Universidade Federal do Rio Grande - FURG
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Análise Cientométrica da Fitorremediação de Ambientes de Água Doce Utilizando Macrófitas Aquáticas

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Orientador: Prof. Dr. Juliano Zanette
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ATA DE DEFESA DE DISSERTAÇÃO DE MESTRADO EM BIOLOGIA DE AMBIENTESAQUÁTICOS CONTINENTAIS – Nº 009/2022

Às 09h00 (nove horas) do dia 22 (vinte e dois) do mês de dezembro de 2022 (dois mil e vinte e dois), no Auditório do C3, Campus Carreiros da FURG, reuniram-se docentes, discentes e comunidade em geral, para a Defesa Pública da Dissertação de Mestrado do acadêmico Saimon Branco Bueno. A Dissertação intitulada "**Análise Cientométrica da Fitorremediação de Ambientes de Água Doce Através de Macrófitas Aquáticas**" foi avaliada pela Banca Examinadora composta pelo Profº. Dr. Juliano Zanette (Orientador ePresidente da Banca); Profª Dra. Fabiana Schneck (FURG); Profº Dr. César Serra Bonifácio Costa (FURG) e Profº Dr. Igor Dias Medeiros (UNIFESP). Após a defesa e arguição pública, a Banca Examinadora reuniu-se, para deliberação final, e considerou o acadêmico **APROVADO**. Desta forma, o acadêmico concluiu mais uma das etapas necessárias para a obtenção do grau de **MESTRE EM BIOLOGIA DE AMBIENTES AQUÁTICOS CONTINENTAIS**. Nada mais havendo a tratar, às 12h00h (doze horas) foi lavrada a presente ata, que lida e aprovada, foi assinada pelos membros da Banca Examinadora, pelo Acadêmico e pelo Coordenador do Curso.

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RESUMO

A fitorremediação pode ser definida como o uso de plantas para a remoção de contaminantes do ambiente. Neste sentido, as macrófitas aquáticas são muito utilizadas. Estas plantas formam um grupo diversificado que apresenta grande variabilidade morfológica e está presentes em todos os habitats aquáticos. A cientometria é o estudo quantitativo da ciência, da comunicação na ciência e das políticas científicas preocupando-se principalmente com a dinâmica científica, analisando a produção, o consumo e a circulação da produção científica. A presente dissertação realizou um estudo cientométrico acerca da fitorremediação de ambientes de água doce através de macrófitas aquáticas, em um intervalo de tempo de 1990 até 2021, com o objetivo de responder as seguintes questões: i) O número de artigos acerca da fitorremediação de ambientes de água doce utilizando macrófitas aumentou ao longo do tempo? ii) Quais os países que mais publicaram acerca deste tema e quais características das colaborações entre eles? iii) Quais jornais que mais publicam sobre este tema? iv) Quais as tendências mais predominantes neste assunto? v) Quais são as macrófitas mais estudadas? vi) Quais os contaminantes mais testados? Utilizamos o *software R*, com o auxílio do pacote *bibliometrix* e o *software VOSviewer*. As análises mostraram um crescimento no número de publicações neste tema ao longo do tempo (R = 0,88). China, EUA, Índia e Brasil, foram os países que mais publicaram, onde a China, os EUA e a Índia foram os que mais realizaram colaborações internacionais. Brasil, Egipto e Arábia Saudita apresentam um grande potencial emergente sobre este tema, uma vez que mais de 60%, 64% e 87% das suas publicações ocorreram nos últimos três anos. O periódico "*International Journal of Phytoremediation*" foi o que mais publicou artigos neste intervalo de tempo. Analisando os artigos mais citados percebe-se uma predominância no estudo de metais pesados. As palavras-chave dos autores com maior ocorrência, "*heavy metals*" e "*eichhornia crassipes*" (denominada atualmente *Pontederia crassipes*) indicam uma dominância de estudos envolvendo metais pesados e essa macrófita. A maioria das plantas utilizadas foram dos ecótipos flutuante e emergente. O aguapé *P. crassipes* foi a macrófita mais utilizada, seguida da alface d'água *Pistia stratiotes*, da lentilha d'água *Lemna minor*, *"common reed*" *Phragmites australis*, e "*common cattail*" *Typha latifolia*. Os contaminantes inorgânicos foram mais avaliados do que os orgânicos, sendo representados principalmente por metais (especialmente chumbo, cobre, cádmio e zinco), seguido de nutrientes (especialmente nitrogênio e fósforo). Dentre os orgânicos, os mais testados foram os persistentes (POPs), representados principalmente por pesticidas. Os resultados apresentados podem ajudar pesquisadores e agências de fomento a se integrarem rapidamente acerca deste assunto, orientando o desenvolvimento de novos projetos e políticas ambientais.

Palavras-chave: Remediação, *Web of Science*, plantas aquáticas, ecossistemas aquáticos, poluição.

ABSTRACT

Phytoremediation can be defined as the use of plants to remove contaminants from environment. In this regard, aquatic macrophytes are widely used. These plants form a diverse group that presents a great morphological variability and are presents in all aquatic habitats. Scientometrics is the quantitative study of science, communication in science and science policy, being manly concerned with the scientific dynamic, analyzing the production, consumption and circulation of the scientific production. The present dissertation carried out a scientometric study on the phytoremediation of freshwater environments using aquatic macrophytes, in a time interval from 1990 to 2021, aiming to answer the followings questions: i) Has the number of articles about the phytoremediation of freshwater environments using macrophytes increased over the years? ii) Which countries published more in this topic and what are the collaboration characteristics between them? iii) Which journals more published about this subject? iv) What are the predominant trends in this theme? v) What are the most studied macrophytes? vi) What are the most tested contaminants? We used the R software with the support of bibliometrix package, the VOSviewer software. The analysis shows a growth in the number of publications on this topic over the years (R = 0.88). China, EUA, India and Brazil were the countries that more published, where China, EUA and India were the most active international collaborators. Brazil, Egypt and Saudi Arabia present a great emergent potential on this topic, once more than 60%, 64% and 87% of their publications occurred in the last three years. The journal International Journal of Phytoremediation was the one that most published articles in this time period. Analyzing the most cited articles one can notice a predominance in the study of heavy metals. The author's keywords with the highest occurrence, "heavy metals" and "*eichhornia crassipes*" (currently called *Pontederia crassipes*) indicate a dominance of studies involving heavy metals and this macrophyte. Most of the plants used were the life form floating and emergent. Water hyacinth *P. crassipes* were the most used macrophyte, followed by the Water lettuce *Pistia stratiotes*, Duckweed *Lemna minor*, Common reed *Phragmites australis*, and Common cattail *Typha latifolia*. Inorganic contaminants were most tested than organic contaminants, being represented mainly by metals (especially lead, copper, cadmium and zinc), follow by nutrients (especially nitrogen and phosphorus). Among the organics, the most evaluated were the persistent organic pollutants (POPs), represented mainly by pesticides. The results presented can help researchers and funding agencies to quickly integrate on this subject, guiding the development of new projects and environmental policies.

Keywords: Remediation, Web of Science, aquatic plants, aquatic ecosystems, pollution.

APRESENTAÇÃO

Essa dissertação está dividida em três segmentos. O primeiro refere-se à introdução geral do tema proposto e as referências utilizadas, seguindo as normas da ABNT. O segundo segmento é representado pelo artigo científico que trata de um estudo cientométrico acerca da fitorremediação de ambientes de água doce através de macrófitas aquáticas a ser submetido para a revista "*Environmental Science and Pollution Research*". O terceiro segmento contém as considerações finais do trabalho.

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INTRODUÇÃO GERAL

A tecnologia da fitorremediação e suas aplicações

A fitorremediação é um método de descontaminação do ambiente que utiliza plantas e seus microrganismos associados. Esta ferramenta utiliza de processos que ocorrem naturalmente, em que a planta e os microrganismos absorvem os contaminantes orgânicos e inorgânicos (Pilon-Smits, 2005). Contaminantes orgânicos são liberados no ambiente através de derramamentos de compostos (ex.: combustíveis fósseis e solventes), atividades militares (ex.: TNT e armas químicas), agricultura (ex.: herbicidas e pesticidas) e indústria química, enquanto os contaminantes inorgânicos chegam ao ambiente através de atividades antropogênicas como mineração, agricultura, indústria e também podem ocorrer naturalmente no ambiente (Pilon-Smits, 2005).

Esta tecnologia pode proporcionar a descontaminação do ambiente de diversos processos. Através da fitoestabilização as plantas "prendem" o contaminante na rizosfera através de produtos excretados pela raiz e os microrganismos associados, imobilizando o contaminante na zona da rizosfera (Lebrun *et al*., 2017). Plantas também podem estimular a biodegradação dos contaminantes pelos micróbios associados às suas raízes, esta ação é chamada de fitoestimulação ou rizodegradação (Pilon-Smits, 2005). No processo de fitovolatização o contaminante é absorvido e transformado pela planta e liberado na atmosfera sob forma gasosa e menos nociva (Pilon-Smits, 2005). Na fitoextração as plantas absorvem os contaminantes e os translocam para suas partes aéreas (sequestrando-os em seus vacúolos ou os incorporando a outras estruturas), permitindo que a biomassa aérea favoreça a remoção efetiva do contaminante do ambiente. Entretanto este processo requer a coleta e a manipulação adequada da planta contaminada após o processo de remediação (Lebrun *et al*., 2017). Fitodegradação é o mecanismo de transformação do contaminante absorvido pela planta através de processos metabólicos intracelulares (Zazouli *et al*., 2014) onde enzimas atuam sobre o contaminante o transformando por completo, parcialmente (formando resíduos ligados) ou o mineralizando em compostos inorgânicos (ex.: H_2O, CO_2) (Figura 1).

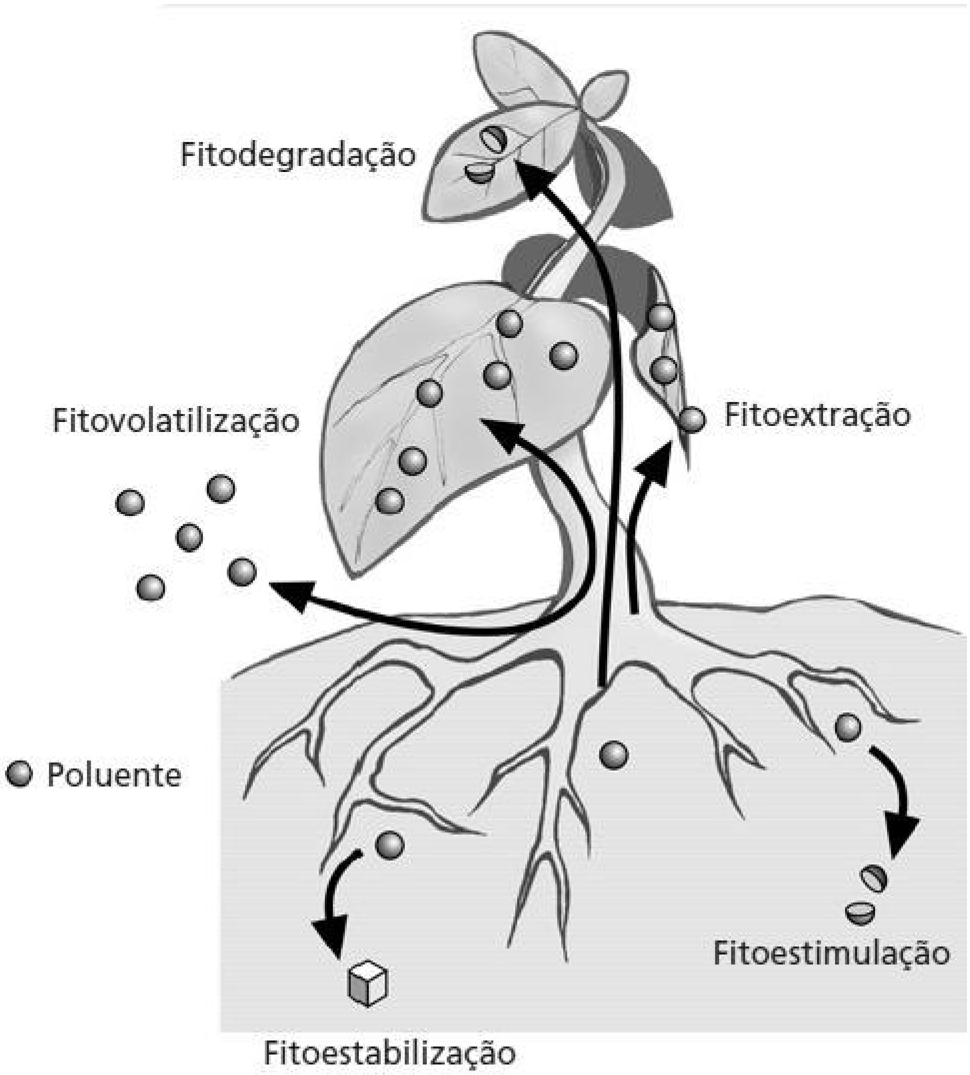

Figura 1: Diferentes processos da fitorremediação. Círculos indicam os poluentes, os círculos quebrados mostram os poluentes após o processo de degradação ou transformação, enquanto os quadrados referem-se aos poluentes estabilizados.

A fitorremediação pode atuar em diversos sítios e pode ser utilizada em substratos sólidos, aquosos e gasosos. O uso de plantas para remediar solos contaminados é visto como uma grande promessa, pois esta tecnologia é mais prática, e mais econômica em relação a outros métodos utilizados, como por exemplo, a lavagem, substituição e solidificação dos solos contaminados (Chaney *et al*., 1997). Outra vantagem é o tratamento do contaminante "*in situ*" (O'Neil e Nzengung, 2004). Para a remediação de ambientes aquáticos contaminados as macrófitas são utilizadas, pois possuem uma grande capacidade de absorver uma série de contaminantes orgânicos e inorgânicos, além de oferecerem inúmeros benefícios como, simplicidade, custo-benefício, e conseguirem remediar grandes áreas contaminadas (Ansari *et al*., 2020; Nguyen *et al*., 2021). As plantas também podem ser utilizadas como filtros aéreos para remediar os contaminantes na atmosfera através das suas folhas e partes aéreas, como o monóxido de carbono (CO), ozônio (O_3), óxidos de nitrogênio (Nox), óxidos de enxofre (Sox), hidrocarbonetos (HC) e a matéria particulada em suspensão (Singh e Verma, 2007; Lee *et al*., 2020). A fitorremediação tem ganhado popularidade graças a seu baixo custo-benefício e pouco impacto na à natureza, se comparada a técnicas baseadas em engenharia (ex.: escavação, lavagem e queima do solo, e bombas de tratamento) (Pilon-Smits, 2005).

Macrófitas como agentes remediadores dos ambientes de água doce

As plantas aquáticas constituem um grupo particularmente diversificado de organismos que apresentam uma grande variação morfológica, e que se adaptam a diferentes habitats aquáticos (Pivari *et al*., 2019). Este grupo de organismos incluem as macroalgas das divisões das clorófitas (algas verdes), xantofíceas (algas verde-amarelas), rodófitas (algas vermelhas) e as cianobactérias (atualmente conhecidas como algas verde-azuladas), briófitas (musgos e hepáticas), pteridófitas (samambaias) e espermatófitas (plantas com sementes) (Chambers *et al*., 2008). Este termo "plantas aquáticas" é menos restritivo às espécies vegetais atribuídas às zonas úmidas, englobando assim as helófitas, limnófitas, plantas aquáticas herbáceas, hidrófitas e plantas palustres, no entanto o termo "macrófitas aquáticas" tem se tornado mais utilizado no Brasil e em relatórios limnológicos para espécies tipicamente aquáticas (Pivari *et al*., 2019). Estes organismos variam muito em seu tamanho, por exemplo a *Victoria amazonica* possui folhas com um diâmetro de 2,5 m, enquanto o gênero *Wollfia* spp. possui uma folhagem com diâmetro de apenas 0,5 mm sendo assim a menor angiosperma do mundo (Chambers *et al*., 2008).

As macrófitas aquáticas estão presentes em todos os tipos de ambientes aquáticos, mesmo que em baixa riqueza ou biomassa, desempenhando um papel importante para o metabolismo do ecossistema, para a ciclagem de nutrientes e para o fluxo de energia (Matos *et al*., 2020). Elas também excutam um importante papel ecológico nos habitats em que estão presentes, servindo como habitat para diversas espécies de organismos invertebrados e também vertebrados. Junto das microalgas as macrófitas aquáticas, atuam como produtoras primárias, além de participarem da estocagem de nutrientes, formação de detritos orgânicos e também desempenharem um papel fundamental no controle da poluição e da eutrofização (Martello *et al*., 2008; Cervi *et al*., 2009). Baseando-se apenas no contexto ecológico, de forma independente aos aspectos taxonômicos as plantas aquáticas podem ser classificadas quanto a sua forma de vida. As macrófitas podem ser classificadas em: emergentes, submersas e flutuantes livres (Chambers *et al*., 2008; Padial *et al*., 2008). As emergentes são aquelas enraizadas no solo submerso ou periodicamente submerso, em que suas partes aéreas se estendem até a superfície. Macrófitas submersas são aquelas que se encontram enraizadas ou livres completamente submersas na água. As flutuantes livres são aquelas em que as partes aéreas se encontram na superfície da água sem estar enraizada no sedimento (Chambers *et al*., 2008; Padial *et al*., 2008).

Cientometria da fitorremediação por macrófitas aquáticas

Conforme a produção científica cresce torna-se necessário reunir informações sobre o desenvolvimento da ciência (Santos e Kobashi, 2009). Aqueles que buscam e necessitam reunir dados científicos acabam, por vezes, enfrentando desafios para localizar os itens mais importantes de seus interesses. Os desafios tornam-se maiores na sociedade atual, pois os métodos de trabalho, a ampliação de formas de armazenamento e circulação dos textos estão em constante progressão (Santos e Kobashi, 2009). Desta forma era inevitável o surgimento de uma medida para os diferentes campos da ciência, assim surgiu a bibliometria ou cientometria, definidas segundo Silva *et al*. (2001) como a mensuração do progresso científico e tecnológico, sendo uma técnica que consiste em uma avaliação quantitativa e uma análise das inter-comparações da atividade, produtividade e progresso científico.

Há certa confusão entre os principais termos métricos, bibliometria, cientometria e infometria (Hood e Wilson, 2001). Segundo Santos e Kobashi (2009) a bibliometria tem os livros e revistas científicas como objetos de estudo e seus objetivos estão vinculados a gestão de bibliotecas e bases de dados, já cientometria investiga o desenvolvimento da ciência analisando o produto, a circulação e o consumo da produção científica, enquanto que a infometria engloba as duas primeiras e analisa as características intelectuais da ciência, dando sentido aos dados obtidos. Isso se traduz em diferentes métodos de pesquisa. Segundo Darko *et al*. (2019) a análise bibliométrica tem como foco principal a literatura em si, enquanto a análise cientométrica possui uma abordagem mais ampla que oferece ferramentas e dados bibliométricos que permitem reconhecer padrões e tendências potenciais de determinado campo de estudo.

A cientometria utiliza métodos estatísticos para analisar e identificar padrões, irregularidades e tendências que podem existir nas publicações de determinado campo da produção científica (Barbosa *et al*., 2012). No campo da fitorremediação dois estudos que realizaram uma análise cienciométrica foram encontrados, o trabalho de Zhang *et al*. (2020) focou nas tendências emergentes da fitorremediação e descobriram um crescimento contínuo deste tema nos últimos ano e colocou os EUA, a França, a Alemanha, a Polônia e a Austrália como os principais "hotspots" deste tópico, enquanto o trabalho de Li *et al*. (2019) observou um grande desenvolvimento na fitorremediação de metais pesados e também uma interdisciplinaridade intensa neste tema.

Contudo nenhum dos trabalhos realizados focaram unicamente na fitorremediação de ambientes de água doce, ou unicamente no uso de macrófitas como agentes remediadores. Com isso conduzimos um estudo cienciométrico focado na fitorremediação de ambientes de água doce através de macrófitas aquáticas. Analisamos artigos publicados na base de dados Science Citation Index Expanded (SCI-EXPANDED) – Clarivate Analytics Web of Science (WoS) em um intervalo de tempo de 1990 a 2021. Buscamos responder as seguintes perguntas: i) O número de artigos acerca da fitorremediação de ambientes de água doce utilizando macrófitas aumentou? ii) Quais os países que mais publicaram acerca deste tema e qual o nível de colaborações entre eles? iii) Quais jornais que mais publicam sobre este tema? iv) Quais as tendencias mais predominantes neste assunto? v) Quais são as macrófitas mais estudadas e a que grupo pertencem? vi) Quais os contaminantes mais testados?

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ARTIGO CIENTÍFICO

Análise cientométrica da fitorremediação de ambientes de água doce utilizando macrófitas aquáticas

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Scientometric analysis of phytoremediation of freshwater environments using aquatic macrophytes

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ABSTRACT

Phytoremediation is a technology that uses plants to decontaminate the environment. In freshwater, aquatic macrophytes are used to remediation. This study adopts the scientometric method to assess the current state and prominent trends of phytoremediation of freshwater environments through macrophytes based on bibliographic records retrieved in the Science Citation Index Expanded (SCI-EXPANDED) - Clarivate Analytics Web of Science (WoS). The analysis shows a growth in the number of publications on this topic over the years (R = 0.986) and specially in China, USA, India and Brazil. Countries like Brazil, Egypt and Saudi Arabia demonstrate a great emergent potential on this topic. The majority of papers were published in high impact journals, which demonstrate the relevance of this field. Of 928 articles that we found, 48.8% used free-floating macrophytes as remediator agent, followed by emergent and submersed macrophytes. The water hyacinth *Pontederia crassipes* (Previously known as *Eichhornia crassipes*) was the most studied macrophyte for phytoremediation, followed by the water lettuce *Pistia stratiotes*, duckweed *Lemna minor*, common reed *Phragmites australis* and common cattail *Typha latifolia*. The majority of studies utilized inorganic contaminants, with the heavy metals having a great prominence in this research being tested in 75.2% articles, follow by nutrients (especially nitrogen and phosphorus). The metals that were more tested were lead, copper, cadmium and zinc. Among the organics, the most tested were the persistent organic pollutants (POPs), represented mainly by pesticides. The results presented can help researchers and funding agencies to quickly integrate on this subject, guiding the development of new projects and environmental policies.

Keywords: Remediation, Web of Science, aquatic plants, aquatic ecosystems, pollution.

1. Introduction

Phytoremediation is an environmental decontamination method that uses plants and their associated microorganisms. This tool uses naturally occurring processes where the plant and microorganisms absorb organic and inorganic contaminants (Pilon-Smits 2005). This technology can provide decontamination of the environment in several ways. Through phytostabilization plants “trap” the contaminant in the rhizosphere through products excreted by the root and associated microorganisms, immobilizing the contaminant in the rhizosphere zone (Lebrun et al. 2017). Plants can also stimulate the biodegradation of contaminants by microbes associated with their roots, this action is called phytostimulation or rhizodegradation (Pilon-Smits 2005). In the phytovolatilization process the contaminant is absorbed and transformed by the plant and released into the atmosphere in a gaseous and less harmful form (Pilon-Smits 2005). In phytoextraction the plants absorb the contaminants and translocate them to their aerial parts sequestering them in their biomass, however this process requires proper collection and handling of the contaminated plant after the remediation process (Lebrun et al. 2017). Phytodegradation is the mechanism of transformation of the contaminant taken up by the plant through intracellular metabolic processes where enzymes act on the contaminant transforming it completely, partially (forming bound residues) or mineralizing it into inorganic compounds (e.g., H_2O, CO_2) (Pilon-Smits 2005; Zazouli et al. 2014).

Developed in 1990s phytoremediation uses hyperaccumulator and accumulator plants to take up a large quantity of contaminants (Wang et al. 2012). It can be applied on a variety of sites being able to be used on solid, gaseous and aqueous substrates. Phytoremediation of contaminated waters is an eco-friendly technology based on macrophytes, where these plants are used as they have a great capacity to absorb a range of organic and inorganic contaminants, as well as offering numerous benefits such as, simplicity, cost-effectiveness, and being able to remediate large contaminated areas (Ansari et al. 2020; Nguyen et al. 2021). Different phytotechnologies make use of different properties of plants, and different plant species are used for each phytotechnology (Pilon-Smits 2005). Some of favorable plant properties to phytoremediation should be (i) fast growing, (ii) accumulate high contents of contaminants, (iii) high metal tolerance, (iv) resistance to disease, pests and etc, (v) possess a dense root and shoot system and (vi) unattractive to animals to avoid the transference to high levels in food chain (Wang et al. 2012; Sharma et al. 2014). In addition, high biomass, competitive, resistant, and tolerant to pollution are favorable properties to plants being chosen for phytoremediation (Pilon-Smits 2005).

The term "aquatic macrophytes" refers to a diverse group of photosynthesizing organisms, large enough to be seen with the naked eye, whose aerial parts are either floating on the water surface, permanently or periodically submerged (Cook 1996). This group of organisms includes the macroalgae divisions of chlorophytes (green algae), xanthophytes (yellow-green algae), rhodophytes (red algae), and the cyanobacteria (now known as blue-green algae), bryophytes (mosses and liverworts), pteridophytes (ferns), and spermatophytes (seed plants) (Chambers et al. 2008). These organisms vary greatly in size, for example *Victoria amazonica* has leaves with a diameter of 2.5 m, while the genus *Wollfia* Horkel ex Schleid. has a foliage diameter of only 0.5 mm and is thus the smallest angiosperm in the world (Chambers et al. 2008). Based only on the ecological context, independently of taxonomic aspects, macrophytes can be classified according to their biotype of occurrence. According to Chambers et al. (2008) aquatic macrophytes can be classified into emergent, submerged, and free-floating. The emergent are those that are rooted in the submerged soil or periodically submerged soils and their aerial parts extend to the aerial surface. They can also be floating-leaved where the macrophytes are rooted in the submerged soil while the leaves float on the water surface. Submerged plants are those that are rooted or free but completely submerged in water. The free-floating plants are those in which the aerial parts are on the water surface without being rooted in the substrate.

Scientometrics analysis is the quantitative study of communication and policy in science. It is the most common method to analyze the research development, allowing identifying the knowledge structure and tracking prominent research frontiers through mathematical models (Lin et al. 2019). As scientific production grows it becomes necessary to gather information about the development of science. Those who seek and need to gather scientific data sometimes face enormous challenges to locate the most important and relevant items. The challenges become greater in today's society, because the methods of work, the expansion of forms of storage and circulation of texts (Santos and Kobashi 2009). Scientometrics uses statistical methods to analyze and identify patterns, irregularities and trends that may exist in publications in a given field of scientific production (Barbosa et al. 2012). For instance, in the field of phytoremediation, Zhang et al. (2020) analyzed the current state and explored the trends of researches, while Li et al. (2019) investigated the main trends related to studies of the phytoremediation of heavy metals. These studies confirmed a widespread interest in phytoremediation, especially in recent years. In addition, phytoremediation is typical interdisciplinary research and involves numerous subject categories.

However, to our knowledge, no scientometric study focused on phytoremediation of freshwater environments, or solely on the use of macrophytes as remediation agents. We therefore conducted a scientometric study focused on phytoremediation of freshwater environments using aquatic macrophytes. We analyzed articles published in the Science Citation Index Expanded (SCI-EXPANDED) database - Clarivate Analytics Web of Science (WoS) in a time interval from 1990 to 2021. We sought to answer the following questions: i) Has the number of articles on phytoremediation of freshwater environments using macrophytes increased? ii) Which countries have published the most on this subject and what is the level of the collaborations between them? iii) Which journals publish the most on this subject? iv) Which macrophytes are the most studied and to which group do they belong? v) What are the contaminants most tested?

2. Methodology

2.1. Data collection

We conducted the search for publications on phytoremediation of freshwater environments through aquatic macrophytes using the Science Citation Index Expanded (SCI-EXPANDED) - Clarivate Analytics Web of Science (WoS) database in March of 2022. The WoS is one of the most reliable databases used in scientific research to search publications of high quality, containing multidisciplinary information from more than 18,000 scientific journals with high impact (Liu 2019; Liu 2020). In our workflow (Figure 1) we searched publications that contained in the title, abstract or keywords the following combination of terms: (phytoremediation) and (macrophyte* or "aquatic plant*" or "aquatic weed*"), using as filters: (i) only articles in English and (ii) the time span between 1990 to 2021; we selected this time interval because according to Zhang et al. (2020) the results using the term “phytoremediation” begun on 1993.
Initially, our search resulted in a total of 1062 articles. Later, we checked the articles manually to exclude those not focus on phytoremediation of freshwater environments and neither utilized aquatic macrophytes in study, resulting in a total of 928 articles to our scientometric analysis. In each selected article we extract the following information: (i) publication year, (ii) scientific journal where the study was published, (iii) autor(s) nationality, (iv) number of citations, (v) authors keywords, (vi) aquatic macrophyte tested, and (vii) contaminant studied.

2.2. Scientometric analysis methods

For the scientometric analysis we download the articles in BibTex, TXT and XLSX format, and analyzed on R software (R foundation 2022) with the support of bibliometrix package (Aria and Cuccurullo 2017), and the VOSviewer software 1.6.18 (Van Eck and Waltman, 2022). We use a nonlinear regression of exponential model to identify trends in the number of articles per year on the topic of phytoremediation of freshwater environments.

We determine the collaboration between the countries through the country of author and country of coauthor, where articles with single country (single country publication) had authors and coauthors from the same country, and articles with multiple countries (multiple country publication) had researchers addressed in different countries (Li et al. 2009). To further analyze the role of countries in the development of phytoremediation with aquatic macrophytes, we create a map of collaboration between the countries with the software VOSviewer on the co-authorship of the articles, we analyzed the links between the countries, the links (lines connecting countries) represents the number of co-authorships any country has, and the link strength (thickness of lines) represents the number of collaborations between the countries. We obtain the impact factor (IF) and h-index of the major journals from the Journal Citation Report 2021 (JCR). Also, we defined the ten global most cited documents in phytoremediation of freshwater environments through the number of total citation (TC) and the total citation per year (TC per year).

Keywords are vital content of articles playing a critical role in revealing the development of research subjects (Lin et al. 2019). According to Su and Le (2010) "keywords represent the core of paper", thus a keywords co-occurrences network was produced using the VOSviewer software. We used the fractional counting methodology and a total of 1945 keywords were extracted from the dataset, as a threshold a keyword should have 20 occurrences to appear in the network. Keywords used to make the research (e.g., phytoremediation, macrophytes, macrophyte, aquatic plants, aquatic plant) that would undoubtedly be the most frequent keywords, were deleted from the analysis (Zhang et al. 2016; Barbosa and Lanari, 2022) and the synonymous keywords were added together, so that the same keywords with the same meaning would not appear more than once time in the network.

In spreadsheets, we organize the macrophytes according to their species and biotype, every each macrophyte was counted just in studies that really used the macrophyte. If a study used more than one species, we counted every species tested in this study. We use the same workflow to organize the contaminants tested.

3. Results and Discussion

3.1. Characteristics of publication

A total of 928 articles focused on phytoremediation of freshwater environments that utilized aquatic macrophytes were published between 1997 to 2021 on Science Citation Index Expanded (SCI-

EXPANDED) - Clarivate Analytics Web of Science (WoS) database. The first study that was found (e.g, Hughes et al., 1997) focused in the ability of submerged macrophytes *Myriophyllum spicatum* and *Myriophyllum aquaticum* to uptake and transform 2,4,6- trinitrotoluene (TNT). From this first study, the number of articles has exponential increased in the last decades (Figure 2), indicating a positive correlation between the years and the number of articles published per year concerning the subject phytoremediation (R squared: 0.986). In the 1990s decade only 11 studies were published, whereas in the 2000s decade the number of articles published has increased to 121 articles in the same time span, and then, increased again to 588 articles published from 2010 to 2019. The present decade has just begun, but 206 articles have already been published in only two years. That represent more than the number that was published in the first two decades, demonstrating an exponential growth rate. The increase in the number of publications about this subject may be related with the continually and growing urbanization and industrialization of countries. These anthropogenic activities lead to a severe degradation of freshwater environments (Chen et al. 2021). The urbanization process creates great social, economic and environmental changes, which enable an opportunity for the development of sustainable technologies (Gu, 2019). The phytoremediation has gained popularity because of its low cost and its ability to clean up the environment (Pilon-Smith 2005). Our findings corroborate with other studies, that focused specifically on phytoremediation. For example, Zhang et al. (2020) showed an accelerated growth of papers about this field of research. Similarly, Li et al. (2019) carried out a scientometric study focused on the phytoremediation of heavy metals and also found a growing trend in the number or articles along the years.

3.2. Characteristics of countries most engaged

In the present study, researchers of 83 countries published articles about phytoremediation of freshwater environments, but just 39 meet the threshold of at least 5 publications (VOSviewer threshold suggestion). From the 928 articles, researchers of China are responsible for 20.2% of total publications, while India, United States of America (USA), Brazil and Argentina have 16.3%, 8.9%, 8.2% and 4.2%, respectively (calculated based on the data showed in Table 1). In comparison to other countries China possesses less than half of cultivable land and less than one quarter of crop water due to contamination (Prabakaran et al. 2019). Since 2012 the country has increased heavy metals emissions by 30 times. Besides heavy metals, organic contaminants like organochlorine pesticides (OCPs), polyaromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) and phthalate acids (PAEs) are also a threat to environment (Prabakaran et al. 2019). According Qian (2000) the rapid industrial development has deteriorated the surface water and groundwater in China since 1980. In agreement to Wang (2018) anthropogenic activities in China have increased the haze especially in regions that included Yangtze River Delta, the Pearl River Delta and the Sichuan Basin. That could be some reasons for China to be so engaged with the phytoremediation of freshwater environments research. In USA agriculture activities have become the main source of contamination of surface water (Jabbar and Grote 2019). This activity has severely altered the natural supply of sediments and organic matter in aquatic environments, which led to the eutrophication of aquatic systems. According with Carpenter et al. (1998) the cultural eutrophication increases the productivity of lakes beyond the original state, and Lakes Michigan, Huron, Erie and Ontario suffer with this problem. In addition, the Onondaga Lake located in state of New York has been polluted with salt brine effluent from a soda ash industry (Baron et al. 2002). In Florida (USA), a state located in subtropical latitudes and that has approximately 8,000 lakes, anthropogenic activities such as smelting, mining and fossil fuel combustion has produced a great pollution of lead (Pb) in lacustrine environment (Escobar et al. 2013). These facts explain, in part, why the USA has engaged with the phytoremediation of freshwater systems. In India the water pollution has reached a critical point; sources of pollution such as agricultural runoff, sewage discharged and industrial wastewater has contributed to contamination of the rivers (Dwivedi 2017). According to Dwivedi (2017) the scientists of the National Environmental Engineering Research Institute (NEERI) Nagpur, discovered that nearly 70% of water in India is polluted. Rivers Ganga, Mirzapur and Varanasi have physico-chemical characteristics of polluted rivers. Brazil has the largest hydrographic network in the whole world, and the aquatic ecosystems (fluvial, lacustrine, permanent or temporary lakes) are of great importance among the Brazilian ecosystems (Cervi et al. 2009; Matos et al. 2020). In 2008 the Iguaçu River, the largest river in the Paraná state, was considered the second river most polluted in Brazil, due the sewage disposal and a significant number of industrial effluents that reached this river (Freire et al. 2015). Patos and Mirim lagoon constitute the largest lagoon system in South America. Mirlean et al. (2003) have demonstrate that the freshwater sediments of these lagoon are polluted with arsenic (As) due the fertilizer industry activities and the estuarine sediments of Patos Lagoon is more contaminated than the freshwater sediments. Medeiros et al. (2012) conducted a study with biotic and abiotic parameters on the Doce River basin to evaluate the degree of pollution and found a great influx of domestic and industrial wastewater. One of the reasons for the large number of publications on phytoremediation of freshwater environments using macrophytes in Brazil is the evidence of wide spread of pollution (Mirlean et al. 2003; Medeiros et al. 2012; Freire et al. 2015). Another factor that may be associated with the high number of publications by these countries is their large populations, and the disponibility of quality freshwater (Kaur et al. 2012). Another reason could be the diseases caused by pollution of aquatic environments and contamination of drinking water (Dwivedi 2017). The phytoremediation seems to be everyday more popular and feasible technology in these countries for the treatment and improvement of water quality (Kumar and Kumar 2019).

3.3. Cooperation among countries

Many studies show that the international collaboration in science has increased rapidly in recent decades through scientific papers with co-authors from two or more nations (Wagner and Leydesdorff 2005; Leydesdorff and Wagner 2008; Leydesdorff et al. 2013). However, only 183 studies on macrophyte use in remediation were published by authors from different countries (MCP), which represent 20% of the total. This result shows the need to increase the international academic cooperation on phytoremediation of freshwater environments. We also note that Europe has the major countries that carried out international collaboration (Italy, Portugal, France and Germany) which can be explained by the proximity of these countries to each other, and the European policy for environmental conservation.

The map of collaborations showed in Figure 3 confirms the trend found in the Table 1 since the large circles were represented by China, USA, India and Brazil meaning that these are the most engaged countries in the theme phytoremediation of freshwater using macrophytes. These results agreed with Zhang et al. (2020) who shows that China, USA and India are major collaborators with the topic of phytoremediation. The lines connecting the circles shows that China, that have a total of 14 links is more related with USA, Pakistan and England, denoted by link strengths (VOS viewer index) of 18, 5, and 4 with these countries, respectively. USA have 10 links and is more related with China and India, by link strengths of 18 and 4, respectively. India, that have 17 links has strong relationship with Portugal, USA and South Korea, by link strengths of 7, 4 and 4 with, respectively. Brazil has one of the largest circles, but it had few international collaborations on this topic, four links, with Canada, Japan, Spain and Germany, denoted by link strengths of 2, 2, 1 and 1, respectively.

We also noted that the colors present in the map demonstrate that countries like Brazil, Egypt and Saudi Arabia are emergent countries in this subject, these countries demonstrate a great number of publications in the last three years, Brazil published a total of 68 articles, where 41 were published in the last three years, that is, more than 60% of the total of publications. Egypt in turn present more than 64% of their publications in the last three years, and Saudi Arabia demonstrate that more than 87% of their publications are in this time interval.

3.4. Journal analysis

Articles about phytoremediation of freshwater environments with macrophytes were published in 231 journals on the Science Citation Index Expanded (SCI-EXPANDED) - Clarivate Analytics Web of Science (WoS). The top twenty journals are responsible for 555 articles of 928 total, representing 59.8% of the publications (Table 2). The journal *International Journal of Phytoremediation* appears in the first place in the rank with 116 articles, followed by *Environmental Science and Pollution Research*, *Chemosphere* and *Ecotoxicology and Environmental Safety* with 66, 52 and 37 articles, respectively. This information agrees with Zhang et al. (2020) who shows that the journals are those with more published articles about the topic of phytoremediation. Besides that, the journal *Water Research* presents the highest impact factor followed by followed by the *Journal of Hazardous Materials* and *Bioresource Technology*. Whereas the journals *International Journal of Phytoremediation* and *Chemosphere* presents the highest *h*-index, followed by the *Ecological Engineering*. The IF and the *h*-index are the main tools used to evaluate the scientific quality of journals, in most cases journals with a high IF and *h*-index have a great quality and importance on its search field (Durieux and Genevois 2010). These results support previous findings that research on phytoremediation of freshwater ecosystems using macrophytes is relevant to the science; as show by other scientometric studies about phytoremediation (Li et al. 2019; Zhang et al. 2020).

3.5. Globally most cited document

The top 10 highly cited articles during the period ranging from 1990 to 2021 in phytoremediation of freshwater environments through macrophytes subject are presented in Table 3. The paper entitled "Accumulation of lead, zinc, copper and cadmium by 12 wetland plant species thriving in metal-contaminated sites in China" by Deng et al. (2004) was the most global cited article, with a total citation (TC) of 466, and a TC per year of 24.53, Followed by articles "Phytoremediation of trace elements by wetland plants: I. Duckweed" by Zayed et al. (1998) and "Lead and nickel removal using Microspora and *Lemna minor*" by Axtell et al. (2003), both second and third ranked articles, with 434 and 246 citation, respectively, and TC per year of 17.36 and 12.30.

In our rank, the research carried out by Hughes et al. (1997) is the only one that is focused on the capacity of two macrophytes to transform an organic contaminant (e.g. TNT) and all other articles are focused on the phytoremediation of heavy metals. Overall, a great number of articles that are focused in heavy metals, compared to other contaminants (Figure 4A, B), which makes articles that address this theme more sought, and consequently more cited. The articles of Deng et al. (2004) and Malar et al. (2014) are the articles with the greater number of TC per year, 24.53 and 21.89, respectively. It is worth to note that those two articles were made by authors from China and India, respectively. Another cause for this result may be the increasing number of articles focused on heavy metals, more specifically lead (Pb), listed in our scientometric analysis as one of the most studied heavy metals in phytoremediation articles (Figure 4C).

3.6. Co-occurrence keywords network

The keywords network provides a good picture of a knowledge domain, offering a way to see how these topics are intellectually connected and associated each other providing insights and new perspectives into the topics (Darko et al. 2019). The resultant keywords network of our research consisted of 31 nodes and 1580 links (Figure 5). Among the 21 keywords that appears in the network the most centralized keyword is "heavy metals", with 152 occurrences and 19 links, followed by "*Eicchornia crassipes*" and "bioaccumulation" with 65 occurrences and 15 links, and 55 occurrences and 15 links, respectively. Author keyword with higher network centrality is those are closely to the core of knowledge (Su and Le 2010). These results, show a clear dominance of studies that carried out analysis with heavy metals. Studies performed with the macrophytes *Ponderia crassipes* (previously called *Eichhornia crassipes*; Coetzee and Hill 2019) also dominated the keywords network. This species was also listed as the first in the ranking of macrophytes that are mainly used in studies about phytoremediation of freshwater environments (Table 4).

3.7. Macrophytes analysis

Of the 928 articles analyzed in this study, 453 contain floating species, being the most tested on studies of phytoremediation of freshwater environments. The emergent and submerged species were tested in 403 and 228 articles, respectively (Figure 6). In the aquatic environments and wetlands, free-floating, emergent and submerged species are main soil and water remediators (Dhir et al. 2009). The floating, emergent and submerged macrophytes have different phytoremediation capacities. According to Thampatti et al. (2020) the free-floating species have a higher bioconcentration factor and translocation ability of heavy metals compared to emergent and submerged species, besides that they have a capacity to reducing other important quality parameters of water such biochemical oxygen demand (BODs) and chemical oxygen demand (CODs) (Ansari et al. 2020). Moreover, floating species have some important characteristics for phytoremediation such as high primary productivity and easy post-culture process since they are not rooted on the sediment (Souza and Silva 2019).

Emerging species are so widely used on phytoremediation (Figure 6). According to Pilon-Smits (2005), emergent genera such as *Typha* spp. and *Spartina* spp. have some important characteristics to phytoremediation such as tolerance, fast growth and high biomass. In study with 34 emergent macrophytes carried out by Shück and Greger (2020) in Sweden they show that *Dryopteris carthusiana* presented a highest total biomass and shows that emergent species with a high metal removal capability generally had a high biomass. Besides that, emergent macrophytes are commonly utilized in treatment systems such as constructed wetlands (CWs). These treatment systems are predominantly used to remove BODs and CODs, stormwater treatment and a variation of wastewater (e.g., landfill leachate, mine drainage waters, agriculture runoff, food processing wastewater, wastewater from heavy industry and urban stormwater) (Vymazal 2005; Headley and Tanner 2012). Furthermore, CWs provides a larger and permanent contact between plant and the wastewater, possibility the application of larger plants with no requirement of removal so frequently allowing the plant to stay in contact with the contaminant for a longer time (Colares et al. 2020).

Submerged species are those macrophytes that grow completely below the water column, where the roots are attached to, or closely to the sediment (Chambers et al. 2008). According to Pilon-Smits (2005) the submerged genera *Myriophyllum* spp. and *Elodea* (= *Egeria*) spp. are good remediators of the herbicide atrazine, because they have high levels of organic-degrading enzymes, which corroborates with Qu et al. (2016) who showed that *Potamogeton crispus* and *Myriophyllum spicatum* enhanced the half-life of atrazine dissipation, decreasing the time of 14.30 days to 8.60 and 9.72 days, respectively. Compared to floating and emergent species, submerged macrophytes can take up metals, not only by their roots, but through their whole body too. Thus, it possesses significant potential to remove heavy metals, since they possess a greater contact surface (Li et al. 2018; Thampatti et al. 2020). These are important properties to phytoremediation (Pilon-Smits 2005). All these three biotypes of macrophytes are efficient on phytoremediation of freshwater environments and possess different properties that makes them good depending on the phytotechnology employed. Due to advantageous culture and pos-culture, floating species are most utilizes on phytoremediation works (Figure 6).

Within the 928 articles analyzed in this study, 528 macrophyte species were used. The twenty species most tested on phytoremediation of freshwater systems accounted for 46.05% of articles, being eight emergent species, six floating and the other six submerged species (Table 4).

Pontederia crassipes (*Eichhornia crassipes*) is the first in the ranking with 181 studies (19.5% of the total), followed by *Pistia stratiotes*, *Lemna minor*, *Phragmites australis* and *Typha latifolia* with 113 (12.1%), 102 (10.9%), 100 (10.7%) and 84 (9.05%) studies, respectively (Table 4). *P. crassipes* (*E. crassipes*) is popular known as “aguapé” or “water hyacinth” and it is a floating aquatic species native from the South America, originating in the Amazon basin and belongs to the Pontederiaceae family (Brundu et al. 2013; Coetzee and Hill 2019; Mnguni and Heshula 2022; Sierra-Carmona et al. 2022).

According to Pilon-Smits (2005), *P. crassipes* (*E. crassipes*) is a good remediator of inorganic contaminants, since this species is a good metal accumulator. This idea is corroborated by Odjegba and Fasidi (2007), which demonstrated that this plant is promising for remediation of natural water bodies and wastewaters containing zinc (Zn), chromium (Cr), cupper (Cu), cadmium (Cd), lead (Pb), argentum (Ag) and nickel (Ni). This plant is also effective in the remediation of nutrients like phosphorus and nitrogen (Jayaweera and Katsuriarachchi 2004), and organic contaminants (Mishra and Maiti 2017). Xia and Ma (2006) demonstrated *P. crassipes* is good for removal of pesticide ethion, since the plant showed efficiency to remove 69% of this contaminant. In another study, Xia (2008) showed that the *P. crassipes* (*E. crassipes*) has a great capacity to remove the pesticide dicofol. Moreover, the water hyacinth demonstrated a significant capacity to remove the contaminant naphthalene present on water bodies in a study conducted by Nesterenko-Malkvskaya et al. (2012). The water hyacinth shows fast growth rate, adaptability to a wide range of environmental conditions, and because it is a floating macrophyte, can be harvested easily. Facilitating its application in phytoremediation systems (Ting et al. 2018).

Pistia stratiotes is a free-floating macrophyte commonly known by "water lettuce" and belongs to the Araceae family (Souza and Silva 2019). This weed has a great widespread distribution been present in tropical and subtropical regions. *P. stratiotes* could cause adversely effects in the environment representing concerns worldwide, for example, because it can form dense mats capable of blocking navigation channels and disrupting hydropower generation (Galal et al. 2019). However, in many cases of tropical or subtropical areas, water lettuce is used for phytoremediation systems, Lu et al. (2010) has demonstrated the potential of this plant to remove nutrients like nitrogen and phosphorus besides improving water quality by decreasing of turbidity and suspended solids. Odjegba and Fasidi (2004) showed that *P. stratiotes* have the potential to accumulate trace elements (e.g., Ag, Cd, Cr, Cu, Hg, Ni, Pb, and Zn) particularly in their roots. In addition, *P. stratiotes* is used for phytoremediation of organic compounds. Gujarathi et al. (2005) showed that the plant has advantages over *Myriophyllum aquaticum* on the remediation of tetracyclines and oxytetracyclines due they longer and denser root systems. In another study conducted by Escoto et al. (2019) the water lettuce has the potential for phytoremediation of herbicide clomazone. Ekperusi et al. (2018) in their research demonstrates that plant *P. stratiotes* have a great potential to remediate agrochemicals, pharmaceuticals, radioactive wastes, nanoparticles and petroleum hydrocarbons from the environment.

Lemna minor, commonly known as "duckweed", is an aquatic macrophyte belonging to the free-floating plants family Araceae (include Lemnaceae) (Driever et al. 2005), This family often form dense mats in eutrophic ponds, being eventually anoxic for local macrofauna survive and submerged macrophytes due the light competition (Driever et al. 2005). In addition, *L. minor* is widely spread across the word being present in every continent, except Antarctica, and has been applied to remediation of a range of contaminants (Ekperusi et al. 2019). In a study carried out by Bokhari et al. (2016) *L. minor* showed the potential to remediate cadmium (Cd), copper (Cu), lead (Pb) and nickel (Ni), besides the sewage mixed industrial effluent (SMIE), demonstrating 99% of capacity to remove Ni from SMIE. Ceschin et al. (2020) has demonstrated the phytoremediation capacity of two Lemnaceae species, *L. minor* and *L. minuta*, where both plants were exposed to high nutrient concentrations, and *L. minor* proved to be a hyperaccumulator of phosphate, but not for nitrate, in this case *L. minuta* proved to be a better hyperaccumulator than *L. minor* because hyperaccumulate both nutrients. In another study Jayasri and Suthindhiran (2017) showed that duckweed has a high tolerance to metals Zn and Pb at 10 and 4 mg. L^{-1}, respectively, that makes *L. minor* useful for remediation of these metals in low concentrations. Zazouli et al. (2022) carried out a study with *L. minor* and demonstrated that the plants are effective in accumulation and degradation of phenanthrene and pyrene, two of the most common polycyclic aromatic hydrocarbons (PAHs). The plant also shows potential to remove the dyes methylene blue as show by Imron et al. (2019). *L. minor* presents the capacity to growth in a variety of climatic conditions in high rates, in addition duckweed is easily raised even in laboratory conditions, can be used as animal feed and human consumption (Singh et al., 2012), which may explain the high number of studies with this plant.

Phragmites australis is an emergent macrophyte belonging to the Poaceae family and is known as "common reed". This plant has a great spread being present in all continents, with a higher presence in North America and Europe (Rezania et al. 2019; Tropicos.org 2022). This macrophyte has abilities like resilient rhizomes, high propagation, strong adaptability and a great resistance to pollution (Rezania et al. 2019), which are good properties for phytoremediation according to Pilon-Smits (2005). Bello et al. (2018) carried out a study to evaluate the capacity of common reed to remove metals. The plants showed capacity to remove 93% of Cd, 95% of Pb and 84% of Ni. In another study Cicero-Fernández et al. (2016) demonstrate that common reed can be used as phytoremediator of estuarine sediments, removing heavy metals (e.g., Co, Ni, Mo, Cd, Pb, Cr, Cu, Fe, Mn, Zn and Hg) and trace elements (e.g., As, Se and Ba). *P. australis* has also shown capacity to remove nutrients like N, P, K, and Na from a lagoon where the nutrient concentration was higher in their shoots, except for Na (Bragato et al. 2006). The common reed also has the ability to remove organic contaminants, as shown by Chu et al. (2006) who demonstrated the capacity of this plant to remove two persistent organic pollutants (POPs), DDT and PCB. In addition, El Shahawy and Heikal (2018) used the dry biomass of the common reed as biosorbent to remove organic contaminants from oil wastewater, demonstrating that this plant can be used as a remediator of a range of organic and inorganic contaminants. However as common reed is an emergent macrophyte, the plant has to be harvest in a high time interval for achieve they maximum phytoremediation capacity.

Typha latifolia was used in 84 studies, is an emergent macrophyte belonging to Typhaceae family. This family is essential for wetland systems and is present in worldwide, except in Antarctica (Tropicos.org 2022; Widanagama et al. 2022). *Typha latifolia* is commonly known as “cattail” and is the most widespread Typhaceae species. *T. latifolia* has great properties for phytoremediation like rapid growth range, large size, tolerance to contaminants and attaining high biomass (Pilon-Smits 2005; Widanagama et al. 2022). Anning et al. (2012) has demonstrated in a study of phytoremediation of wastewater using *Limnocharis flava*, *Thalia geniculata* and *T. latifolia* the high potential for hyperaccumulating mercury (Hg) of *T. latifolia*. In another study Hejna et al. (2020) has shown the capacity to take up, accumulate and translocate two heavy metals (Zn and Cu) demonstrating the potential of cattail to be used in phytoremediation systems. Ahmad (2022) used *T. latifolia* to remediate petroleum second effluent (PSE) and the plant showed the capacity to phytoremediate heavy metals like Cd, Co and Mn, and total petroleum hydrocarbons (TPH). The cattail shows a good potential for phytoremediation systems and for a series of contaminants. In a comparative study between *Typha* species (*T. angustifolia*, *T. domingensis* and *T. latifolia*) where all three species were exposed to a range of heavy metals Al, As, Cd, Cr, Cu, Hg, Ni, Pb and Zn. The three species presented similar capacities of remediation (Bonanno and Cirelli, 2017) which suggests that the preference for *T. latifolia* in phytoremediation studies is not exclusively because of remediation capacity, but could be specially related with its higher distribution.

3.8. Most tested contaminants

Among the 928 articles that were analyzed, 712 articles evaluated inorganics contaminants alone, 178 articles studied only organics contaminants, 21 tested both contaminants and 17 articles did not make clear which type of contaminant were studied (Figure 4A). Most of the inorganic contaminants exist as a natural form in the environment, but also can arrive to the environment via anthropogenic activities like mining, agriculture, industry. Among the inorganic contaminants are the heavy metals, nutrients, industrial wastes and radionuclides (Pilon-Smits 2005; Madima et al. 2020). Between the organic contaminants, the most dangerous to the environment are the persistent organic pollutants (POPs). This group of organic compounds can remain in nature for a long time due their low solubility. POPs include (Figure 4E) the polycyclic aromatics hydrocarbons (PAHs) (e.g., phenanthrene, benzo pyrene, naphthalene), polychlorinated biphenyls (PCBs), pesticides, toluene, benzene, xylenes

(Akram et al. 2018). The organic contaminants can arrive to the environment through human activities like military activities, agriculture, industry, wood treatment and spills (Pilon-Smits, 2005).

Heavy metals were the most tested inorganic contaminant, followed by nutrients, radionuclides and inorganics salts, appearing in 537, 206, 15 and 15 articles, respectively (Figure 4B). The term "heavy metal" is frequently used to refer to the metals which have weights more than 5 g. cm^3, about 40 elements fall into this category (Sharma and Agrawal 2005). Heavy metals reach to the environment through anthropogenic activities, achieving freshwater, marine and groundwater systems (Necebi and Mzoughi 2017; Kurwadkar 2019), and unlike organic contaminants, heavy metals cannot be biodegraded and thus end up accumulating in the environment (Ali et al. 2013). Heavy metals are documented as the cause of many toxicity issues around the world, threatening the safety of more than 10 million people in many countries (Jadia and Fulekar 2009). Thus, remediation of heavy metal pollution deserves attention. About the 537 articles who tested heavy metals, Pb, Cu, Cd, and Zn were the most prominent, appearing in more than 200 articles each (Figure 4C), this could be related by their significant environmental toxicity and highly poisonous (Saha and Paul 2016; Muthusaravanan et al. 2018). Thus, constructed wetlands offers a cost-effective and feasible technology with an effective and successful remediation of heavy metals,

Modern society has used chemical fertilizers to improve agricultural production because of crops quick response (Lu et al. 2010). However, the increasing use of these chemicals has resulted in significant increase of nitrogen (N) and phosphorus (P) in the soil, which with the leaching and surface runoff these nutrients reach the aquatic environment (Lu et al. 2010). This over-enrichment of lakes, rivers, estuaries and coastal oceans leads to some of the greatest problems caused by humanity activity, the eutrophication (Carpenter et al. 1998). In our results, N and P appearing as the most prominent nutrients in the studies of phytoremediation of freshwater environments (Figure 4D), since that technology demonstrate the potential to improve water quality to eutrophic environments. Lu et al. (2008) demonstrate that phytoremediation decreased in more than 50% the concentration of N, and 14% to 31% the concentration of P. Besides Nash et al. (2019) demonstrate the capacity of plants *P. crassipes* (*E. crassipes*) to survive in rich nutrients effluents, in addition the plants were capable to remove 91.4% to 97.4% of N, and 80.4% to 97.2% of P, respectively, demonstrating the efficiency of phytoremediation technology in the nutrients remove.

Concerning organic contaminants among the 198 articles, 100 studies tested persistent organic pollutants (POPs), followed by pharmaceuticals, cyanotoxins, dyes and explosives, appearing in 36, 18, 16 and 9 articles (Figure 4F). POPs are defined as organics compounds that: (i) are persistent; (ii) possess toxic characteristics; (iii) are liable to accumulate; (iv) posse a long-range of atmospheric transport and deposition; and (v) can affect adversely the human and environmental health at locations near and far from their sources (Vallack et al. 1998). There are thousands of POPs chemicals and this group of contaminants have long half-lives in soil, sediments, air and\or biota, they are typically hydrophobic and lipophilic avoiding the aqueous phases in aquatic systems, which make them persistence in the environment (Jones and Voogt 1999). The total lake area in China accounts for 30% of the global total, according to Bao et al. (2012) who assess the states of POPs contamination in China, the contamination including POPs like organochlorine pesticides (OCPs), polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), perfluorooctane sulfonate (PFOS), polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDD/Fs) and perfluorooctanoate (PFOA), has affected the drinking water and water sources, indicating that POPs in China's water higher in comparison to the global range. Vasseghian et al. (2021) demonstrate in their research that the most to least polluted by POPs areas included South Africa, India, Turkey, Pakistan, Canada, Hong Kong and China, where China and Turkey present the higher carcinogenic risk due the pollution by β-Hexachlorocyclohexane (β-HCH). Besides that, POPs are considered silent killers due their bio-accumulative capacities and long-persistence in environment which can cause different diseases like: diabetes, obesity, endocrine disturbance, cancer, cardiovascular, reproductive and environmental problems (Alharbi et al. 2018), which creates the necessity of the development of technologies that can remediate this kind of contaminants like the phytoremediation. The aquatic systems are severely affected by hazardous organic contaminants including the POPs, in addition to these organic contaminants pharmaceuticals that included: anticoagulants, analgesics, antipyretics, anti-inflammatories, antimicrobials, hypertensive blockers, antibiotics, personal care products, endocrine-disruption compounds (EDCs), phycholeptics and adrinergic antagonists are also detected in aquatic environments and municipal wastes (Antoniadou et al. 2021). There is evidence that pharmaceuticals have negative effects on the health of the environment and humans, for example, selecting for antibiotic resistance bacteria, feminizing fish and increasing the susceptibility of fish to predation (Wilknison et al. 2022), which make that group possess global highlight.

In our research about the persistent organic pollutants (POPs) we found a great number of articles that studied pesticides, these kinds of POPs were tested in 65 articles, followed by the polycyclic aromatic hydrocarbons (PAHs) and the personal care products (PCPs) (Figure 4E). Pesticides are any substance or mixture of substances that are used to prevent, destroy, repel or mitigate any pest, that include insecticides, herbicides, fungicides and various other substances used to control pests (Zhang et al. 2011). It has been estimated that just 0.1% of the pesticides employed to crops really reaches to their target pests, all the rest enter the environment contaminating soil, water and air, where can affected nontarget organisms (Arias-Estéves et al. 2007), this may be one of the reasons why pesticides are so studied within the POPs, another reason could be related with the great attention that these contaminant have is the great number of areas around de world that presented a risk of pesticides pollution, about 64% of agricultural land (~ 24.5 million Km^2) present a risk of pesticides pollution and 31% present a high risk. Among the high-risk areas 34% are in high biodiversity regions and 5% are in water-scarce areas (Tang et al. 2021). Some countries like Argentina, South Africa, China, India and Australia are high concern regions because they have high pesticide pollution risk of their watersheds (Tang et al. 2021). Polycyclic aromatic hydrocarbons (PAHs) are by-products of incomplete combustion of organic materials and there are several ways for these contaminants to reach the environment including petroleum contamination, terrestrial runoff and fallout from air pollution (Cheung et al. 2007). Net et al. (2015) carried out a study about PAHs and found that Scarpe River located in France presented a high concentration of PAHs in their sediments. Besides Meng et al. (2019) shows high levels of PAH pollution in lake waters in China, with the naphthalene (Nap) being the most prominent, and a potential risk to human health and ecosystems.

4. Conclusion

The number of publications in phytoremediation has continuously increased since it first appearance in 1990s decade and we could expect that will continue to increase in the next few years. The research results show that China, India, USA and Brazil are the most engaged countries in this topic. We also find that the research on this topic present low international collaboration, demonstrating few exchanges between research groups of different countries. Brazil, Egypt and Saudi Arabia present a great emergent potential on this topic, once more than 60%, 64% and 87% of their publications occurred in the last three years, respectively. The papers have been published in high impact journals in the area of phytoremediation and environmental sciences, demonstrating the importance of phytoremediation of freshwater environments using macrophytes (PFEM).

Macrophytes with biotype free-floating were the most studied, followed by emergent and submerged macrophytes. The *Pontederia crassipes* (*Eichhornia crassipes*) was the species most tested. Inorganic contaminants were more prevalent than organic ones. The most prominent inorganic contaminant was the heavy metals, with a highlight to copper (Cu), lead (Pb), cadmium (Cd) and Zinc (Zn), which appear in more than 200 articles each. Among the organic compounds, the most tested was the persistent organic pollutants (POPs), where pesticides were the highlighted group. Based on that, we suggest that have more projects focused in the phytoremediation of organic contaminants, as well studies that seek to understand the mechanisms of degradation of organics contaminants. We also suggest searching for endemic and little studied species that may have great capacity for phytoremediation.

These findings could help to prioritize the future research efforts related to PFEM, serving as an aid to new researchers who are entering this field.

5. Declarations

5.1 Ethics approval.

Not applicable in this section.

5.2 Consent to participate

Not applicable in this section.

5.3 Consent for publication.

Not applicable in this section.

5.4 Availability of data and materials

The authors declare that (the/all other) data supporting the findings of this study are available within the article (and its supplementary information files).

5.5 Competing interests.

The authors declare that they have no competing interests

5.6 Funding.

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Figure captions

Figure 1: Framework of the methodology used in the research

Figure 2: Number of articles published on phytoremediation with macrophytes on the Science Citation Index Expanded (SCI-EXPANDED) - Clarivate Analytics Web of Science (WoS) between 1990 to 2021.

Figure 3: Map of international collaboration between countries on phytoremediation of freshwater environments with macrophytes articles from 1990 to 2021 on the Science Citation Index Expanded (SCI-EXPANDED) - Clarivate Analytics Web of Science (WoS). On the map the circles and their sizes indicate countries and their production. The lines and their thickness indicate the collaboration between countries, while the colors indicate the year, respectively.

Figure 4: Evaluation of number of articles with different groups of contaminants in phytoremediation using aquatic macrophytes. The quantification was made considering the classification in inorganic and organic (A), types of inorganic contaminants (B), types of heavy metals (C), types of nutrients (D), classes of persistent organic pollutants (POP) (E) and classes of organic contaminants.

Figure 5: Co-occurrence network of keywords in phytoremediation of freshwater environments through macrophytes based on authors keywords.

Figure 6: Number of articles that tested the biotypes floating, emergent, submerged in phytoremediation studies of freshwater environments from 1990 to 2021 on Science Citation Index Expanded (SCI-EXPANDED) – Clarivate Analytics Web of Science (WoS).

Figure 1

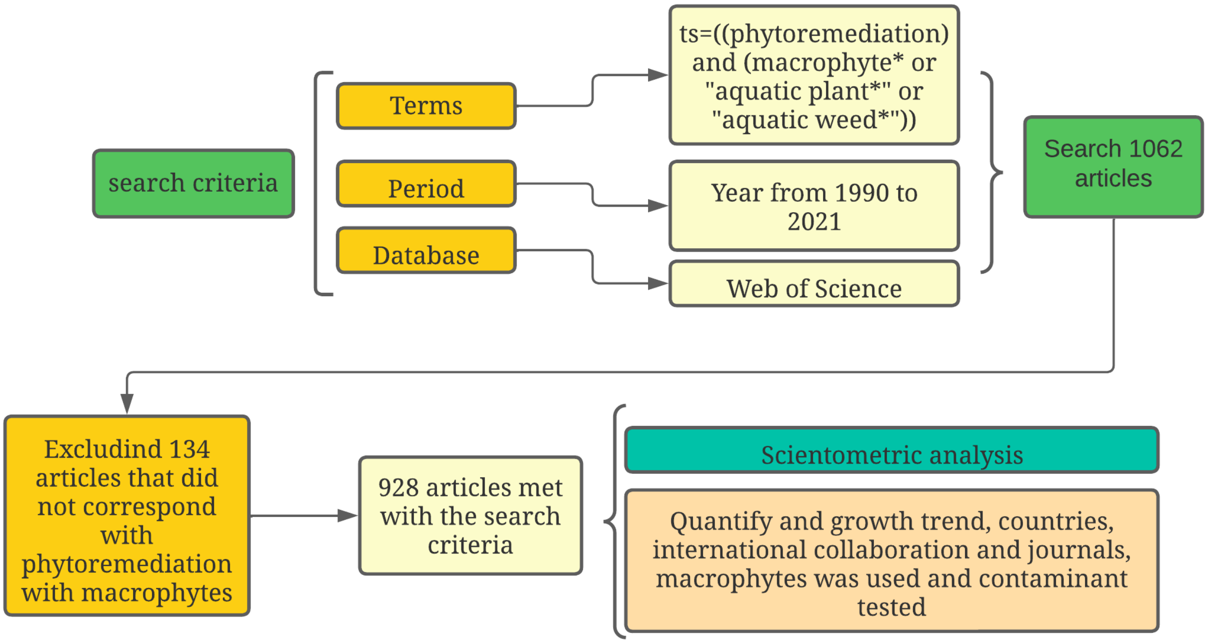

search criteria
Terms
Period
Database
ts=((phytoremediation) and (macrophyte* or "aquatic plant*" or "aquatic weed*"))
Year from 1990 to 2021
Web of Science
Search 1062 articles
Excludind 134 articles that did not correspond with phytoremediation with macrophytes
928 articles met with the search criteria
Scientometric analysis
Quantify and growth trend, countries, international collaboration and journals, macrophytes was used and contaminant tested

Figure 2

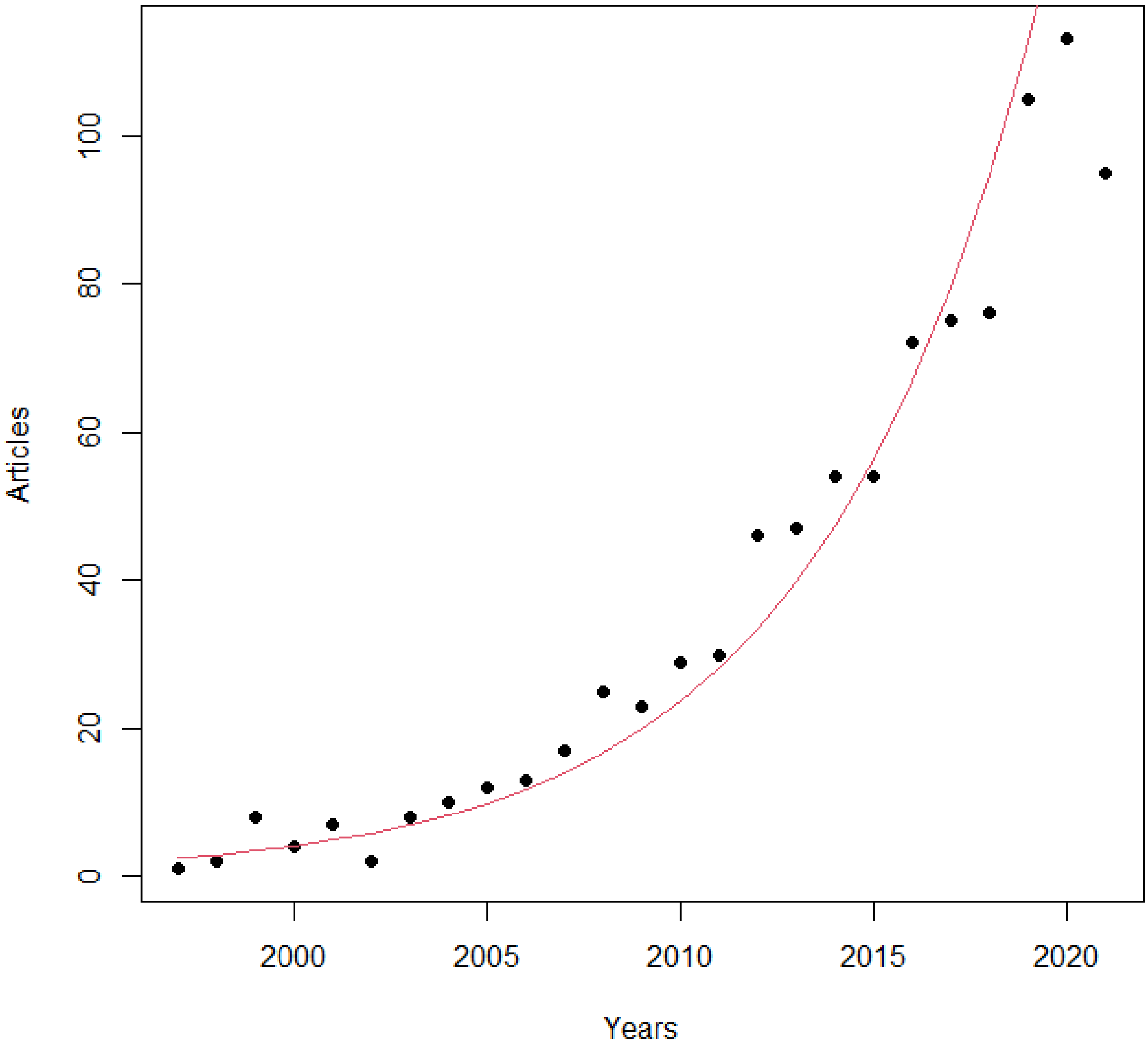
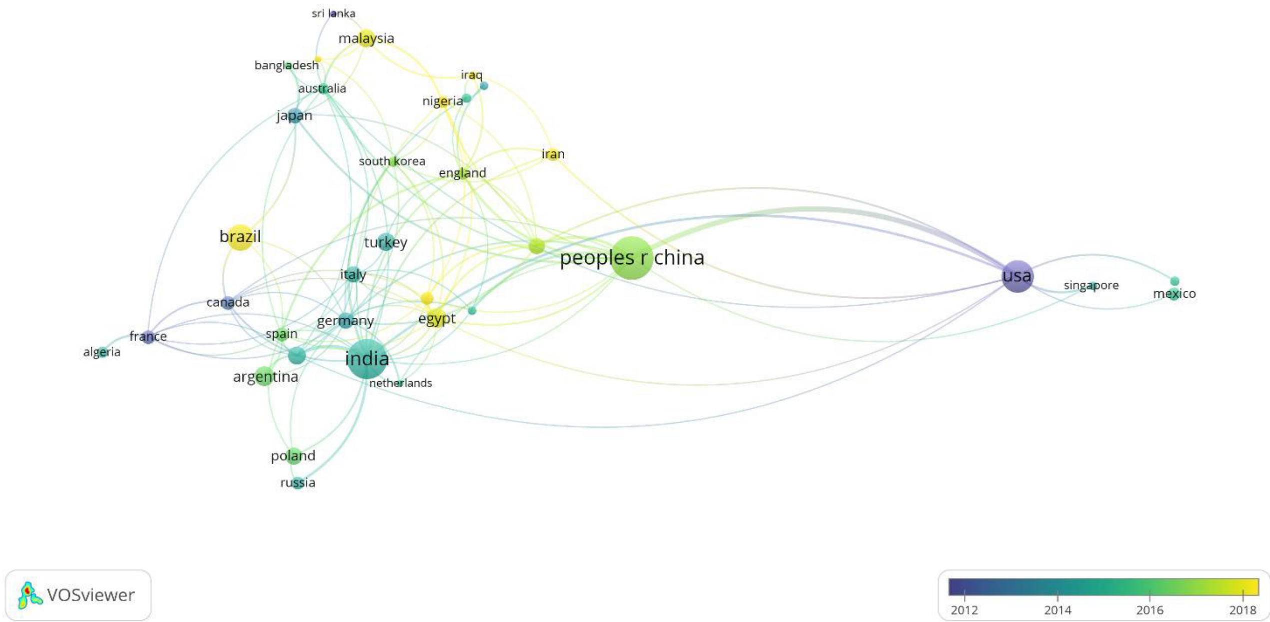


Figure 3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italy
usa
singapore
mexico
canada
egypt
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2014
2016
2018

Figure 4

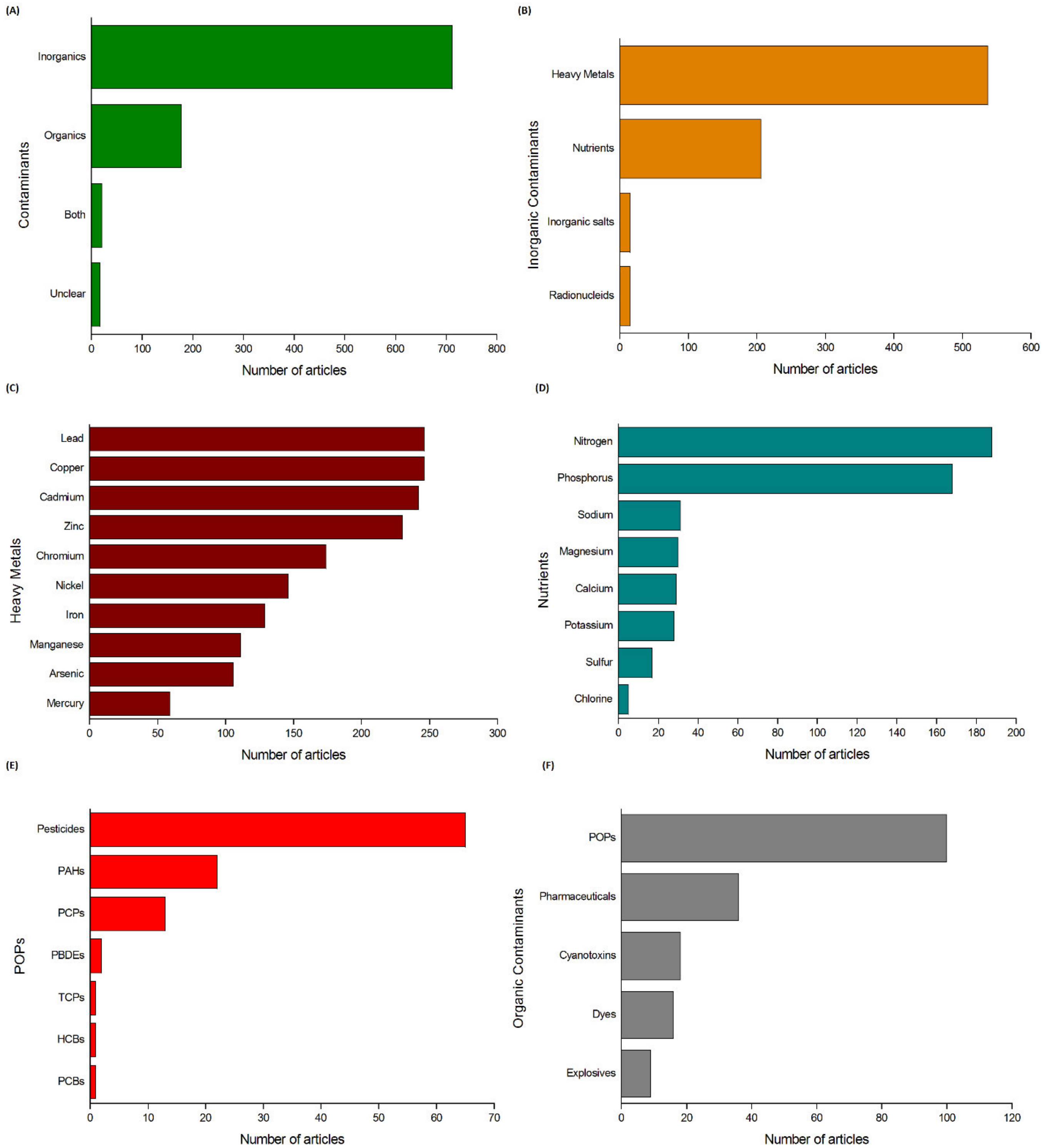

(A)
Contaminants
Inorganics
Organics
Both
Unclear
0
100
200
300
400
500
600
700
800
Number of articles
(B)
Inorganic Contaminants
Heavy Metals
Nutrients
Inorganic salts
Radionucleids
0
100
200
300
400
500
600
Number of articles
(C)
Heavy Metals
Lead
Copper
Cadmium
Zinc
Chromium
Nickel
Iron
Manganese
Arsenic
Mercury
0
50
100
150
200
250
300
Number of articles
(D)
Nutrients
Nitrogen
Phosphorus
Sodium
Magnesium
Calcium
Potassium
Sulfur
Chlorine
0
20
40
60
80
100
120
140
160
180
200
Number of articles
(E)
POPs
Pesticides
PAHs
PCPs
PBDEs
TCPs
HCBs
PCBs
0
10
20
30
40
50
60
70
Number of articles
(F)
Organic Contaminants
POPs
Pharmaceuticals
Cyanotoxins
Dyes
Explosives
0
20
40
60
80
100
120
Number of articles

Figure 5

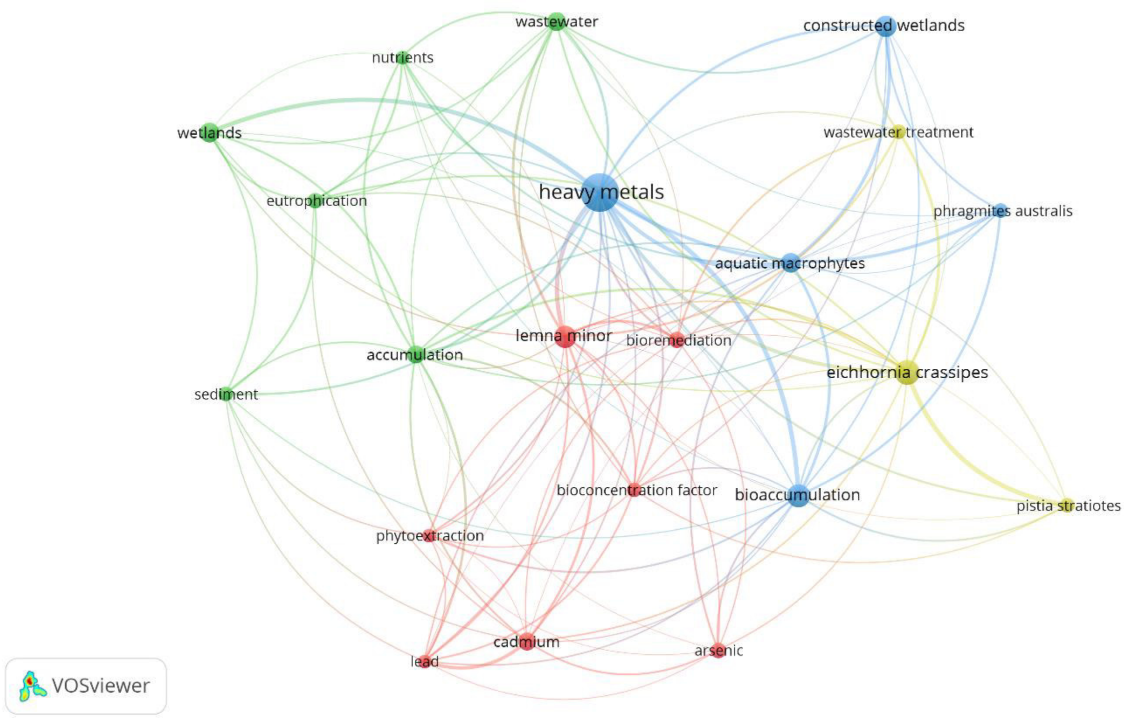
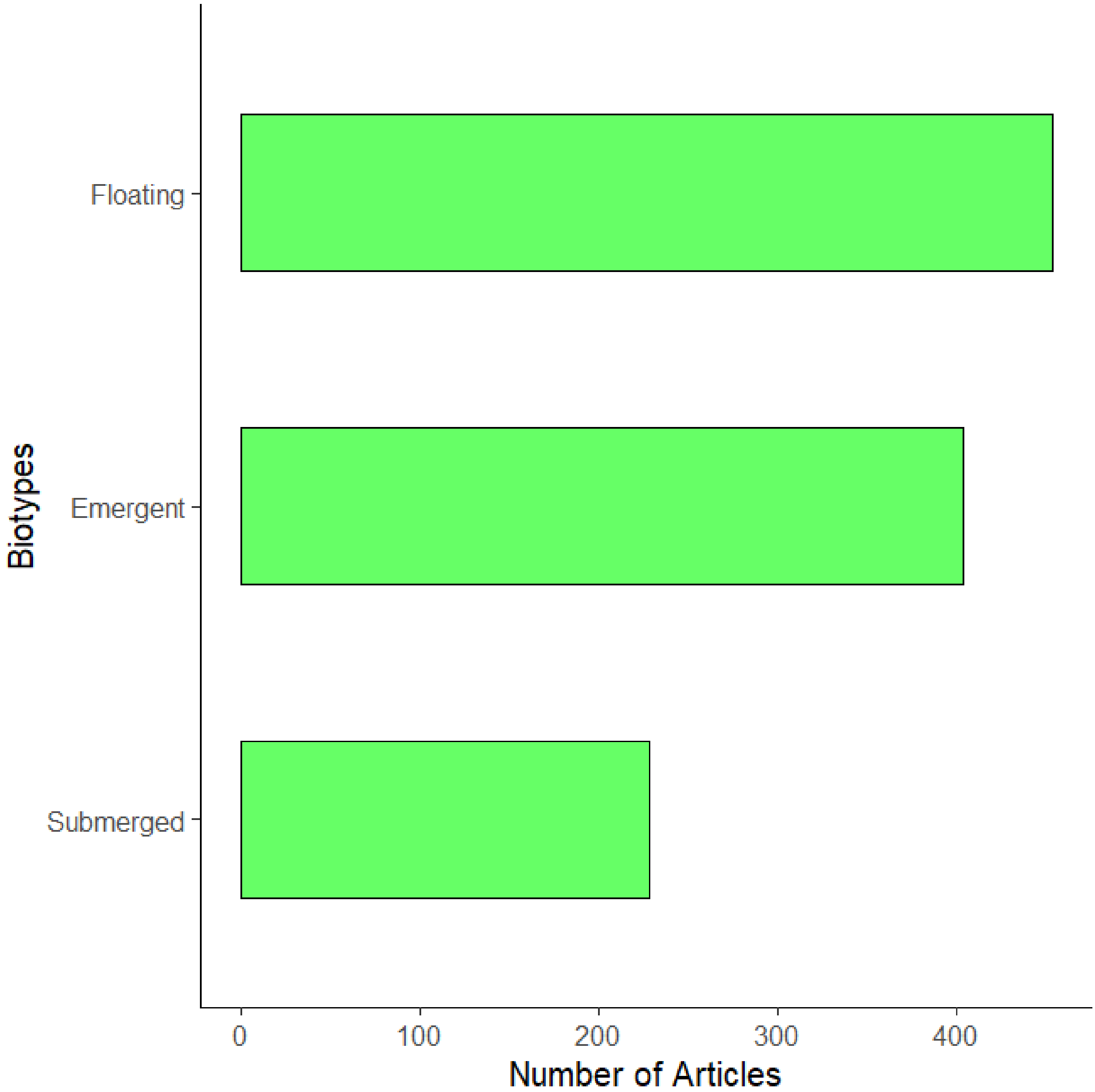

wastewater
constructed wetlands
nutrients
wetlands
wastewater treatment
heavy metals
eutrophication
phragmites australis
aquatic macrophytes
lemna minor
bioremediation
accumulation
eichhornia crassipes
sediment
bioconcentration factor
bioaccumulation
pistia stratiotes
phytoextraction
cadmium
arsenic
lead
VOSviewer

Figure 6


Biotypes
Floating
Emergent
Submerged
0
100
200
300
400
Number of Articles

Tables

Table 1: Ranking of 20 most productive countries that published articles on phytoremediation of freshwater environments with macrophytes from between 1990 to 2021 on the Science Citation Index Expanded (SCI-EXPANDED) - Clarivate Analytics Web of Science (WoS).

Rank	Country	Articles	SCP	(%)	MCP	(%)
1	China	168	138	82	30	18
2	India	135	127	94	8	6
3	USA	74	68	92	6	8
4	Brazil	68	62	91	6	9
5	Argentina	35	29	83	6	17
6	Turkey	31	30	97	1	3
7	Poland	27	26	96	1	4
8	Portugal	27	18	67	9	33
9	Egypt	26	18	69	8	31
10	Malaysia	26	19	73	7	27
11	Italy	25	19	76	6	24
12	Pakistan	21	15	71	6	29
13	Japan	15	10	67	5	33
14	France	14	8	57	6	43
15	Germany	14	10	71	4	29
16	Iran	14	10	71	4	29
17	Russia	14	11	79	3	21
18	Canada	13	9	69	4	31
19	Mexico	12	11	92	1	8
20	Algeria	11	9	82	2	18
	Total	770	647		123	
	Average (%)			84		16

SCP – Single country publication. MCP – Multiple country publication.

Table 2: Ranking of the 20 journals that most published articles on phytoremediation between 1990 to 2021 on the Science Citation Index Expanded (SCI-EXPANDED) - Clarivate Analytics Web of Science (WoS). The number of publications, H-index and impact factor (If, JCR) were showed.

Rank	**Journals**	**Number of publications**	**H-index**	**If**
1	International Journal of Phytoremediation	116	24	3.2
2	Environmental Science and Pollution Research	66	14	4.2
3	Chemosphere	52	24	7.0
4	Ecotoxicology and Environmental Safety	37	19	6.2
5	Ecological Engineering	33	20	4.0
6	Water Air and Soil Pollution	27	12	2.5
7	Science of The Total Environment	26	15	7.9
8	Journal of Hazardous Materials	21	13	10.5
9	Environmental Monitoring and Assessment	19	11	2.5
10	Bioresource Technology	18	17	9.6
11	Bulletin of Environmental Contamination and Toxicology	18	9	2.1
12	Desalination and Water Treatment	17	6	1.2
13	Environmental Pollution	17	13	8.0
14	Journal of Environmental Management	17	12	6.7
15	Water Research	16	14	11.2
16	Fresenius Environmental Bulletin	13	4	0.4
17	International Journal of Environmental Research and Public Health	11	4	3.3
18	Water Science and Technology	11	4	1.9
19	Environmental Technology	10	7	3.2
20	Environmental Technology & Innovation	10	8	5.2

Table 3: The 10 most global cited documents in the phytoremediation of freshwater environments through macrophytes subject from 1990 to 2021.

Rank	Article	Author(s) (Publication Year)	Journal	Total Citation (TC)	TC Per Year
1	Accumulation of lead, zinc, copper and cadmium by 12 wetland plant species thriving in metal-contaminated sites in China	Deng et al. (2004)	Environmental Pollution	466	24.53
2	Phytoaccumulation of trace elements by wetland plants: I. Duckweed	Zayed et al. (1998)	Journal of Environmental Quality	434	17.36
3	Lead and nickel removal using Microspora and *Lemna minor*	Axtell et al. (2003)	Bioresource Technology	246	12.30
4	Effect of copper and cadmium on heavy metal polluted waterbody restoration by Duckweed (*Lemna minor*)	Hou et al. (2007)	Plant Physiology and Biochemistry	235	14.69
5	Phytoaccumulation of heavy metals by aquatic plants	Kamal et al. (2004)	Environment International	221	11.63
6	Constructed wetland system vegetated with different plants applied to the treatment of tannery wastewater	Calheiros et al. (2007)	Water Research	217	13.56
7	Concurrent removal and accumulation of heavy metals by the three aquatic macrophytes	Mishra and Tripathi (2008)	Bioresource Technology	216	14.40
8	Lead heavy metal toxicity induced changes on growth and antioxidative enzymes level in water hyacinth [*Eichhornia crassipes* (Mart.)]	Malar et al. (2014)	Botanical Studies	197	21.89
9	Transformation of TNT by aquatic plants and plant tissues cultures	Hughes et al. (1997)	Environmental Science and Technology	189	7.27

10	Influence of temperature and salinity on heavy metal uptake by submerged plants	Fritiof et al. (2005)	Environmental Pollution	177	9.83

Table 4: Ranking of 20 macrophytes most tested on phytoremediation articles and their biotype.

Rank	Species	Number of articles	Biotype
1	*Pontederia crassipes* (*Eichhornia crassipes*)	181	Floating
2	*Pistia stratiotes*	113	Floating
3	*Lemna minor*	102	Floating
4	*Phragmites australis*	100	Emergent
5	*Typha latifolia*	84	Emergent
6	*Hydrilla verticillata*	48	Submerged
7	*Typha domingensis*	40	Emergent
8	*Ceratophyllum demersum*	39	Submerged
9	*Typha angustifolia*	38	Emergent
10	*Spirodela polyrhiza*	33	Floating
11	*Lemna gibba*	32	Floating
12	*Elodea canadensis*	27	Submerged
13	*Myriophyllum aquaticum*	27	Submerged
14	*Iris pseudacorus*	26	Emergent
15	*Potamogeton crispus*	26	Submerged
16	*Ipomea aquatica*	25	Emergent
17	*Myriophyllum spicatum*	24	Submerged
18	*Juncus effusus*	23	Emergent
19	*Azolla pinnata*	20	Floating
20	*Cyperus alternifolius*	18	Emergent

CONSIDERAÇÕES FINAIS

Os resultados encontrados em nossa pesquisa responderam às perguntas propostas e também nos permitiram ter um panorama do estado atual do campo da fitorremediação de ambientes de água doce através das macrófitas aquáticas. O número de publicações acerca deste tema aumentou consideravelmente no decorrer dos anos, os resultados demonstram que o número de publicações nos últimos dois anos supera o número de artigos publicados em toda primeira década. Este resultado já era de certa forma esperado, uma vez que a publicação cientifica aumenta exponencialmente ao longo dos anos. Os países que mais demonstram engajamento com a fitorremediação foram a China, os USA, a Índia e o Brasil. Os países China, USA e Índia também foram os que mais realizaram colaborações internacionais. Países como Brasil, Egito e Arabia saudita, se demonstraram como países emergentes neste assunto, uma vez que mais de 60%, 64% e 87% de suas publicações ocorreram nos últimos três anos, Respectivamente. Este tema tem ganhado reconhecimento ao longo dos anos. Isso pode ser visto na qualidade dos jornais que mais publicaram artigos de fitorremediação. O jornal *International Journal of Phytoremediation* foi o jornal com maior número de publicações e apresenta um fator de impacto de 3.2, seguido pelos jornais *Environmental Science and Pollution Research* e *Chemosphere* com fatores de impacto de 4.2 e 7.0 respectivamente, contudo no nosso top 20 dois jornais apresentam fatores de impacto superiores a 10.0, sendo eles o *Journal of Hazardous Materials* e *Water Research*, com 10.5 e 11.2 respectivamente, enquanto os jornais *International jornal of phytoremediation* e *Chemosphere* apresentam os maiores índices-h (esses dados representam os FI de 2022).

A análise dos artigos mais citados neste tema demonstrou uma grande predominância de trabalhos realizados com metais pesados, onde nove dos dez artigos que aparecem no top 10 testaram metais pesados em suas análises. Apenas um artigo realizou análises de contaminantes orgânicos, Hughes et al. (1997) analisou a capacidade de macrófitas de transformar o contaminante orgânico TNT. Sobre as palavras-chave de autores encontramos a palavra-chave "*heavy metals*" com maior centralidade no mapa e com o maior número de ocorrências, demonstrando novamente um predomínio de trabalhos que utilizam metais pesados em suas análises. Outra palavras-chave de autores com grande destaque para a palavra-chave "*Eichhornia crassipes*" (atualmente *Pontederia crassipes*) demonstrando grande ocorrência desta macrófita em estudos de fitorremediação de ambientes aquáticos continentais, devido suas características favoráveis para a remediação. Tais resultados corroboram com a contagem total de contaminantes e macrófitas, onde os metais pesados foram os mais estudados e a macrófita aquática *Pontederia crassipes* foi a mais testada.

Nossos resultados demonstram um grande predomínio de países como China e USA nas publicações deste tema, porém também destaca a presença do Brasil dentro do top 5 países que mais publicam, demonstrando que este tema tem potencial de seguir se desenvolvendo aqui, uma vez que o Brasil possui a maior rede hidrográfica do mundo. Apesar disso, o Brasil apresentou uma baixa colaboração internacional, se comparado com os outros países. Além disso, os resultados apontam uma grande predominância de estudos com metais pesados, contudo demonstra uma carência na pesquisa da fitorremediação de contaminantes orgânicos.

Também foi observada uma predominância do estudo de macrófitas dos ecótipos flutuantes, seguidas pelas emergentes e submersas. Sendo as flutuantes mais estudadas em relação as demais, possivelmente devido as suas características e facilidade de manejo e de pós-cultura. Desta forma, sugerimos o desenvolvimento de mais projetos voltados para a fitorremediação de contaminantes orgânicos, bem como estudos que procurem compreender os mecanismos envolvidos na degradação dos contaminantes orgânicos. Além da busca por espécies endêmicas do Brasil que sejam pouco estudadas e que possam vir a ter alta capacidade de fitorremediação. Tendo conhecimento destas informações, as mesmas podem auxiliar novos pesquisadores a se integrar rapidamente a fitorremediação de ambientes de água doce através de macrófitas, bem como apontar às agências de financiamento as lacunas presentes neste assunto e suas principais tendências, o que pode vir a orientar o desenvolvimento de novos projetos de pesquisa, bem como políticas ambientais.