Beyond Phragmites and Typha: A Global Bibliometric Analysis and Strategic Selection of Pioneer Macrophytes for Wastewater Treatment

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Systematic Review

Keywords: Phytoremediation, Wastewater Treatment, Pioneer Species, Phragmites, Macrophytes, Sustainability, Biological Diversity.

Posted Date: December 12th, 2025

DOI: https://doi.org/10.21203/rs.3.rs-8337730/v1

Additional Declarations:
The authors declare no competing interests.

Table 1 and 2 are available in the Supplementary Files section.

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Abstract

Rising global wastewater generation is damaging aquatic ecosystems resulting in the need for sustainable treatment options, such as Constructed Wetlands (CWs). At this time, phytoremediation is primarily relying on a few predominant plant species ("monoculture"). This research maps the current global research landscape (1969-2025) to identify neglected "pioneer" macrophyte species to expand treatment options for CWs and quantify species saturation. A complete multi-database search (Scopus, Web of Science, OpenAlex) was performed, and after extensive harmonization in R software, the corpus was comprised of 37,379 unique documents detailing the environmental use of over 100 plant genera. Results indicate overwhelming research saturation for *Phragmites australis* (877 papers), *Eichhornia crassipes* (534), and *Typha latifolia* (370) compared to the cluster of "pioneer" candidates, which are rarely cited (<10 times for each) and have only recently emerged (e.g., *Mentha aquatica, Salicornia persica, Cyperus eragrostis*). Although current "star" species comprise the majority of the existing knowledge base, these plants may not have the desired resilience to certain abiotic conditions (e.g., high salinity). Conversely, the currently undefinable "pioneer" species also represent an untapped potential reservoir, however hypothetical, for application in CW phytoremediation. This analysis offers a foundation for future experimental validation of the identified "pioneer" candidates to facilitate advancements in phytotechnologies and extend the biological applications beyond what is currently known.

Keywords

Phytoremediation; Wastewater Treatment; Pioneer Species; Phragmites; Macrophytes; Sustainability; Biological Diversity.

1. Introduction

Population growth is increasing at an accelerated rate globally through urbanization and industrialization. The ever-increasing demand for water resources worldwide has made this a major environmental issue and as a result, some of the biggest conflicts politically, economically, and socially today will be related to water resource management. In addition to the need for water, managing wastewater from domestic wastewater sources, industrial sources, and agricultural runoff is a significant challenge. Wastewater contains a tremendous amount of nutrients (phosphorus and nitrogen), organic material that does not break down in nature easily, many different types of heavy metals, and emerging micropollutants that are sometimes found in very large quantities in surface water and groundwater resources [1, 2, 3]. This shift in the paradigm of water management demonstrates the need to look at how we can treat wastewater and reuse it in order to conserve our current supply of freshwater resources. This means that treatment and reuse of wastewater will not be regarded as optional, but rather as mandatory elements for achieving a sustainable future [4,5].

However, the reuse of agricultural wastewater is fraught with specific physicochemical challenges that threaten soil health and crop productivity. In regions like North Africa, and specifically Morocco, pollution is compounded by high evaporation rates and geogenic factors. Recent investigations have highlighted the critical nature of these stressors. Sanad et al. (2025) recently provided compelling evidence of the ecological and human health hazards posed by toxic metal contamination in the agricultural lands of the Mnasra area within the Gharb Plain [6]. Their findings underscore the persistence of heavy metals in the environment, which necessitates remediation technologies capable of bio-stabilizing or extracting these elements [7]. Furthermore, salinity remains a major abiotic stressor limiting the reuse of treated water. The deleterious effects of saline irrigation water on strategic crops, such as durum wheat (*Triticum turgidum* L. ssp. *durum*), have been extensively documented in the Moroccan context. Manhou et al. (2024; 2025a; 2025b; 2025c) have repeatedly demonstrated through rigorous field and laboratory trials in Jemâa Shaïm and other regions that salinity severely impairs germination rates, disrupts physiological responses, and significantly reduces yield in various local wheat varieties grown on silty clay and sandy soils [7, 8, 9, 10]. These findings define a clear technological requirement: wastewater treatment systems in these regions must not only remove organic pollutants but must also be biologically resilient to high salinity and heavy metal loads to prevent the secondary salinization of arable lands.

To successfully tackle this complex issue, it is critical to develop robust, scalable and economically sustainable solutions for the treatment of wastewater on a large scale. Existing mechanical-biological processes have proven to be successful in treating municipal wastewater [12] , however, they tend to be expensive to operate, require substantial amounts of energy and involve complicated technical components, thus limiting their adaptability in rural areas and developing countries. Therefore, worldwide interest has begun to grow in using phytoremediation via Constructed Wetlands (CWs) as an alternative, environmentally friendly approach to the treatment of wastewater. In the scientific literature, various CW systems have been shown to be highly adaptable to a wide variety of effluent types, including greywater from rotating biological contactors or integrated wetland systems [12, 13], complex industrial wastewater streams such as refinery effluent [15] and tapioca starch wastewater [16]. Additionally, phytoremediation is also an effective tool for the remediation of heavy metals from contaminated soils [16, 17,18] and for the elimination of specific classes of organic contaminants like phenols [20].

The efficacy of Constructed Wetlands' treatment capabilities comes down to the complex relationship of the substrate, microorganisms, and crucially, macrophyte plants acting in concert. Plants play an important part in Constructed Wetlands' treatment process by absorbing and accumulating nutrients/heavy metals from the water [21], producing root exudates that stimulate the activity of microorganisms, and providing physical stability to the filter media (the filtering material used in the Design). A review of the literature currently available in this area shows a drastic lack of diversity in terms of plant species being used. Much of the research and application focuses on a very small number of dominant plant species, specifically, *P. australis* (Common reed) and *T. latifolia* (Cattail), which have a monopoly in this area due to their rapid biomass generation [22] and overall ability to filter water [23]. Although there have been studies on hyperaccumulator plants such as *S. alfredii* [24], *Nopcala cohenillifera* for chromium [25], and *H. annuus* [18] under controlled conditions, however large-scale applications continue to rely on monoculture systems of these previously established dominant species.

This dominance presents a significant strategic gap. The widely used species may not be universally adaptable to the specific climatic stresses (extreme heat, drought) or the pollutant cocktails (salinity plus heavy metals) identified in the Moroccan studies by Sanad et al. (2025) and Manhou et al. (2025a) [6,7]. There is a risk that *Phragmites* based systems may underperform or fail under such specific local constraints. This raises a pivotal question: Are there neglected or emerging pioneer plant species potentially phylogenetically related to successful families that could offer comparable remediation performance while exhibiting superior tolerance to saline and metallic stresses? The systematic evaluation of such species on a global scale is largely absent from the current body of knowledge.

This article aims to meld the existing body of knowledge with new, growing knowledge. Through performing a large-scale bibliometric analysis of the global phytoremediation literature and mapping this over a broad date range from 1969 to 2025, the major objective of this bibliometric analysis is to Creation's Map of the evolution of the field and the distribution of research on "star" species to be able to provide quantitative evidence about the saturation level of research on such "star" species. This bibliography research has gone beyond basic descriptive statistics; it has used advanced computational text mining techniques to analyse the conceptual structure of the phytoremediation field, enabling us to discover weak signals that indicate potentially beneficial plant species that could be used for phytoremediation that have not yet received sufficient experimental research attention. Ultimately, this research intends to combine all of this bibliometric information to create a scientifically based collection of possible candidate species for utilization in future experimental research trials.

2. Materials and Methods

2.1. Comprehensive Data Sourcing

To guarantee a comprehensive and unbiased representation of the global research landscape, this study employed a robust multi-source data collection strategy designed to minimize coverage bias. We queried three major bibliographic databases: Scopus (Elsevier), the Web of Science (WoS) Core Collection (Clarivate Analytics), and OpenAlex. This tripartite selection was strategic: while WoS and Scopus ensure the inclusion of high-impact, peer-reviewed literature indexed in major catalogs (SCI-Expanded, SSCI), OpenAlex was integrated to capture a broader spectrum of scientific outputs, including regional journals, conference proceedings, and grey literature. This inclusion is critical for identifying niche studies on local plant species that may not yet have reached high-impact international journals.

2.2. Search Strategy and Query Formulation

The data retrieval was executed on June 26, 2025. To ensure the relevance of the dataset, a complex Boolean search string was designed to capture the intersection of three conceptual domains: remediation technologies, biological agents (plants), and performance metrics. The specific query applied to the "Topic" fields (Title, Abstract, and Keywords) across all databases was formulated as follows:

((phytoremediation OR "constructed wetland" OR "wastewater treatment" OR "wastewater purification" OR "wastewater remediation") AND (plant* OR "aquatic plant*" OR macrophyte* OR reed* OR helophyte*) AND (efficiency OR performance OR removal OR absorption OR uptake OR "heavy metals" OR nutrient*))*

The study period spans from 1969 to 2025. It should be explicitly noted that data for the year 2025 is partial, reflecting publications indexed up to the date of extraction. No language restrictions were initially applied to ensure a global perspective.

2.3. Data Collection, Integration, and Advanced Curation

The initial search yielded a substantial volume of raw records, reflecting the intense global interest in this domain. Specifically, the extraction resulted in 50,184 documents from Scopus, 41,375 from Web of Science, and 1,126 from OpenAlex, totaling 92,685 raw records. Metadata including article titles, authors, publication years, source titles, abstracts, and author keywords were exported in standardized formats (BibTeX for WoS/Scopus and CSV for OpenAlex) to facilitate downstream processing.

Data integration and cleaning were performed within the R programming environment (version 4.3.3+), utilizing the specialized Bibliometrix R-package and the Tidyverse suite for advanced data manipulation. Dealing with such a large and heterogeneous dataset required a rigorous curation workflow to resolve interoperability issues between databases.
First, a custom R script was developed to harmonize variable names across the three databases (e.g., mapping display name from OpenAlex and Article Title from WoS to the standard TI tag). Subsequently, the datasets were merged into a single master corpus. A strict algorithmic deduplication process was then applied to eliminate redundant records resulting from the overlap between databases. Duplicates were identified based on normalized titles (conversion to lowercase, removal of punctuation and special characters) and matching publication years. To ensure the highest quality of metadata for the subsequent analysis, a priority rule was implemented: in cases of duplicate records, entries from the Web of Science and Scopus were prioritized over OpenAlex due to their generally superior consistency in citation data. Following this extensive cleaning process, the corpus was reduced from the initial 92,685 raw records to a final consolidated dataset of 37,379 unique documents, ensuring a statistically robust basis for analysis.

2.4. Computational Taxonomic Extraction Strategy

Standard bibliometric analysis tools (like Biblioshiny) provide general keyword statistics but do not inherently distinguish between biological taxa and general scientific terminology (e.g., differentiating "efficiency" from "Ludwigia"). To overcome this limitation, a novel Taxonomic Extraction Strategy was implemented using R. We utilized a dedicated script to filter the corpus against a predefined botanical dictionary. This dictionary included over 100 genera of aquatic and semi-aquatic plants known for their phytoremediation potential (e.g., *Phragmites, Typha, Ludwigia, Mentha, Cyperus, Iris, Rumex*). The script parsed the Title, Abstract, and Keyword fields of the 37,379 documents to calculate the frequency and temporal distribution of each specific plant genus. This computational approach allowed us to screen thousands of abstracts to isolate rare plant species that are phylogenetically close to well-known phytoremediation families but possess distinct, under-studied traits.

2.5. Criteria for Pioneer Species Selection

To determine the best "pioneer" species for experimental testing, a series of specific criteria were created to identify which species could be considered for selection as candidates. Three basic criteria had to be satisfied by an eligible species; the first was the number of citations thus far in peer-reviewed publications after 2020. A species will not be chosen if the total number of citations is greater than a total number of citations published prior to 2020, therefore showing a trend toward increased interest in the species. The second criterion is related to the number of total citations in the world, known as "non-saturation". A species would not qualify if the total number of citations were greater than 20 references in the total world database. In contrast, many species are known as "star" species and receive many hundreds of citations, so it is easy to see that the total number of occurrences would be extremely high. The last criterion is based on ecological viability, and so to qualify the species should come from either a family or from a family of plants that exhibit strong resilience traits (examples of families that meet this criterion are *Cyperaceae*, *Lamiaceae*, or *Chenopodiaceae*), or demonstrate certain characteristics that allow them to withstand challenging climatic scenarios (such as salinity, drought, or heavy metal exposure), as well as maintain their ability to treat wastewater.

3. VISUAL SUMMARY OF METHODOLOGY

Table 1: Flowchart of the bibliometric methodology, data fusion process, and species selection strategy.

- **PHASE 1: Data Identification & Extraction**
  - **Scopus:** 50,184 records
  - **Web of Science:** 41,375 records
  - **OpenAlex:** 1,126 records
  - *Total Raw Records: 92,685*

- **PHASE 2: Data Processing & Curation (R Studio)**
  - Harmonization of metadata fields (Tag mapping)
  - Merging of heterogeneous datasets
  - Algorithmic Deduplication (Title Normalization)
  - *Reduction from 92k to 37k records*

- **PHASE 3: Final Consolidated Corpus**
  - **n = 37,379 unique documents**
  - *(Timeframe: 1969 - 2025)*

- **PHASE 4: Taxonomic Mining**
  - Application of Botanical Dictionary (>100 genera)
  - Semantic filtering of Keywords, Abstracts, and Titles
  - Cluster Analysis: "Star" Species vs. "Pioneer" Candidates

- **PHASE 5: Candidate Selection**
  - Criteria: Emergence + Rarity + Local Ecological Suitability
  - **Result:** Selection of Pioneer Species

3. Results

3.1. Temporal Dynamics and Maturity of the Research Field

The merging of the three databases resulted in a collective total of 37,379 original documents which were published between 1969 and 2025. Analyzing the number of scientific papers published yearly indicates an exponential trend of growth. The period of this analysis was divided into three separate time frames; a latency period between 1969 and 1999 when few papers were published, a developing period between 2000 and 2010 where phytotechnology began to be adopted, and finally an exponential growth period beginning in 2011 and continuing through 2025. There are indications that the upward trend will continue based on the limited data available to date for 2025. This ongoing success is indicative of how phytoremediation has gone from being a relatively obscure experimental topic to becoming a widely accepted global method for addressing environmental concerns through engineering.

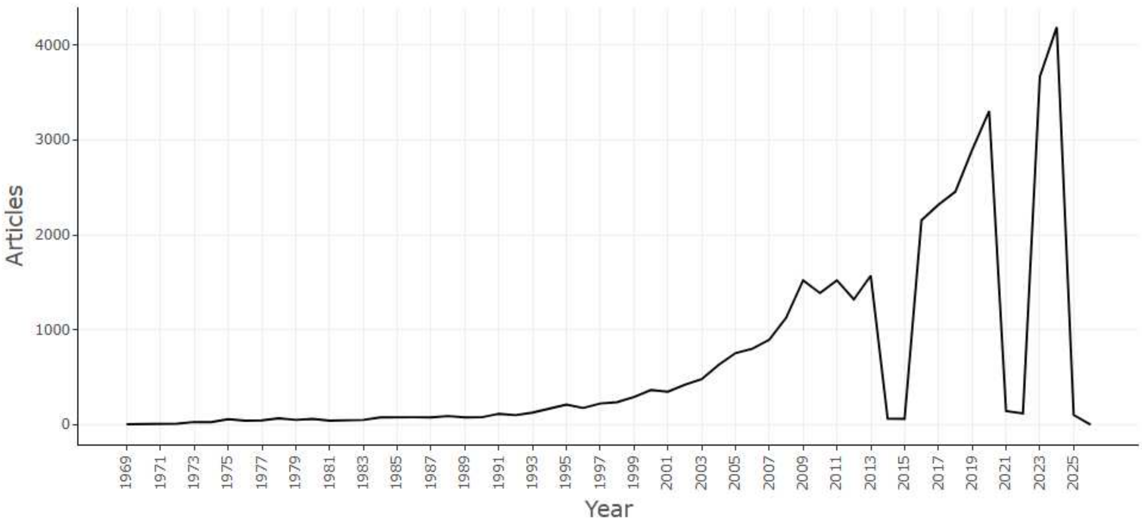


Figure 1: Annual scientific production

To evaluate the development of the industry over time, a Logistic Growth Model was created by using Life Cycle Analysis (Figure 2). This model describes how the Logistic Growth Model accurately describes Phytoremediation, as shown by the R2 value of 0.493. The Logistic Growth Model estimates that phytoremediation peaked between 2019-2021. However, as in the case of an industry with a declining period, the Logistic Growth Model shows that while the idea of doing Phytoremediation is a well-established concept, the focus has shifted to how this concept can be improved to be utilized for specific purposes, e.g., in terms of Agricultural Reuse. As shown in the Average Citations per Year graph (Figure 3), although there was an increase in the number of publications published in scientific journals, the impact of these publications continues to be high, which is evidence that Phytoremediation is still a relevant field.

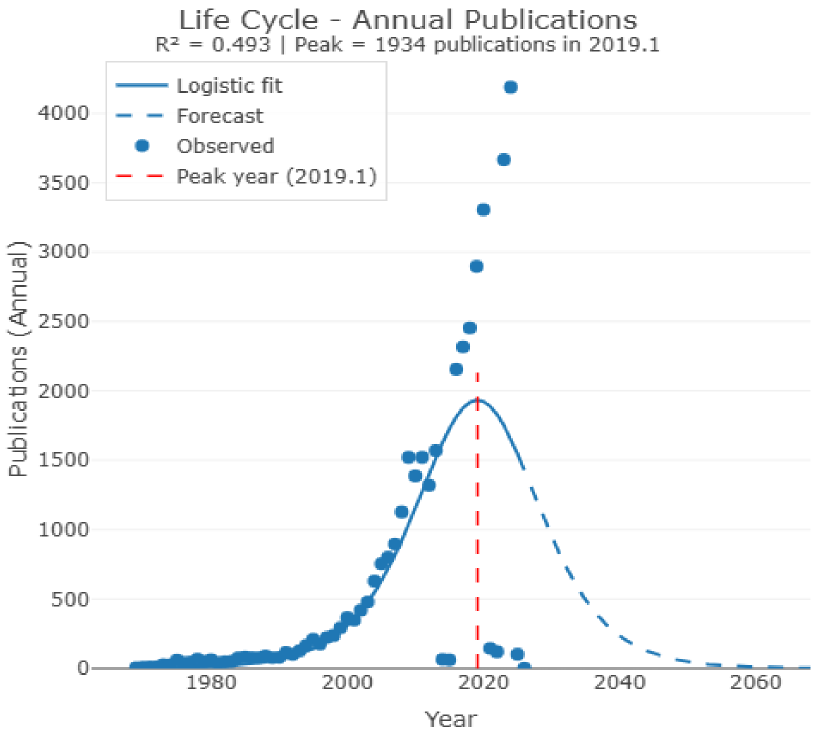


Figure 2: Life Cycle of Scientific Production

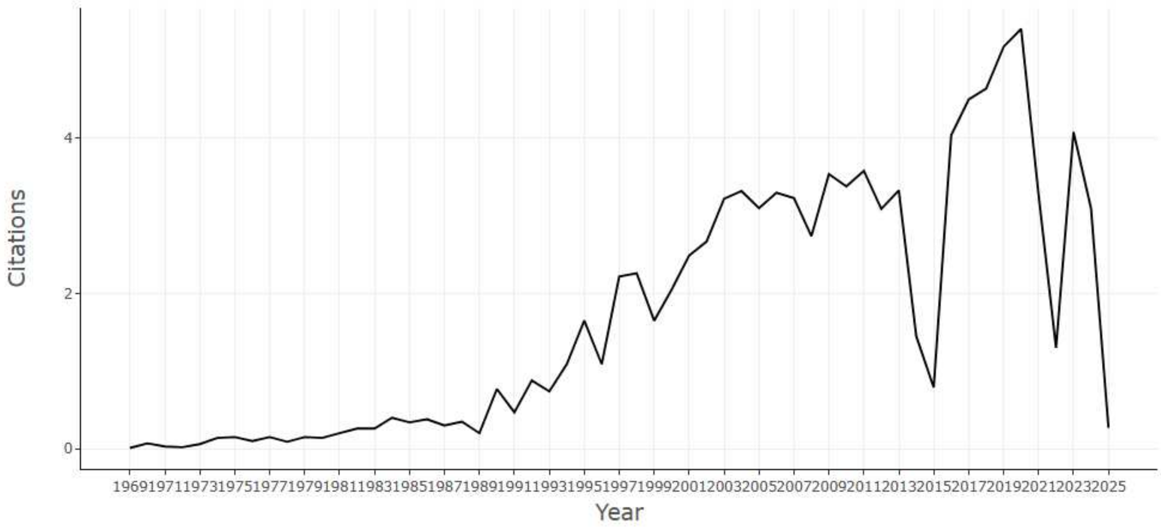


Figure 3: Average citations per year.

3.2. Structural Analysis: Sources and Geopolitical Landscape

The leading environmental journals publishing research about phytoremediation are shown in Figure 4. Water Science & Technology has published 1,737 articles, followed by Science of the Total Environment (1,531 articles) and Water Research (1,489 articles). The importance of these journals suggest that phytoremediation falls between two disciplines or fields: Environmental Engineering and

Ecological Science. Due to the effects of scientific leadership in Asia (Figure 5) on developing countries, science is experiencing a dramatic change in power bases. China's FDA and Tsinghua University have surpassed the previous leaders of Western Nations. As shown by the temporal development of association (Figure 6), the increase in Chinese production is clearly represented by the increase in production after 2010. China's growth in productivity has also been driven by government-sponsored efforts to control water pollution and restore ecosystems in developing nations, resulting in a growing body of research documenting these two phenomena.

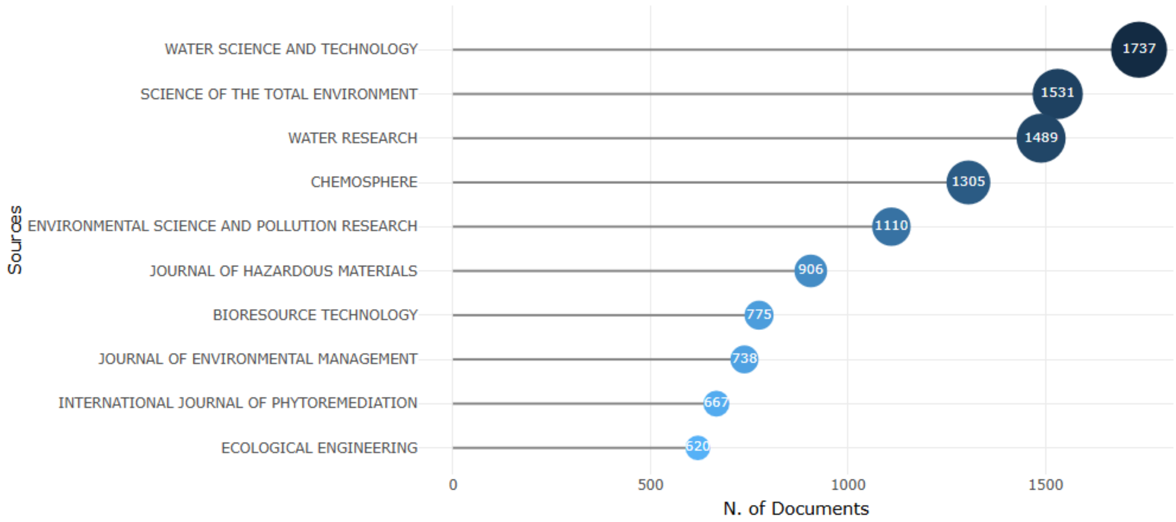


Figure 4: Most relevant sources

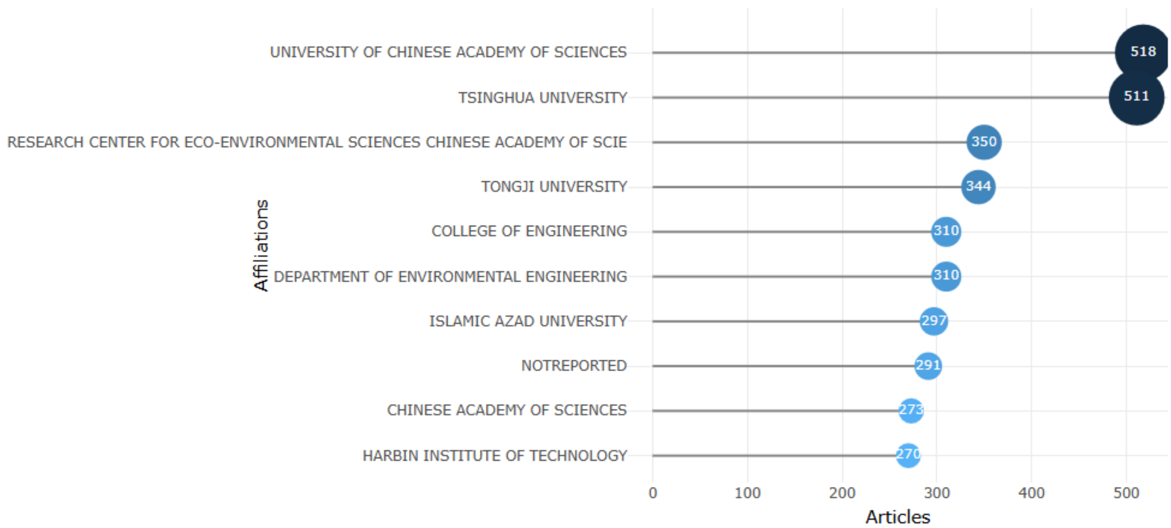


Figure 5: Most relevant affiliations

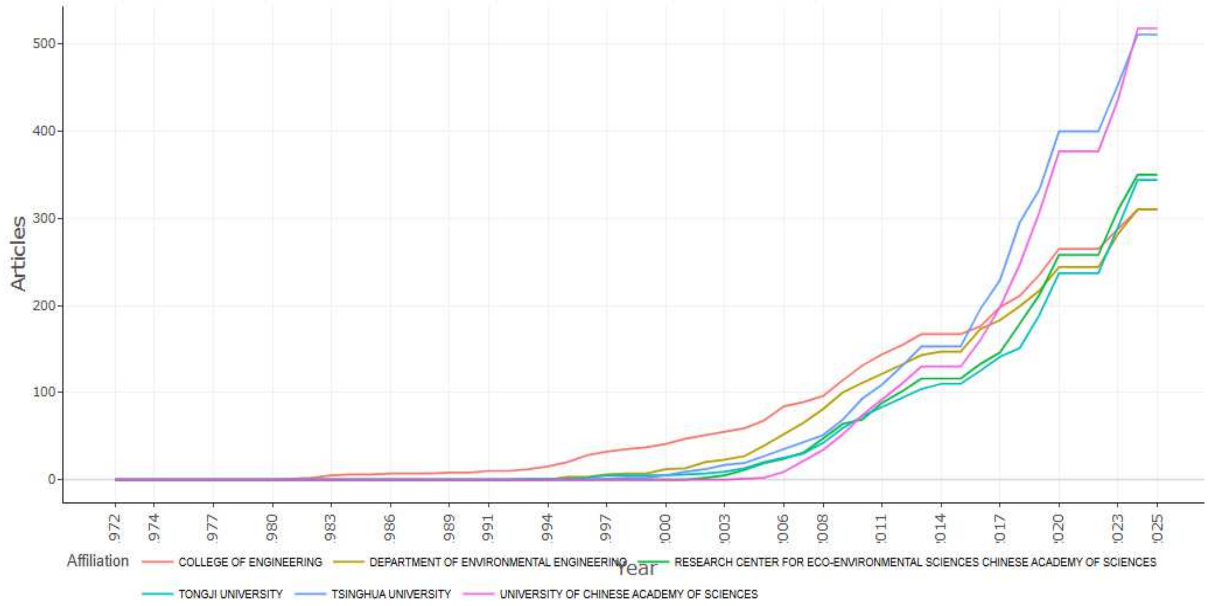


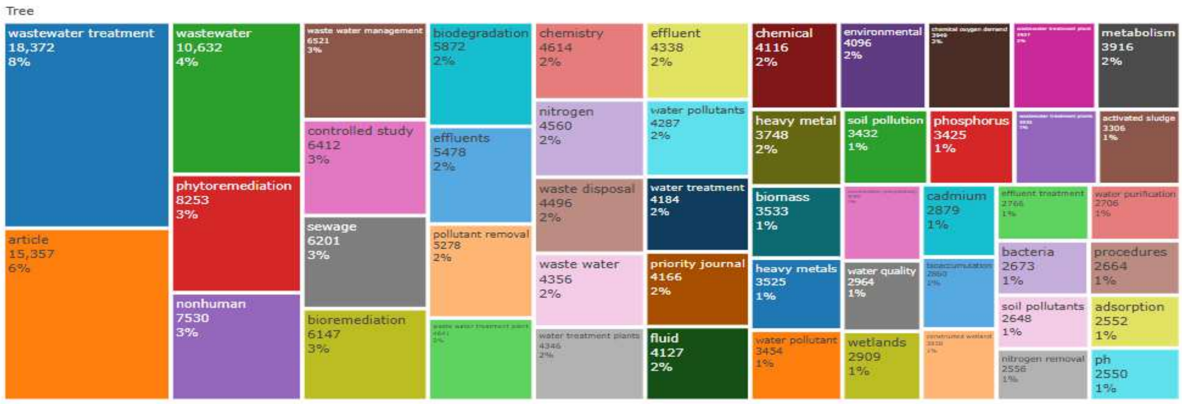
Figure 6: Affiliations Production over Time

3.3. Conceptual Architecture and Network Topology

Using keyword frequency visualizations, a Semantic analysis of the domain was performed to help identify its intellectual structure. From the WordCloud (Figure 7) displaying the frequencies of the higher-level terms such as "Wastewater treatment", "Biomass" and "Heavy metals", we can see that the major focus of research exists in the area of pollutant removal performance and efficiency. Additionally, the TreeMap shows how the topics are related using a hierarchical presentation. Both "Phytoremediation" and "Wetlands" are two of the most significant blocks in the TreeMap (Table 2); however, some of the subtopics in these larger blocks, such as "Biodegradation" and "Nutrient Removal" (Nitrogen/Phosphorus), make up a large amount of the research work done on these topics. These subtopics represent a biological process with a chemical focus.

Figure 7: WordCloud

Table 2: TreeMap (Visualizations of keyword frequency)



The VOSviewer-generated keyword co-occurrence network (Figure 8) shows that there are three major themes visible through the three distinct thematic clusters within the network. The first thematic cluster, in red, represents a cluster of terms within the engineering dimension of constructed wetlands and includes technical types of processes (e.g., sludge management, bioreactors, effluents, chemical oxygen demand (COD)). The second thematic cluster, green, represents biological processes occurring at the rhizosphere level (e.g., biodegradation, bacterial communities, enzymatic activity, and genetic processes). The yellow and blue thematic cluster includes wetland technology and is of particular interest to this study. This cluster illustrates how constructed wetland technologies and biological agents connect; however, it does so using very few, but large nodes (i.e., "star" plants); Phragmites and Typha. The visualization illustrates that the field is primarily focused on these few species of plants with other possible plant species appearing as small, isolated nodes. This indicates that constructed wetlands are poorly integrated into general research networks and are under-explored.

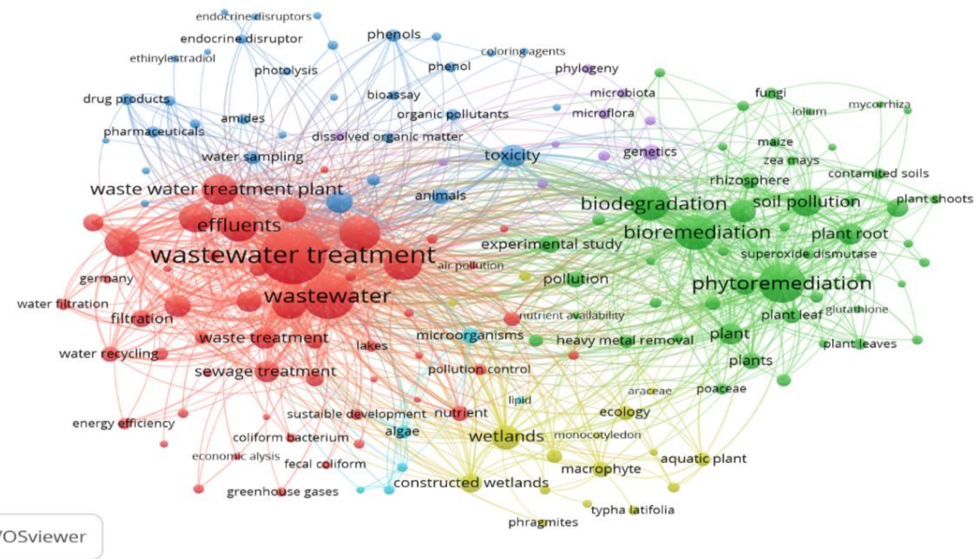


Figure 8: VOSviewer Co-occurrence Network Map

3.4. Taxonomic Analysis: Quantifying the "Monoculture" of Research

A taxonomic extraction script was designed to quantify the occurrence of the various genera of aquatic vegetation in the literature. The result of this analysis is found in figure 9, and is incontrovertible evidence that the research has reached a saturation point for those types of macrophytes.

Phragmites australis (commonly referred to as the "common reed") has the largest number of published articles (877) and serves as the "reference" point for all of the other species. Following *Phragmites* is the aquatic invasive species *Eichhornia crassipes* (floating herb; 534 articles), and the aquatic sedge *Typha latifolia* (370 articles). Other species that have considerable literature include *Agropyrum repens* (210 articles), *Zea mays* (corn; 382), and *Helianthus annuus* (sunflower; 221 articles). These are often addressed within the context of their use for the phytoremediation of soil rather than their treatment of water.

The data further conform to the "Pareto Distribution" principle in that 20% of the species produce 80% of the literature on those types of plants. With the present body of literature on *Phragmites* being what it is, further research into this species will likely yield diminishing returns with respect to scientific novelty.

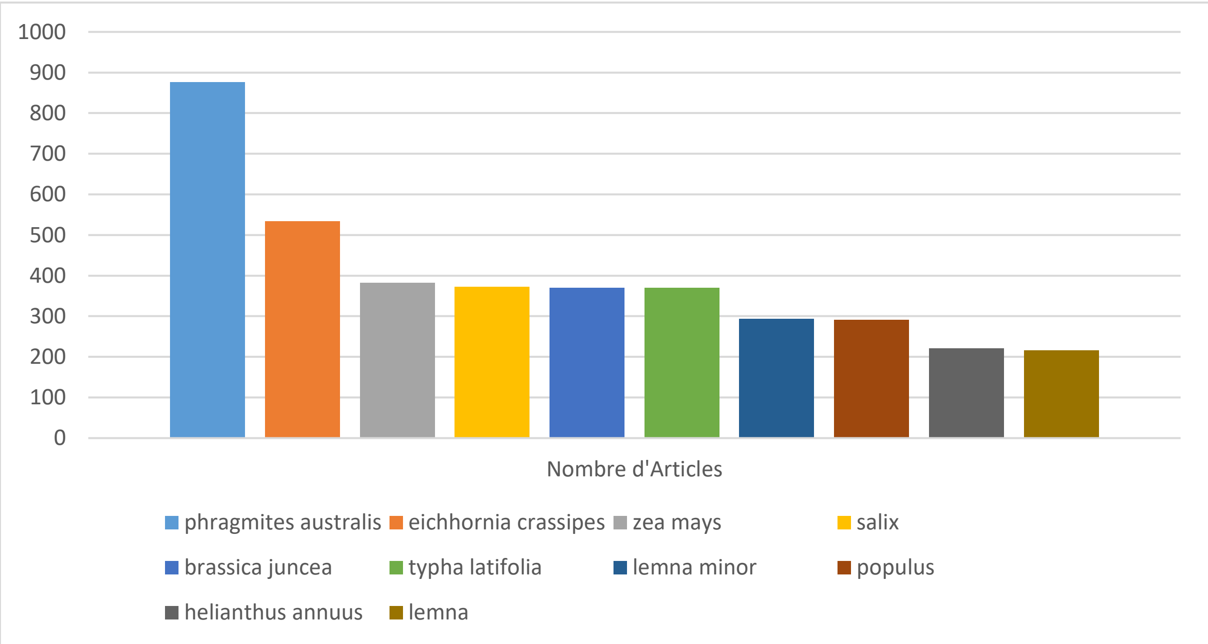


Figure 9: Bar chart of the "Top 10 Star Species" (Phragmites, Eichhornia, etc.).

3.5. Strategic Identification of Pioneer Candidates

The data mining of the keyword datasets created through bibliometric methods has uncovered a collection of scientific literature pertaining to 'Pioneer' species that were previously considered to be in the long tail of the dataset (Figure 10). These species have not been studied extensively, but they have only recently begun to be described within the scientific literature (< 10 global citations) since the beginning of the COVID-19 pandemic (i.e. after 2020), indicating that they have received, or have the potential to receive, the interest of scientists. Some of the identified Pioneer species could adapt to the saline and drought conditions of the test site. A few examples of the identified candidates are:

- *Mentha aquatica*: *M. aquatica* is a potential source of essential oils; however, it has only been described by a limited number of researchers (approximately 5 articles), despite its use within agriculture.
- *Salicornia persica*: Although *S. persica* is a niche halophyte (as demonstrated in two articles), theoretical evidence indicates that this species will confer a degree of resistance to highly saline wastewater and will provide an important resource for arid regions.
- *Cyperus eragrostis*: The genus *Cyperu*s is well-studied; however, *C. eragrostis* (two articles) has received little scientific attention compared to C. papyrus and represents a 'safe yet novel' phylogenetic alternative.
- *Ludwigia adscendens*: This species has received four articles and represents an example of the increasing scientific research interest in creeping floating macrophytes. Additionally, it provides an alternative to the invasive aquatic plant, Hyacinth.

The bibliometric screening process provides a rationale for identifying a test species based on scientific novelty and relevance to the ecological community.

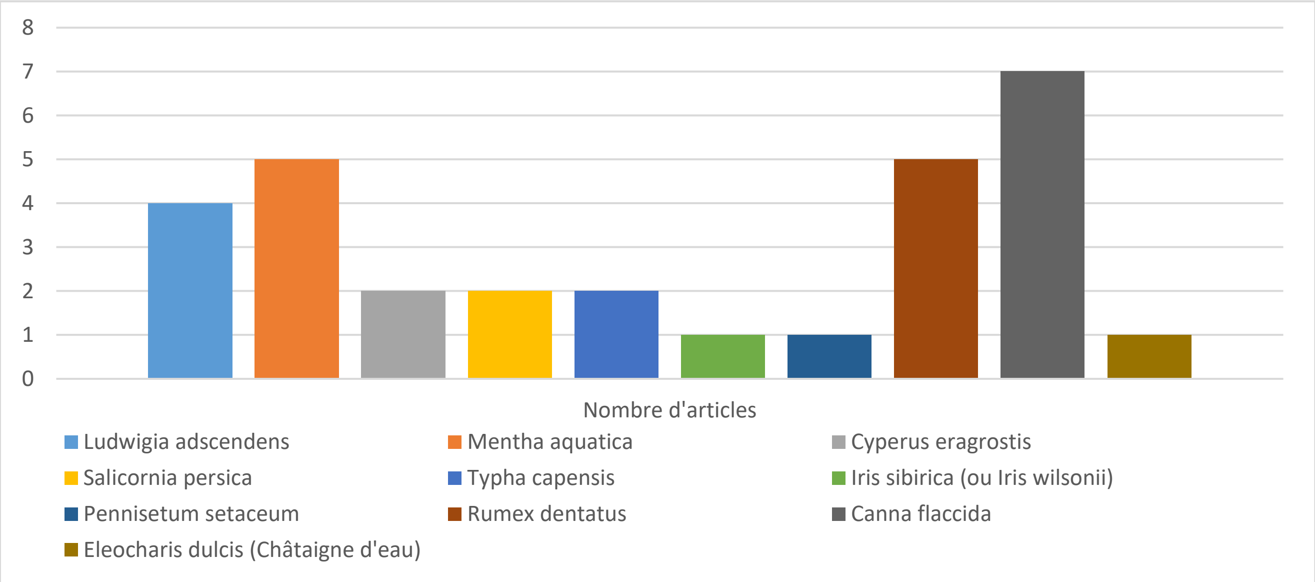


Figure 10: Bar chart of "Pioneer/Candidate Species" (The 10 rare plants selected).

1. Discussion

4.1. The Global Convergence on Phytotechnologies

Results of bibliometric analysis provide evidence that Phytoremediation technology has matured, becoming an experimentally-based technology for Phytoremediation of wastewater managed globally by mixing, matching, and/or recycling waste streams based on process efficiencies needed [24, 25]. The significant increase in the number of published articles reflects a global requirement to find low-cost alternatives for treating wastewaters [26]. The popularity of the words "Efficiency," "Removal," and “Heavy Metals” found within the WordCloud display reflects primarily a utilitarian approach to the applied research of phytoremediation [28] where research is primarily aimed at compliance with discharge standards for wastewater. In addition, this research supports examples of sufficient evidence that there are volumes of papers published on the removal of individual contaminants such as Heavy Metals [23, 27], Pharmaceutical Products [28, 29], Organic Matter [14].

4.2. The "Phragmites Paradox": Success and Limitation

This analysis demonstrates a heavy reliance on a small research sample, or "research monoculture". As well, *Phragmites australis* and *Typha latifolia* are stated as being the benchmark species in the literature and this is consistent with other authors [30, 31]. The strength of these species is well established; however, the dominance of both species creates bias in knowledge production. Figure 8 demonstrates that "Constructed Wetlands" have an almost synonymous link to both genera, indicating that much of the knowledge about constructed wetland systems has been derived from studies focusing on the two genera listed.

This lack of diversity in the established research sample presents an obstacle to widespread global application. In countries where the sources of wastewater are more saline and have a greater variety of pesticides and residuals from Agriculture, it could be detrimental to only rely on the use of Phragmites. There is clear evidence that although Phragmites is highly efficient, performance could decline due to extreme abiotic stress [34]. In addition, the reliance solely on the use of these "star" or "model" species may preclude consideration of the ecosystem-based potential for local diversity to provide resilience/resilience benefits and/or economic opportunities, as highlighted by recent studies examining alternative crops or species, such as Ricinus communis [35] and Helianthus annuus [36].

4.3. The Potential of Pioneer Species in Saline and Heavy Metal Contexts

The identification of a collection of pioneer species (*Mentha aquatica, Salicornia persica, Cyperus eragrostis*) provides new opportunities for exploration. In contrast to the more thoroughly documented

Eichhornia crassipes [35, 36] and *Pistia stratiotes* [39], which tend to be more invasive, the proposed pioneer candidates possess a unique combination of "novelty" and "ecological fit".

For instance, the inclusion of *Salicornia* on the list of pioneers has significant implications for coastal and arid regions throughout the world. All *Salicornia* species are halophytes and, therefore, can thrive in highly saline conditions. This trait is essential for remediating agricultural drainage where salinity is the principal limiting factor for crop production [8]. Although isolated studies from the literature have indicated the potential for nutrient recovery using halophytes in saline aquaculture [38, 39], they tend to be utilized much less as a treatment option in agricultural wastewater than glycophytes.

On the other hand, *Mentha aquatica* provides a dual benefit of removing pollutants from the water while at the same time producing essential oils, thereby creating economic benefits from the treatment of the wastewater, consistent with the "wastewater to energy/value" theme discussed by Batten et al. (2013) and Ge et al. (2013) [40, 41].

Although there have been many studies on hyperaccumulators, such as *Sedum alfredii*, regarding their ability to absorb heavy metals, it is currently unknown how well they adapt to different climatic conditions. Local pioneer plant species that are already found in many areas may prove to be a more resilient option for phytostabilizing metals (i.e. Copper and Zinc) commonly seen in agricultural runoff; an example of this would be *Cyperus eragrostis.*

4.4. Justification for Future Experimental Validation

Using bibliometric data, we propose that the best way to advance global wastewater treatment should be through investigating the phylogenetic neighbourhoods of what we describe as "Star Genera" (ex: *Phragmites* or *Typha*) and not be through replicating studies already done on those genera. The success of both *Phragmites* and *Typha* [31, 30] is related to the morphological and anatomical traits they possess as a result of their family membership, such as the presence of extensive aeration tissue in their roots providing a means for oxygenating roots and rapidly accumulating biomass. Hence, it is reasonable to hypothesise that genera not studied as thoroughly as *Phragmites* or *Typha* but within the same family, or within closely related families, would potentially possess similar remediation capabilities, while each offering unique advantages that may be suited to specific pollution types. This idea promotes the marriage of innovation by testing a new genus, as well as maintaining secure biological conditions through the selection of a genus with known familial traits.

As an illustration, the genus *Cyperus* is well documented in the scientific community through its most well-known representative, the papyrus (*C. papyrus*), and *C. alternifolius* [42, 43]. Despite this extensive documentation, we identified *Cyperus eragrostis* as an underappreciated species that may not be represented in the available scientific literature. Testing *C. eragrostis* will enable us to take advantage of the extensive fundamental understanding of *Cyperaceae* root systems's ability to support active microbial biofilms [46], while simultaneously allowing us to investigate a species which may be better suited than its tropical relatives to variable conditions of use. Thus, we will be able to reduce the potential risk of failure associated with planting while increasing the novelty of the research report presented to scientists across the world.

Pioneer species must be selected on criteria other than phylogenetically relatedness, due to the worldwide growth and complexity of wastewater matrices containing emerging contaminants, heavy metals, and variable salinity levels [6]. The pioneer cluster of this study included one halophyte, *Salicornia persica,* and demonstrated a major shift in thinking regarding the applicability of the halophytic phytoremediation process versus the selection of a glycophyte, such as *Typha,* which is less adapted to high osmotic pressures. Salicornia species, like those discussed by de Lange et al. (2013) and Shpigel et al. (2013) [38, 45], are suited for phytoremediation of saline drainage waters, a problem experienced in numerous agricultural regions worldwide, including North Africa [8]. Therefore, the addition of considerations for economic value to the remediation process may facilitate wider adoption of constructed wetlands globally. The choice of *Mentha aquatica* (*Lamiaceae*) represents the concept of "constructed wetlands for cash crops", while the *Mentha* genus is not closely related to the *Phragmites* genus, *Mentha* is also capable of rapid vegetative propagation. The selection of *Mentha aquatica* provides opportunities for the economic viability of constructed wetland processes, converting a wastewater treatment cost to a potential value-added opportunity via essential oil production; this is an area largely unexplored with traditional *Phragmites* growing beds [42].

As a result of this focus on one of our selected pioneer species, during the experimental phase of validation, we will be able to analyse whether the species will be a 'relative' of a star species or even a functional specialist. In order to qualify for this assessment, the selected species must meet our triple criterion: bibliometric novelty of < 10 global citations ('long tail') based on our bibliometric analysis; physiological plausibility based on the successful performance of related taxa; and theoretical tolerance to harsh environmental factors such as high salinity and heavy metal loads. This stringent selection process will allow us to ensure that future experiments will not simply add to the already over-researched field, but instead will provide opportunities to research and fill critical gaps in knowledge regarding the diversification of phytotechnologies for complex wastewater treatment applications.

2. Conclusion

This systematic review presents a broad overview of global research activities on the use of plants to treat wastewater over a 56-year period (1969-2025) from 37379 scientific papers compiled and analysed. Using bibliometrics, this study clearly shows that although the area of wastewater phytoremediation has matured and reached a plateau, it is also very dependent on a "mono-culture of research", which makes it weak and vulnerable structurally. Quantitatively, this review provides evidence that the majority of knowledge related to wastewater phytoremediation is focused on an extremely narrow group of macrophyte genera. There is a large disparity in the number of studies examining wastewater phytoremediation of certain "star" macrophytes (*Phragmites australis* (877 studies), *Eichhornia crassipes* (534) and *Typha latifolia* (370)). Well-known mechanisms of removal for these macrophytes, as evidenced by their extensive use in municipal wastewater treatment, provide ample proof that these three macrophyte genera are all effective for treating standard municipal sewage [30, 21]. However, the heavy concentration of research on these macrophytes has left an enormous knowledge gap with respect to the adaptability of Nature-based Solutions (NbS) for wastewater treatment to various, more specific, and increasingly common abiotic stresses such as high salinity and heavy metal contamination, which are present in large quantities in industrial and agricultural effluents around the world [6, 25 ,46].

Through the innovative method of extracting computational taxonomies, our research identified many previously unexamined species of plants in the "long tail" of the literature. Our results also showed that there is a group of potential "Pioneer" candidates that have extremely low publication frequency (< 10 global occurrences), but have the potential for sustainable wastewater treatment based on their physiological properties. Some of the notable candidates we found were: *Mentha aquatica*, *Salicornia persica, Cyperus eragrostis, and Ludwigia adscendens*. While the ubiquitous *Phragmites* has a long history of use, these other plants belong to families (*Lamiaceae, Chenopodiaceae*, and *Cyperaceae*) which have not been exploited to their full potential to support both dual-purpose or extreme tolerance to use on saline environments. For example, *Salicornia* is one of the candidates that could help us meet our urgent need for treatment of saline drainage [38, 45], and *Mentha aquatica* could help us create economically viable means of producing essential oils to support the goals of energy efficiency established by Batten et al. (2013) [42].

Importantly, based on these bibliometric data, a clear distinction must be made regarding what constitutes a candidate as being "technologically advanced". Specifically, we show that although we have been able to identify and quantify the relative number of candidate species in scientific literature as documented through the bibliometric method, the relative rarity (or lack thereof) of this "scientific" classification does not mean the candidate will perform well biologically. This has already been demonstrated by differences observed in laboratory and field performance between holm and heinsoo, 2013; sharma et al, 2013 [20, 34]. Thus "pioneering" will continue to be a bibliometric hypothesis and a biological uncertainty. Some of the candidates that have the greatest potential to fill particular niches may in fact contain no valid data because previous discoveries in the field produced no positive results or because of lack of published results in the past. Ultimately, therefore, to view specific candidates on this list as being the definitive and conclusive solution should be seen as premature. These comprise a "high risk/high reward" opportunity for exploration of unorthodox plant diversity, but they remain hypothetical until confirmed experimentally under a controlled environment.

In summary, this review suggests that the future of wastewater treatment worldwide will not be through further studies on a select range of the existing species typically used for wastewater treatment, but instead by testing the range of new potential species that have been identified through our work, to see if they provide valid solutions to many of the contamination challenges being faced in different parts of the world, such as heavy metals and high salinity levels. The classification of species as "Pioneers" provides a strategic direction for diversifying the use of plants for wastewater remediation in many regions. The immediate direction of the research will be to transfer from gathering and compiling data to evaluating the selected candidate pioneer plant species through laboratory experiments. Such experiments will provide the means to determine whether the bibliometric novelty posted by the individual candidate species has resulted in improved remediation efficiencies. The confirmation of the hypothetical potential of these pioneer plants will provide resiliency in the form of additional biological tools for water management in a continuously changing global community, and in a sustainable manner.

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