of the medium, which has a positive effect on phosphorus removal.

The study by Karthik and Philip (2020) analysed the sorption of pharmaceutical compounds and nutrients using various materials and ranked the various substrates in this decreasing order of efficiency: charcoal, followed by natural zeolite, aerated concrete blocks, light expanded clay aggregate, blast furnace slag, natural pyrite, bricks and finally sand. This classification provides valuable insight into the efficiency of these materials in sorbing pharmaceutical compounds and nutrients. The results showed that the selected materials were more effective in removing phosphate (with efficiencies ranging from 70% to 90%) compared to ammonia (with efficiencies ranging from 20% to 81%) and nitrate (with efficiencies ranging from 14.1% to 61.8%). The use of recycled waste materials, such as construction debris and slag, has been studied. These materials can help in reducing waste and provide an eco-friendly option for CW substrates. Recently, the performance of two recycled materials, waste clay bricks (CWB) and palm kernel shells (PKS), were evaluated as suitable substrates to be used in CW for wastewater treatment, by assays carried out in five horizontal subsurface flow wetlands (HSSF CW) installed for the treatment of domestic wastewater (sewage) (Obeng et al., 2023). The study, besides assessing physical and biological performance of CWB and PKS, also evaluated the influence of substrate size and wastewater loading rate on wastewater treatment fficiency. Sand was used as control. With the exception of coliform removal, CWB showed better potential than PKS and sand for all the other parameters evaluated in the study, i.e. biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), turbidity, total phosphorus and nitrogen removals. Vegetation development was also relatively better with the CWB than with the PKS. Treatment efficiency was improved at lower hydraulic loading rates. The study by Obeng et al. (2023) also showed that a substrate particle size between 5 and 14 mm seems to be the most suitable for optimum performance. Waste generated in the civil construction has also been studied as a possible substrate, with a view to reuse and the circular economy. Souza et al. (2023) evaluated the efficiency of fragments of plasterboard sheets (PS) (30% porosity) and modified PS (35% porosity) as substrates in two 28 L vertical flow CW planted with *Eichhonia crassipes*, for the removal of carbonaceous, nitrogenous and phosphoric matter from a synthetic wastewater. Despite small differences between the two systems, one better at removing some compounds and the other better at removing others, in general both proved to be very efficient (Table 3). The removal of organic matter and phosphorus occurred through different processes: adsorption on the substrate, precipitation, absorption by the plants, and sources for the microorganisms.

The use of composite substrates, combining materials like biochar with other adsorbents (e.g., zeolites, activated carbon), has been investigated. These composites can provide synergistic effects, improving the overall removal efficiency of contaminants (Abedi and Mojiri, 2019; Deng et al., 2021).

3.3.2. Formation of biofilms in CW

In the biological treatment process of effluents, microbial growth can occur either in a dispersed or immobilized manner, with immobilization often carried out on various support materials introduced into biological reactors (Narayanan and Narayan, 2019; Pereira and Alves, 2012). These substrates provide a conducive area for the development and adherence of biofilm. So, the choice of substrate significantly affects biofilm development. In CW, there is a variety of structures that enable this growth and adherence, ranging from the substrate itself to plant roots, creating a favorable environment for effluent treatment.

The use of plastic media as a filling medium in CW systems is illustrative in this context. Corzo and Sanabria (2019), emphasized the importance of these media in wetland ecosystems, noting their significant impact on the initial growth and physiological performance of plants cultivated in these systems. This effect is associated with the extensive available surface area provided by these materials. The extensive surface area of the support medium promotes a longer contact time of the effluent with the microbial biomass, as also noted by Saeed et al. (2019a). Plastic media have a higher anti-clogging potential compared to other media (than gravel, for example), because they are lightweight and can float easily (Zidan et al., 2015). Additionally, these support media contribute to protection against increased hydraulic load, preventing biomass removal (Saeed et al., 2019a). These results highlight the importance of support media in the efficiency and stability of these biological effluent treatment systems. Notwithstand, despite plastic media can offer benefits such as high surface area for biofilm growth and durability, the environmental drawbacks, particularly related to microplastic pollution (e.g. degradation into microplastics), chemical leaching from plastics additives (such as plasticizers, stabilizers, and flame retardants), and long-term persistence of plastics, raise significant environment and health concerns (Hofmann et al., 2023; Xu et al., 2023). Moreover, at the end of the lifespan of the CW system, disposing of or recycling plastic media can be challenging. Inadequate disposal practices can exacerbate environmental pollution (Hofmann et al., 2023; Xu et al., 2023). Therefore, it is crucial to carefully evaluate these environmental impacts and consider alternative, more sustainable materials for use in CW systems. Sustainable practices, proper maintenance, and innovative designs that mitigate these environmental issues are also essential for the effective and eco-friendly implementation of CW (Hofmann et al., 2023). Natural materials like gravel and sand, as well as engineered materials like biochar, provide different levels of support and surface area for biofilm growth and can be eco-friendly alternatives.

The use of biochar as a support medium is a promising area of research due to the potential of this material to act as an efficient adsorbent, which is due to its porous structure and presence of active sites, as well as its ability to facilitate biofilm growth on its surface (Sanjrani et al., 2019; Tomczyk et al., 2020; Layek et al., 2022). These authors note that the key premise behind implementing such support media is to facilitate favorable conditions for both aerobic and anaerobic zones. Support media enabled the creation of distinct environments in a singular system, as per the discussion by Vymazal et al. (2021). In this context, the outermost region of the substrate or support media, in contact with the environment, stimulates the growth of aerobic microorganisms, while moving inward, oxygen transfer declines, thereby enhancing the growth of anaerobic microorganisms. Oxygen levels influence the type of microbial communities that develop in the biofilm. Aerobic conditions favor bacteria that degrade organic matter and remove nitrogen through nitrification, while anaerobic conditions support denitrification and the breakdown of more recalcitrant organic compounds (Semenov et al., 2020). These various regions enable the processes of denitrification and nitrification. Techniques such as intermittent aeration and the use of denitrifying bacteria have shown promising results on optimizing nutrient cycling within CWs to improve the removal of nitrogen, and also phosphorus (Yu et al., 2019; Lai et al., 2020).

The roots and rhizomes of plants also serve as support mediums for biofilm development. In the experiment conducted by Mateus and Pinho (2020), optimal growth rates of the *Phragmites australis* plant, and removal of organic matter and nitrogen, were achieved for a CW system with beds composed of cork residues from the cork industry, snail shells, coal slag, ceramic brick, and limestone rock. The one consisting of limestone with coal slag provided better indicators of plant growth and efficiency in pollutant removal. Also, the biomass of *Phragmites australis* colonising a CW operating as a post-treatment of a textile industrial effluent wastewater from an activated sludge plant in Italy, promoted the removal of trace metals (Cu, Fe and Zn) (Bianchi et al., 2021). This is quite interesting in terms of the circular economy approach, as it demonstrates the possibility of using a CW surplus, a dried biomass of *Phragmites australis*, as a renewable biosorbent to improve the removal of other compounds.

In planted CWs, biofilms interact with plant roots, which can enhance microbial activity by providing additional nutrients and oxygen through root exudates. This symbiotic relationship benefits the overall performance of the system. The studies reviewed by Kataki et al. (2021a), addressed the production of root exudates by rooted emergent macrophytes. These exudates serve as an important source of organic carbon that contributes to the denitrification process and promotes metal chelation, thereby reducing their toxicity. The availability of nutrients like carbon, affects biofilm growth and activity. Adequate nutrient supply is necessary for maintaining robust microbial communities within the biofilm. Therefore, when implementing natural waste treatment systems, it is crucial to assess the performance of the plant, with particular attention to root exudate production, which plays a fundamental role in the denitrification process.

It is worth notting that regular maintenance and monitoring of biofilms are needed to manage biofilm growth and prevent clogging as, over time, they can become too thick, causing clogging and reducing the flow of water through the system (de Matos et al., 2018). Also, variations in flow rates or physical disturbances can cause biofilms to shed, leading to fluctuations in treatment performance. Designing CWs to minimize these disturbances can help maintain biofilm stability (de Matos et al., 2018).

3.3.3. Functions of macrophytes and their peculiarities

In CW, macrophytes, or aquatic plants play a central role as they are the primary mechanism for transferring dissolved oxygen (DO) within the system (Jehawi et al., 2020). Macrophytes function as pollutant uptakers absorbing nutrients like nitrogen and phosphorus, so reducing eutrophication in downstream waters (Singh et al., 2024). They can also uptake and transform certain toxic substances, such as heavy metals and organic pollutants, into less harmful forms (Basile et al., 2012; Singh et al., 2024). Plants like Phragmites australis and Typha latifolia can uptake and degrade pollutants through phytoremediation, contributing to overall system efficiency (Jehawi et al., 2020). Other relevant features of these aquatic plants is that they provide surfaces for biofilm growth, and their dense root systems trap suspended solids, aiding sedimentation and improving water clarity their roots release oxygen into the rhizosphere, promoting aerobic bacteria crucial for organic matter biodegradation and nitrification (Kochi et al., 2020; Singh et al., 2024). Macrophytes influence the hydraulic flow patterns within CW, enhancing the contact between wastewater and the substrate. This improve contact time increases the efficiency of pollutant removal. In addition to their functional roles, macrophytes enhance the aesthetic value of CWs and provide habitats for wildlife, including birds, insects, and amphibians (Kochi et al., 2020). This biodiversity can contribute to the overall ecological health of the system.

As noted by Kataki et al. (2021a), careful selection of different aquatic plant species is essential, taking into account factors such as type of wastewater, location, uptake capacity, survival, availability, tolerance and productivity. Macrophytes must be able to withstand the specific conditions of the CW, including varying water levels, temperatures, and pollutant loads. Their ability to thrive in these conditions affects the overall effective performance of the systems (Singh et al., 2024). Moreover, the root structure of macrophytes varies among species and influences their effectiveness in pollutant removal. Plants with extensive and deep root systems are generally more effective at nutrient uptake and providing surfaces for biofilm development.

The supportive function of substrates is required for germination and survival of most submerged and emergent plants (Jehawi et al., 2020; Ji et al., 2022). In the study of Jehawi et al. (2020), two similar systems were compared for the treatment of a domestic wastewater, with the only difference being fact that one was planted with S*cirpus grossus* and the other was not (Table 3). The presence of the plants increased the removal of NH_4-N and PO_4-P by approximately 10%. Authors stated that total nitrogen removal was not achieved probably due to the lack of denitrifying bacteria in the rhizosphere of the plant, causing a slower rate of denitrification than that of the nitrification rate. Indeed, in a pilot-scale study, with CW planted with *Scirpus grossus*, the effects of applying a consortium of three rhizobacteria (2 % *Bacillus cereus* strain NII, *Bacillus subtilis* strain NII and Brevibacterium sp. strain NII) on the growth of the plant and also on the accumulation of iron (Fe) and aluminium (Al), grossus were investigated by Ismail et al. (2020), by comparing the same system but without the rhizobacteria. Authors concluded that the addition of 2% of the rhizobacteria consortium increased both the growth of Scirpus grossus and the accumulation of metals on the plant. Other authors, for instance Rahman et al. (2022), also stated that plants improve the efficacy of CW in reducing organic matter and nutrients (Table 3).

Negi et al. (2022), observed that nitrification and denitrification processes in CW systems are limited due to low oxygen transfer and the absence of a carbon source. In response to this issue, authors examined scientific studies investigating nitrogen removal through the anammox process in CW systems. This is due to the need for low DO and no carbon source to remove nitrogen from the liquid. When examining various systems of this type, they observed that aquatic plants, including Typha and Phragmites species, are promising for promoting anammox enrichment. Fig. 7 illustrates the processes involved in CW-type systems.

A CW system containing *Phragmites* macrophytes was operated by Saeed et al. (2019b). A mass balance assessment was carried out demonstrating Low removal percentages of nitrogen (7%) and phosphorus (14%). Authors reported that the main route for the removal of these nutrients was the biological pathway. This indicates that each plant has its own unique characteristics, which depend on the environment they are placed in and the environmental conditions they experience. In the studies analysed, various plants were used in different environmental conditions, which suggest that the same plant may be more effective in some studies than in others, depending on the conditions.

Plants in CW, in addition to their aesthetic function, play a fundamental role because they provide attachment sites for the biofilm, they release oxygen within the media bed, absorb nutrients, accumulate pollutants, and act as thermal insulation. In this sense, it is crucial to select the right species according to their stability and good adaptation to the target wastewater, the pollutants in question and the local environmental conditions, in order to guarantee the best treatment performance (Hernández and Sanabria, 2019). In this context, Table 2 presents the categorization of macrophyte species used in the studies mentioned

Table 2
Examples of plant species used in different studies.

References	PLANT SPECIE
Chaves et al., 2019	*Canna x generalis* *Coix lacryma-jobi* *Dioscorea* spp. *Zingiber officinale*
Hernández and Sanabria, 2019	*Cyperus alternifolius* *Heliconia burleana* *Zantedeschia aethiopica*
Corzo and Sanabria, 2019	*Cyperus alternifolius* *Heliconia burleana* *Zantedeschia aethiopica*
Saeed et al., 2019a	*Phragmites australis*
Saeed et al., 2019b	*Phragmites australis*
Saeed and Khan, 2019	*Phragmites australis*
R. Bianchi et al., 2020	*Phragmites australis*
Ismail et al., 2020	*Scirpus grossus*
Jehawi et al., 2020	*Scirpus grossus*
Mateus and Pinho, 2020	*Phragmites australis*
Wu et al., 2020	*Calamus and Reeds*
Hamada et al., 2021	*Phragmites australis*
Rahman et al., 2022	*Schumannianthus dichotomus*
Khajah and Ahmed, 2023	*Imperata cylindrical*
Khajah et al., 2023	*Phragmites Australis*
Obeng et al., 2023	*Thalia geniculata*
Souza et al., 2023	*Eichhornia crassipes*

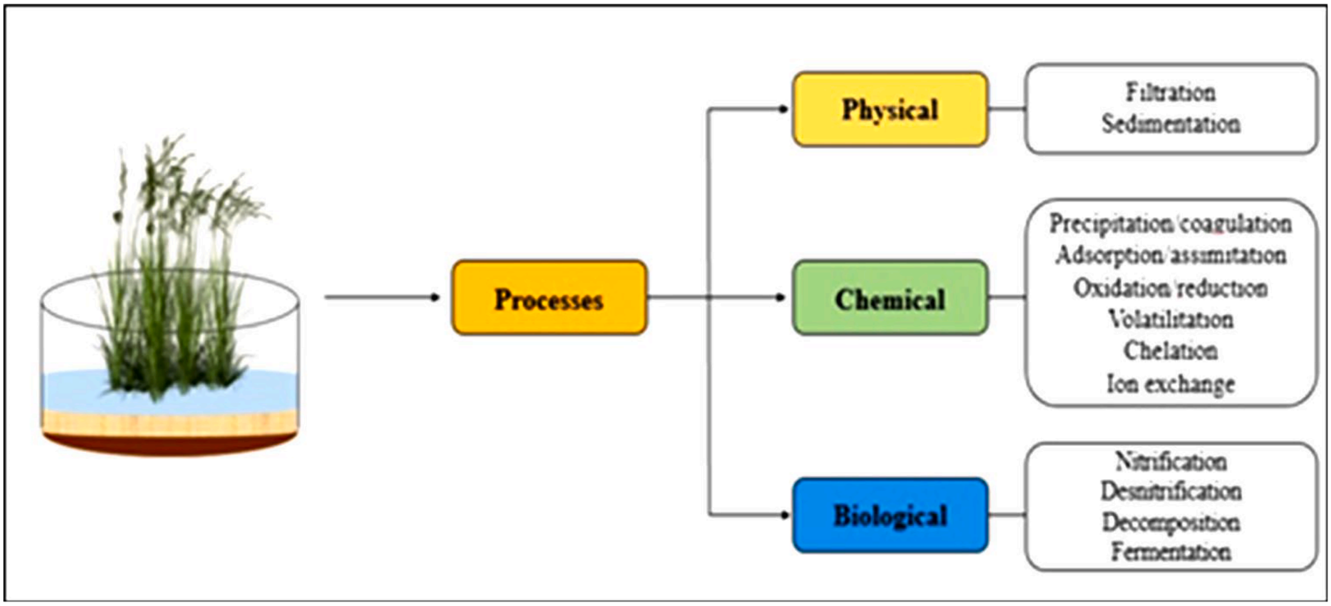

Fig. 7. Processes Involved in Contaminant Removal in Wetland Systems.

earlier. Among the macrophyte species mentioned, a variety of plants can be observed, used in an effort to achieve promising results in line with the specific objectives of each research study, but the *Phragmites australis* stand out. Further studies are therefore needed to establish a robust reference of species targeting each type of pollutant, building upon the successful application of the technology.

3.3.4. Design and operation criteria for CW

CW can have different configurations and designs and operate either in single-stage or combined designs (Jehawi et al., 2020). Design and operation criteria are multifaceted and require careful consideration of various physical, chemical, and biological factors. Although the most common concept of CW is that of surface horizontal flow, CW can have other different designs, including subsurface flow (vertical or horizontal flow), surface flow or floating treatment wetlands, or hybrid systems (Table 3). In the horizontal surface flow, water flows over the surface of the wetland from the inlet to the outlet. The water depth is usually shallow (10–45 cm). These CW mimic natural marshes and swamps with emergent vegetation and are suitable for treating stormwater, agricultural runoff, and secondary or tertiary domestic wastewater. They are simple to design and construct, and provide wildlife habitat. However, they face with the higher risk of mosquito's growth, odor issues due to greater exposure to air, and can have lower treatment efficiency for certain contaminants compared to subsurface flow systems (Vymazal, 2005; Koech et al., 2017; Tebitendwa and Cowan, 2021). In the horizontal subsurface flow CW, water flows horizontally through a porous medium (usually gravel or sand) beneath the surface, from the inlet to the outlet, so water is not exposed to the surface, reducing odor and mosquito problems. This design is effective for treating domestic wastewater, industrial effluent, and agricultural runoff. They promote high treatment efficiency for BOD, TSS, and pathogens due to increased contact with biofilms on the substrate. The main disadvantages are the potential for clogging, requiring regular maintenance, and can be more expensive to construct compared to surface flow wetlands (Vymazal, 2005; Koech et al., 2017; Tebitendwa and Cowan, 2021). Lastly, in the vertical subsurface flow CW, water is intermittently loaded onto the surface of the wetland and flows vertically through the substrate before being collected at the bottom. They often involve a series of vertical flow beds to enhance treatment and are particularly effective for treating high-strength wastewater and for nutrient removal, due to higher oxygen transfer rates, enhancing nitrification and overall treatment efficiency. This design require reduced land area requirement compared to horizontal flow systems, however demands more complex operation and maintenance. There is a high risk of clogging if careful maintenance is not carried out (Vymazal, 2005; Koech et al., 2017; Tebitendwa and Cowan, 2021). Hybrid systems are more often made up of vertical flow systems and horizontal flow systems arranged in stages (Vymazal, 2005). Due to the limited oxygen transfer capacity in horizontal flow systems, nitrification does not occur; however, vertical flow systems provide good conditions for nitrification, but denitrification does not occur in these systems (Vymazal, 2005). The combination of the two systems has been proposed to complement the processes in each system and produce an effluent with a low BOD content and much lower nitrogen due to the total nitrification and partial denitrification that occurs in the hybrid system (Vymazal, 2005).

The effective performance of CW systems depends on various factors, as emphasized by Saeed et al. (2019a), when investigating four hybrid wetlands for the treatment of a Municipal waters of Bangladesh, with different flow configurations (vertical and horizontal flow CW), operated in two stages and varying hydraulic loads (constant rate only varying the load, and shock load, i.e. sudden tenfolds increment of incoming). They observed that the efficiency of the second-stage configuration depended on the performance of the previous stage during periods of constant load. In their study, the most promising results were obtained in the vertical flow system with a high load, where the removal of organic matter, nitrogen, and phosphorus reached approximately 70% to 90%. Horizontal flow systems, acting as post-treatment, showed average efficiencies around 50%. In the total system, removals above 90 % were achiened with exception fot total nitrogen which reached 86%. In fact, several studies have shown that the right combination of wetland systems, such as vertical flow systems followed by horizontal flow, makes it possible to achieve higher removal rates, especially with less biodegradable water such as industrial wastewater (Saeed et al., 2019a, 2019b; Saeed and Khan, 2019). Saeed and Khan (2019) evaluated the performance of a vertical flow wetland combined with a surface flow wetland, operated during 21 weeks, for the treatment of an industrial wastewater of poor biodegradability. They hypothesised that the presence of a network of floating roots within the water column and the sequential formation of aerobic-anaerobic zones in the upper and lower parts of the surface flow wetlands may promote microbial transformations in a carbon-deficit environment, so increasing the global removals of hybrid wetland system (Table 3). Authors concluded that with this combination of systems it is possible to achieve efficient removal rates even with very recalcitrant effluents. The average overall removal percentages, considering the two systems, were $\geq$90.0% for NH_4-N, $\geq$ 86.0% for Total Nitrogen (TN), $\geq$ 91.0% for phosphorus, $\geq$ 92.0% for BOD, $\geq$ 85.0% for COD and $\geq$ 87.0% for colour. It should be noted that the removal of phosphorus in the vertical flow wetlands of system 2 with construction materials is due to the adsorption characteristics of the media used and that none of the vertical flow wetlands of both systems were efficient in removing coloured compounds. The removal of pollutants in the surface flow wetlands occurred via physico-chemical and microbial pathways around the floating root network, with the surface flow wetland of system 2 being more efficient, which authors attributed to the disproportion in the input biodegradation ratio.

Phosphorus, plays a vital role as a nutrient for the growth of various plants. However, its excessive presence in aquatic environments can promote the uncontrolled growth of algae, exacerbating the eutrophication process. Dell'Osbel et al. (2020), conducted a comprehensive review covering scientific studies exploring the relationship between HRT and water depth in the context of phosphorus removal. The results revealed that phosphorus removal efficiency exceeded 95% when the systems operated with an HRT of 8 days, ranging from the lowest HRT, 3 days, to the highest, 12 days. These findings highlight the importance of considering HRT in the effective management of phosphorus in aquatic environments as an approach to mitigate eutrophication issues.

The influence of pH and zeta potential on the phosphorus adsorption capacity was evaluated by Chaves et al. (2019) using gravel and ferric sludge as adsorbent materials resulting from water treatment chemical processes. The researchers obtained phosphorus adsorption capacities ranging from 1.44 mg.P/g (pH = 9) to 4.76 mg.P/g (pH = 3.9) at a zeta potential of ≈ -20 mV (pH = 9) and ≈ -12 mV (pH=3.9), highlighting the influence of pH in the process. Thus, it is deduced that at low pH, phosphate adsorption is facilitated by electrostatic and chemical attraction on the evaluated adsorbent materials. However, as pH increases, the surface charge changes and becomes more negative, associated with higher negative values of zeta potential.

The type of system regarding operational flow also influences the treatment process, as mentioned by Parde et al. (2021), in a review on the technology. Authors reported that the vertical flow CW systems present higher performance efficiency in nitrification and denitrification processes compared to horizontal flow. This higher efficiency can be attributed to factors such as longer residence time, natural aeration, and increased contact surface between liquid and substrate. When used in wastewater treatment, these vertical systems are more accurate in removing organic matter, nitrogen and suspended solids, that occours through the combined mechanisms of absorption, translocation, sequestration and degradation of pollutants (by macrophytes), transformation and degradation processes, biosorption, bioaccumulation and specialised transformation (by microorganisms) and filtration, adsorption, ion exchange, biofilm attachment, plant support, complexation and

Table 3
Summary of technology arrangement, substrate characteristics, and removal efficiencies observed in different studies using CW. The plant species used in each study are described in Table 2.

References	Wastewater	System configuration	Substrate	Removal of targeted compounds (%)	Observations
Chaves et al., 2019	–	VFCW	Gravel and ferric sludge from water treatment	DQO = 94.4 SS = 91.2 DRP = 95	Study focused on phosphorus recovery and recycling of ferric sludge from water closets CW The removal efficiency of DRP decreased as the maximum adsorption was reached. Promising results for phosphorus removal were obtained
Hernández and Sanabria, 2019	Synthetic wastewater	HFCW	Plastic media	n.a.	Research based on phytopathological indicators to assess the growth of three different plant species (*Cyperus alternifolius, Heliconia burleana*, and *Zantedeschia aethiopica*)
Saeed et al., 2019a	Municipal waters of Bangladesh	VFCW followed by HFCW	Gravel, construction materials, brick, or organic sugarcane bagasse	NH_4^+ = 99 COD = 93 TP = 86 TN = 93	Hybrid system
Saeed et al., 2019b	Surface water	CW with VF followed by SF or FT wetland	Biochar; Crushed Cement Mortar	In VF: COD = 39 - 97 TN = 11–83 TP = 20 – 100 In HF: COD = 4 – 85 TN = 16–86 TP = 1.4 – 100	Hybrid system The accumulation in the plants of TN and TP were ≤7 % and ≤14 % respectively, so dynamics of removal were controlled by microbial and adsorption kinetics.
Saeed and Khan, 2019	Industrial wastewater (mixture of metal, paper and textile effluents).	Two VF wetlands arranged in series, followed by a SF wetland as the final treatment stage (2 similar systems)	System 1 - organic bagasse, biochar, coal and oyster shell. System 2 - construction materials(recycled brick, mortar, gravel and sand).	NH_4-$N \geq 90.0\%$ TN ≥ 86.0% TP ≥ 91.0% BOD ≥ 92.0% COD ≥ 85.0% Colour ≥ 87.0%	Use of mixed industrial wastewater with poor biodegradability. Higher P removals in the VF wetland of system 2, related to the P adsorption properties of the construction materials used. The vertical flow wetlands of both CW systems were inefficient in removing colour compounds.
Ismail et al., 2020	Synthetic mining wastewater	SF system with 2% of 3 rhizobacteria (*B. cereus, B. subtilis* and *Brevibacterium* sp.)	From the bottom layer to the upper layer: 15 cm gravel (ϕ 10–20 mm), 5 cm fine sand (ϕ 2 mm) and (3) 1 cm gravel (ϕ 1–5 mm)	–	The presence of the rhizobacteria consortium caused an increase of around 30 per cent in the growth of *Scirpus grossus* (26%t in height and 29% in dry weight) and increased Fe accumulation by 48% and Al accumulation by 19%, as compared with the control without the rhizobacteria consortium.
Jehawi et al., 2020	Domestic wastewater	SF – VF – HF system in series	Medium gravel (φ 10–15 mm) at the top, river sand (φ 3–5 mm) in the middle, and larger gravel (φ 30–35 mm) in the bottom	NH_4^+ -N = 84.7 PO_4-P = 71.0	*Scirpus grossus*-unplanted system removed only 74.8% NH_4-N and 60.4 % of PO_4-P. Total nitrogen removal was not achieved as the amount of nitrate is increasing throughout the research period, which may be due to the lack of denitrifying bacteria in the rhizosphere, so denitrification was lower than the nitrification rate.
Mateus and Pinho, 2020	Synthetic wastewater and industrial effluent	VFCW	LCG - Limestone + Cork granulates	COD = 37–84 TP = 21–75 TN =19–62	Experiments conducted under 5 distinct experimental conditions. The data is reported from the most promising removal conditions.
			LSS - Limestone + Snail shells	–	
			LCS - Limestone + Coal slags	COD = 75–95 TP = 76–86 TN = 35 –82	
			LBF - Limestone Clay brick fragments	COD = 53–88 TP = 28–73 TN = 24–83	
			LO - Limestone fragment	–	
Wu et al., 2020	Domestic wastewater	Dual pipeline system	–	COD = 68 TP = 90 TN = 94 NH_3-N = 95	The study suggests building an anti-sedimentation layer to reduce the risk of groundwater contamination and strengthening management to prevent such contamination.
Hamada et al., 2021	Municipal wastewater	Two systems with two VF each	VFCW 1- olivepomace charcoal, sand and gravel	COD = 94 BOD = 94 TKN = 69 TP = 80 TSS = 97 Fecal coliforms = 98	The results obtained in both systems were similar in terms of final removal percentages. Olive pomace charcoal proved to be a faster adsorbent than citrus charcoal, but the combination of citrus charcoal and olive pomace charcoal makes the system more effective as the HRT increases.

(*continued on next page*)

Table 3 (*continued*)

References	Wastewater	System configuration	Substrate	Removal of targeted compounds (%)	Observations
			VFCW 2- olivepomace charcoal + citrus charcoal, sand and gravel	COD = 98 BOD = 98 TKN = 71 TP = 71 TSS = 96 Fecal coliforms = 99	
Chairopoulou et al., 2022	–	–	Oyster Shell	–	Study focused on the particle characteristics such as morphology, charge, and surface area of oyster shells
Lin et al., 2022	–	Upflow filter	Oyster Shell	NH_4^+ = 43.27	Tests were conducted with surface water contaminated with NH_4^+, and crushed oyster shell residues comprised the filter filling
Rahman et al., 2022	Sewage wastewater	Lab-scale VF: one planted (experimental) and other unplanted (control)	Gravel of different sizes and coconut fiber	Planted CW: BOD_5 = 61.60 ± 2.85 COD = 53.98 ± 11.84 NO_3-*N* = 70.25 ±15.33 NO_3-*N* = 39.36 ±30.85 Unplanted CW: BOD_5 = 43.31 ± 9.37 COD = 45.34 ± 8.88 NO_3-*N* = 9.92 ± 5.32 NO_3-*N* = 15.87 ± 25.07	*Schumannianthus dichotomus* has significant efficacy in reducing organic matter and nutrients when applied in VF CW. With increasing doses of contamination, the rate of reduction increased.
Khajah and Ahmed, 2023	Wastewater	VFCW	Gravel	BOD = 59.1 COD = 59.1 PO_4 = 24.7 NH_3 = 76.6 TN = 55 Heavy metals > 70	Higher organic matter and nutrient removal efficiencies were achieved when higher hydraulic loading rates were applied (1.67 m^3/m^2.d versus 1.04 m^3/m^2.d). Negligible removal of P due to the fact that this CW system was not designed to treat P.
Khajah et al., 2023	Synthetic domestic wastewater	Lab-scale Tidal VFCW Step-feeding strategies	Gravel: 10 cm bottom layer (φ 20–25 mm), 50 cm midle layer (φ 4–9 mm) and top layer 10 cm (φ 10–19 mm)	COD = 91–95 NH_4^+ -*N* = 74 - 91 TN = 66 - 81	Improved nitrogen removal performance at a phased feed ratio of 80:20, giving a carbon/nitrogen ratio (COD/N) of 4–5. The bacterial diversity observed suggested N removal via diverse metabolic pathways: autotrophic nitrification, heterotrophic, denitrification, autotrophic denitrification, and possibly anammox
Obeng et al., 2023	Domestic wastewater (sewage)	5 HSSF CW	Clay bricks and palm kernel shell	With clay bricks: BOD_5 = 73.97 COD = 71.89 TSS = 90.82 TP = 71.13 TN = 49.41 With palm kernel shell: Coliform removal = 98.6	Wastewater treatment efficiency decreased with increasing wastewater loading rates for all parameters with clay brick waste, and for BOD_5 and TP with palm kernel shells. Superior treatment potential with clay bricks than palm kernel shells for all parameters except coliform removal.
Souza et al., 2023	Synthetic wastewater	VFCW	Fragments of plasterboard sheets and modified plasterboard sheets	COD = 65 - 70 TP = 54 - 64 TN = 49.41	Removal of organic matter and phosphorus by different processes: adsorption on the substrate, precipitation, absorption by plants and as a source of carbon and nutrients for microorganisms.

COD - Chemical Oxygen Demand; CW – Constructed wetlands; DRO - Dissolved Reactive Phosphorus; FT - Floating treatment; HSSF - horizontal subsurface flow; SF - Surface flow; SS - Suspended Solids; TN - Total Nitrogen; TP - Total Phosphorus; TSS - VF – Vertical flow; n.a.- non-aplicable.

precipitation (by substrate) (Ji et al., 2022; Lee, 2013; Wang et al., 2020, 2022). Therefore, despite wetlands presenting as a simple technology, studying all variables involved in the physical, chemical, and biological processes in this type of technology seems to be a challenging endeavor, given that all these processes can occur simultaneously, and the maximum performance capacity can vary depending on the flow characterizing the system and the substrates constituting it.

Mateus and Pinho (2020), evaluated the performance of wetlands under different operational conditions, varying the reaction time in five systems. They observed that the increase in hydraulic load did not significantly affect the removal efficiency of COD, total nitrogen, and total phosphorus. On the other hand, in the review by Mlih et al. (2020), it was revealed variations in reaction time for the removal of metals and emerging pollutants, ranging from 1 h to 3 days. For metals such as cadmium and lead, adsorption occurred rapidly, in 1 to 2 h, while the stabilization of emerging contaminants required 3 days.

When projecting an CW, it is also important to take into account the possibility of contamination of surface water and groundwater. For instance, Wu et al. (2020) examined the surface and groundwater quality, from 2012 to 2018, of a CW from Xiantao, treating domestic wastewater, in order to assess its efficiency for domestic wastewater treatment, but also to analyse the risk to groundwater after a long period of operation. Authors found that the efficiency of the CW system was high, but the degradation of COD, NH_3-N, TN and Total phosphorous (TP) decreases over the time the CW is in operation, which was due to the accumulation of water pollutants in wetland environments, and the lodging and decomposition of wetland plants caused by poor management. Moreover, due to the high level of groundwater in the area and the lack of an anti-filtration layer, the groundwater and surface water have a high connectivity, which represents a high risk of pollution of the shallow groundwater in the wetland. The study by Wu et al. (2020) provided suggestions for the construction and operational management of constructed wetlands, namely that an anti-seepage layer should be constructed to reduce the risk of groundwater contamination and that management should be strengthened.

It is clear that the studies mentioned emphasise the fundamental importance of the design and operating criteria of CW systems. Variations in parameters such as hydraulic load, reaction time, pH and substrate can have a significant impact on the performance of these systems in treating pollutants, including nutrients and metals. Therefore, careful consideration and optimisation of these criteria are crucial to ensuring the efficiency and effectiveness of wetlands in removing contaminants and promoting environmental sustainability. However, as research is directed with this focus, increasing challenges related to wastewater treatment arise, but the development of sound design and operating guidelines is essential to maximise the technology's potential as a sustainable and effective approach to resource management.

Given the wide range of applications and their efficiencies in pollutant removal, various configurations are widely debated in different countries with distinct contexts and cultures (Table 3). Meeting stringent environmental regulations for effluent quality requires precise design and operational standards, preventing legal and environmental issues. Furthermore, as aforementioned, the discussions also extended to plant species as part of an improved process efficiency (Hernández and Sanabria, 2019). As previously mentioned, each biological effluent treatment system may provide varying levels of efficiency, even when sharing the same design parameters. In such cases, operation and environmental conditions emerge as decisive factors. Rigorously, before determining the design and operation criteria for nature-based systems, it is of utmost importance to carefully select the type of substrate and plants most suitable for the characteristics of the influent sewage and the prevailing environmental conditions.

3.3.5. *Water reuse*

Freshwater sources are limited, and the demand for clean water is continuously rising (James and Yadav, 2021). From a sustainability and circular economy perspective, the reuse of water from wastewater treatment can be a valuable water resource, especially for countries that are suffering the most from freshwater scarcity. However, ensuring that the treated water meets regulatory standards for specific reuse applications is crucial for safety and compliance. The safe reuse of wastewater presupposes that its treatment is effective in removing nutrients such as nitrogen and phosphorus, chemicals as example fertilisers, heavy metals, and also pathogens, which can be harmful to the ecosystem and human health (Khajah and Ahmed, 2023). However, addressing the presence of emerging contaminants (e.g., pharmaceuticals, microplastics) in treated water is an ongoing challenge that requires advanced treatment processes. Failure to manage this ecosystem service of water reuse could lead to the depletion of essential drinking water, a finite natural resource. Several methods are used to determine the suitability of water reuse such as regional flux-based risk assessments, multiple isotope approaches, and TRIAD-like approaches. Conventional techniques like trilinear plots, Multiple-criteria decision analysis and statistical methods are also widely accepted (Kindie et al., 2019; Teferea et al., 2021). However, the Water Quality Index (WQI) is the most effective tool for monitoring surface and groundwater pollution. WQI converts extensive water quality data into a single score ranging from zero to one hundred, indicating water suitability for human consumption. For example, Teferea et al. (2021) used WQI to evaluate groundwater quality in northwestern Ethiopia. Their study helped understand groundwater contamination based on various physicochemical parameters and provided useful policy insights. It also assessed the suitability of shallow groundwater for drinking and irrigation, which is vital for rural populations depending on these sources. Additionally, they used geographic information systems (GIS) to map WQI spatial variations, highlighting areas that need more attention for future pollution control efforts.

Numerous studies aim to develop low-cost, easy-to-operate technologies for the production of reused water. Nature-based solutions, such as CW, are considered viable alternatives due to their sustainability and cost-effectiveness in providing an efficient treatment process at a relatively lower cost compared to conventional technologies (Mlih et al., 2020; Kataki et al., 2021a; Khajah and Ahmed, 2023). In a systematic review study using the Ordinátio methodology, Boano et al. (2020) examined 30 pilot-scale CW systems for treating greywater. More than half of these systems utilized horizontal subsurface flow to treat both raw and treated greywater. These authors compared the efficiency of these systems in treating both types of effluents and found that CW achieved organic matter removal of up to 83% for raw greywater, and 60% for lightly loaded greywater. In another literature review study on wetland technology for treating various types of wastewater, it was observed that these systems had the capacity to reduce BOD by 60–93%, COD by 34–93%, TSS by 74–98%, nitrogen by 14–82%, and phosphorus by 35–82% (Kataki et al., 2021a). Additionally, significant efficiencies in removing surfactants were demonstrated, with removal rates exceeding 82%. However, it is worth noting that the presence of emerging pollutants, such as surfactants, poses a challenge to the safe application of water reuse since these components are not significantly regulated by some countries legislation, as for example in Brazil. Nevertheless, several studies have been conducted to propose removal processes for these pollutants and micropollutants (Pereira et al., 2014, 2015b, 2016; Silva et al., 2021). These studies seek innovative approaches to address emerging pollutants, contributing to the safety and efficiency of water reuse in nature-based treatment systems such as CW.

Recently, a CW with a vertical flow has been designed, constructed and its performance evaluated to treat wastewater and reuse it for irrigation of landscape in Kuwaiti (Khajah and Ahmed, 2023). The authors tested two hydraulic loading rates (1.04 m^3/m^2.d and 1.67 m^3/m^2.d) and obtained good removal of organic matter, nutrients and metals (Cd, Cr, Hg, Fe), with even better removal when operating at a higher hydraulic loading rate (Table 3). The TN, the total amount of PO_4 of all the treated effluents was lower than the local legislation standards for water reuse, and only 1/3 of the samples had NH_3 above the legislation standards. Although some of the heavy metals analysed had higher concentrations in the affluent than in the treated effluent, possibly due to leaching, all the values remained within the standards for water reusing

4. Conclusions and future perspectives

This literature review assessed the main factors influencing the performance of CW and evaluated the application of CW systems, from their construction to their operation. It is well-established that, regardless of the design of a wastewater treatment system, the way the system is operated is a determining factor in achieving its maximum efficiency. The most frequently mentioned primary factors in the reviewed sources include the type of substrate, the selection of macrophytes, the applied hydraulic load, and the HRT.

Recent findings in CW systems highlight significant advancements in both substrate selection and process optimization. Among the studied substrates, construction waste and biochars emerge as a viable alternative for composing the most commonly used substrates in CW (Fahim et al., 2023). This is due to the adsorption capacity of materials from these activities, low acquisition cost, and ease of application (Cui et al., 2022). Biochar differs from other organic materials mainly due to the large fraction of aromatic carbon, surface functional groups and high porosity (Cui et al., 2022; Layek et al., 2022; Fahim et al., 2023). Additionally, along with other carbon materials, biochar has been considered a low-cost efficiency material (Cui et al., 2022; Fahim et al., 2023). Waste from shellfish farming has also shown promise for wastewater treatment, particularly for those wastewaters containing high phosphorus levels, but there are still few studies on the application of seashells to effluent treatment technologies, especially in nature-based systems (Wani et al., 2023).

The choice of plant species must be carefully evaluated on a case-by-case basis. Macrophytes are integral to the functioning of CW, offering multiple benefits that enhance the treatment of wastewater. Their ability to uptake nutrients, transfer oxygen, support biofilm growth, facilitate sedimentation, transform toxins, and influence hydraulic flow makes them indispensable components of CW systems. The selection and management of macrophytes are crucial to optimizing the efficiency and sustainability of these systems. Depending on the geographical location of the study, it is advisable to use autochthonous plants or those that, although not native to the region, show good adaptation to the climate and local environment conditions.

Biofilm formation is a cornerstone of CW performance, driving the biological processes that underpin wastewater treatment. Understanding and optimizing the factors that influence biofilm development can lead to more efficient and sustainable CW systems, capable of addressing both traditional and emerging contaminants. Advances in monitoring techniques, including molecular biology tools and real-time sensors, are providing better insights into biofilm dynamics and their role in pollutant removal. Research is ongoing into substrates that not only support biofilm growth but also enhance microbial activity through additional properties, such as antimicrobial resistance or pollutant adsorption.

The use of innovative materials and hybrid systems, along with a deeper understanding of microbial and plant interactions, has led to more efficient and sustainable wastewater treatment solutions. These advancements not only improve the removal of traditional pollutants but also address emerging contaminants, making CW a versatile and valuable technology in the field of wastewater management. Using data analytics and machine learning algorithms to predict system behavior and optimize maintenance schedules can improve the reliability and efficiency of CW. Moreover, implementing sensors and automated control systems can optimize the performance of CW by monitoring water quality parameters in real-time and adjusting operational conditions accordingly.

Although the keyword "reuse" was employed in compiling the articles, a limited approach to this topic was observed in the selected studies. This suggests that, in the context of wetland technology for effluent treatment, the issue of reuse received little attention from the academic community. Evaluating the potential for the production of reusable water through this type of system can drive scientific progress in this area and, consequently, promote the implementation of these systems as a social technology for effluent treatment. These natural approaches play a significant role in the conservation and effective treatment of water, contributing to the preservation of this essential resource. Promoting CW for water reuse applications can help mitigate water scarcity issues exacerbated by climate change, particularly in arid and semi-arid regions. Still, it is crucial to ensure that the treated water meets regulatory standards for specific reuse applications. Addressing the presence of emerging contaminants (e.g., pharmaceuticals, microplastics) in treated water is an ongoing challenge that requires advanced treatment processes. Future CW designs could focus on the removal of emerging contaminants like pharmaceuticals, personal care products, and microplastics, using advanced biological and chemical processes.

In summary, the discussed studies highlight the effectiveness of CW technology in treating greywater. They demonstrate significant removal rates for various pollutants, including organic matter, suspended solids, nitrogen, phosphorus, and surfactants. These findings emphasize the promising capability of CW as a sustainable and effective approach for treating wastewater. The presence of emerging pollutants in wastewatersposes a continuous challenge as they are not extensively regulated by legal standards. CW systems represent a viable and economical alternative compared to conventional wastewater treatment technologies. Furthermore, they promote the conservation of resources, supporting the search for more sustainable solutions in the context of the growing demand for water in various segments of society, and, in addition, can use substrates considered to be "rubbish", giving them a new destination. Notwithstanding, it is essential to continue research and innovation to address future challenges, such as the removal of emerging pollutants, adapting CW to the specific demands of different locations. With proper investment and ongoing advancements, CW systems have the potential to play a crucial role in the efficient management of greywater, contributing to the preservation and responsible use of this vital resource. Increasing public awareness about the benefits of CW for wastewater treatment can foster community acceptance and support for these systems. Implementing educational programs and demonstration projects about the safety and benefits of water reuse is also important for gaining acceptance and support.

CRediT authorship contribution statement

Joice Santos: Writing – original draft, Methodology, Investigation, Conceptualization. **Sara Rodrigues:** Writing – review & editing, Supervision, Resources, Conceptualization. **Marcelo Magalhães:** Software, Methodology. **Kelly Rodrigues:** Writing – review & editing, Supervision, Resources, Conceptualization. **Luciana Pereira:** Writing – review & editing, Validation, Supervision, Data curation. **Glória Marinho:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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