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Review

Advancements in Phytoremediation Research in South Africa (1997–2022)

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Abstract: Several mining-related pollutions, industrial waste, and soil deterioration define South Africa's environmental landscape. These have led to the consumption of unhealthy food, contaminated agricultural products, and polluted water. The polluted environment has been linked to numerous diseases among the populace, thus making environmental remediation an important issue in South Africa. Phytoremediation has been identified as a biological method for the restoration of polluted environments naturally and holistically. Therefore, it is vital to evaluate the level of phytoremediation-related research in South Africa in pursuit of a way out of environmental pollution. Thus, the purpose of this study was to map phytoremediation-related research in South Africa from inception to 2022. Statistical records from the Web of Science Core Collection were analyzed with the bibliometric package in RStudio, while mapping was performed via VOSviewer. Our study showed a low annual growth rate of publication (4.49%). The analysis uncovered that the 39 documents analyzed were written by 112 authors, and the first document was featured in the Journal of Geochemical Exploration in 1997. Kirkham, MB and Liphadzi, MS are the most relevant authors. USA has the strongest collaboration with South Africa, while the *International Journal of Phytoremediation*, the *South African Journal of Botany*, and *Water SA* are the most relevant journals. The result of this study can guide upcoming researchers and policymakers, together with essential facts for enhancing the restoration of the polluted environment in the country.

Keywords: bibliometrics; phytoremediation; phytoextraction; phytostabilization; South Africa; VOSviewer

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1. Introduction

Environmental pollution is a critical global challenge that demands novel and sustainable solutions. To curb the unprecedented rate of environmental degradation, cutting-edge, sustainable technologies are being developed to degrade and recycle dangerous waste generated by human activities [1]. Common remediation methods like chemical, thermal, physical, and other treatment methods are costly and potentially damaging to the environment. It is becoming a race against time to find more ecological-friendly remediation approaches, given the enormous risks associated with mining activities. Biological restoration techniques have received much-deserved recognition due to their ability to operate within the boundaries of natural processes. The phytoremediation approach contributes to soil health, conserves water quality, and safeguards biodiversity. Phytoremediation is a nature-based procedure that leverages the innate abilities of plants to absorb, cleanse, and amass pollutants from soil, water, and air [1,2].

The phytoremediation approach may include phytoextraction, phytostabilization, phytodegradation, phytovolatilization, and rhizofiltration [3]. Phytoextraction involves the use of plants to absorb the pollutants and translocate them from the roots to the leaves, and the roots and shoots are subsequently harvested to remove the contaminants from the soil [4,5]. Phytostabilization uses plant roots to decrease the amount of water percolating through the soil matrix, reduce the formation of hazardous leachate, and prevent erosion, thereby decreasing the mobility and bioavailability of toxic metals in the soil [6,7].

Rhizofiltration uses plants to absorb toxic metals from polluted aqueous environments via their roots [8,9]. Phytovolatilization uses plants for the uptake of contaminants from the soil and then transforms them into volatile forms, which are released into the atmosphere by transpiration [10,11]. Phytodegradation involves the uptake of organic pollutants by plant roots, which are metabolized in plant tissues to less toxic substances [12,13]. The phytoremediation technique has several benefits, including the ability to be used in situ without the need for extensive excavations or the transfer of pollutants, minimizing harm to ecosystems and habitats. Additionally, phytoremediation may be customized to target certain pollutants, providing a flexible answer to a variety of contaminants (such as heavy metals and organic pollutants) in the environment and even radioactive elements. Its potential goes beyond mitigation since some plant species are advantageous in resource recovery because they may collect important components [6,7]. Several studies confirm the feasibility and potential of phytoremediation. Studies have shown that some plant species can hyperaccumulate heavy metals, successfully cleaning up polluted soils [14–16]. The complex interplay between plant–microbe interactions in boosting phytoremediation processes has been identified [17]. These studies highlight the complexity and promise of phytoremediation as a multidisciplinary strategy, including environmental chemistry, soil microbiology, and plant physiology.

South Africa is struggling with a host of environmental challenges that pose significant threats to its ecosystems, public health, and economic stability. South Africa has a significant problem with land degradation, especially by mining activities; over 0.19 million hectares are degraded by mine tailings, overburden, mine dams, waste rock dumps, and surface-based mining [18]. Despite reports of some successes in post-mining restoration, Africa still lags in mainstreaming the rehabilitation of mine wastelands [6]. South African landscapes are littered with mine wastes, including residues from mining activities. These wastes are often stockpiled or insecurely disposed of in open waste dumping sites, leading to leaching and acid mine drainage. Johannesburg, one of the most developed cities in the African continent, is surrounded by piles of mine waste and abandoned mines. The clouds of dust and leachate, which are contaminated with cyanide, arsenic, lead, copper, and even radioactive uranium from the mine tailings, are having a devasting effect on the health of poor residential communities and ecosystems, including rivers, wetlands, and agricultural lands [19,20]. There are about 270 tailings facilities that cover approximately 400 km^2 in the Witwatersrand gold fields [21]. Climate change will make matters worse; the hazards of mining wastes are expected to increase in the coming years. However, South Africa's rich biodiversity and exceptional adaptation of indigenous plant species to local conditions offer an invaluable asset in the pursuit of successful phytoremediation projects.

Furthermore, several mining-related pollutions, industrial waste, and soil deterioration define South Africa's environmental landscape [22]. These challenges inspired researchers to investigate phytoremediation as a potential fix. For instance, heavy metal contaminants from mining operations plague the Limpopo Province, prompting researchers to look into how native flora may be used to address this problem [23,24]. In addition, South Africa's commitment to sustainable development, as indicated in the National Development Plan (NDP) and the Green Economy Strategy, aligns seamlessly with the principles of phytoremediation. This will enhance the restoration of balance between human activity and the preservation of the natural environment in South Africa's landscape. However, there are no studies on bibliometric analysis of phytoremediation study in South Africa, and this requires deeper consideration.

Bibliometric is the statistical analysis of scientific publications for the identification of research trends, impacts, and comparison of research output of scholars, including scientific collaboration among researchers, institutions, and countries over the years in a specific field of interest [25–27]. It uses various methods to measure the effect of published scientific articles to offer suggestions and direction for forthcoming projects [28,29]. Based on bibliometrics, scientific mapping and performance analysis related to authors, institutions, and countries can be identified. Therefore, a bibliometric analysis of phytoremediation-related research in South Africa was assessed in the Web of Science (WoS) from inception to 2022. This study provides access to essential facts on developments and identifies current snags for future investigation in phytoremediation-related research in South Africa.

2. Materials and Methods

2.1. Data Mining

Web of Science is one of the highly comprehensive and reliable databases for bibliometric studies. Statistical records for bibliometric analysis of research developments on phytoremediation from inception to 2022 were mined in the core collection of WoS. The search approach was TITLE ("phytoremediation" OR "phytoextraction" OR "phytostabilization" OR "photovolatilization" OR "rhizofiltration"). A set of articles (n = 5076) was found, and the search was refined to South Africa (n = 39). These articles were pulled from WoS and kept for additional analysis.

2.2. Mapping and Data Analysis

Rstudio (v.4.1.1) was used for data analysis [27,30]. The recovered records were uploaded into biblioshiny in Rstudio and analyzed for the annual scientific production, total citations, most relevant authors, institutions, and journals on phytoremediation-related research in South Africa. Consequently, VOSviewer software version 1.6.17 [31] was used for scientific mapping of phytoremediation-related research in South Africa from inception to 2022.

3. Results and Discussion

3.1. Major Information and Publication Trend

Key information on phytoremediation-related research in South Africa retrieved from WoS is shown in Table 1. We used WoS because it is one of the most popular databases for bibliometric analysis [32,33]. The 39 documents pulled from WoS were published in 30 sources by 112 authors. The average number of citations per document was 22.31, while the average age of documents was 7.82. Authors' collaboration indicated that co-authors per document were 3.54, while international co-authorship was 41.03%, consisting of 2198 references in the retrieved documents. The total keywords plus and the authors' keywords recognized in these documents are 200 and 141, respectively.

Table 1. Main information on phytoremediation-related research in South Africa.

Description	Results
Timespan	1997:2022
Sources (Journals, Books, etc.)	30
Documents	39
Annual Growth Rate %	4.49
Document Average Age	7.82
Average Citations Per Doc	22.31
References	2198
DOCUMENT CONTENTS	
Keywords Plus (ID)	200
Authors' Keywords (DE)	141
AUTHORS	
Authors	112
Authors of Single-Authored Docs	1
AUTHORS COLLABORATION	
Single-Authored Docs	1
Co-Authors Per Doc	3.54
International Co-Authorships %	41.03
DOCUMENT TYPES	
Article	25
Article; Proceedings Paper	3
Correction	1
Meeting Abstract	3
Review	6
Review; Book Chapter	1

The first paper on phytoremediation-related research in South Africa that was published in the WoS database focused on the potential of *Berkhya coddii* for the phytoextraction of nickel by Robinson et al. [34]. From the 2000s, the number of publications started increasing, while a major increase occurred in 2019 when phytoremediation technology was proven to be a sustainable and ecologically friendly remediation approach in terms of its efficiency, cost-effectiveness, and potential for long-term environmental restoration—Figure 1. The annual growth rate is 4.49%, which signals a slow positive trend in phytoremediation-related research, and scientists in South Africa have not made significant contributions in this field over time. Notwithstanding, their work is published in quality journals that are indexed in WoS. The data in this article may perhaps not signify the entire published document on the subject matter in the field. The low number of documents may be attributed to the attitude of some researchers who do not worry about the quality of the journal and/or bother to confirm the journal is indexed in PubMed, Scopus, or WoS database before publishing their work. Perhaps this is a result of the desire to submit articles to journals where they will quickly be accepted for publication, not taking into account how visible their papers would be to other researchers. In addition, the annual list of accredited journals from the Department of Higher Education and Training (DHET) might have contributed to the low research output. A researcher might publish in a journal that is DHET accredited this year and removed the following year from the DHET list and tagged as a predatory journal. These, among others, might be responsible for the low research output recorded in this study. Similarly, the average total citations per year analyzed showed fluctuations in citation pattern, and the highest citation was observed in the year 2022. Several factors can influence the citation of an article. Examples of such are free or paid access journals and years of publications. It is assumed that citation is a reflection of the quality or impact of research [35]. However, citations of an article do not determine the quality of the article. It is normal for older papers to receive more citations than more recent ones. Papers in open access make their content widely accessible to other scholars and thus receive more citations than those in paid access.

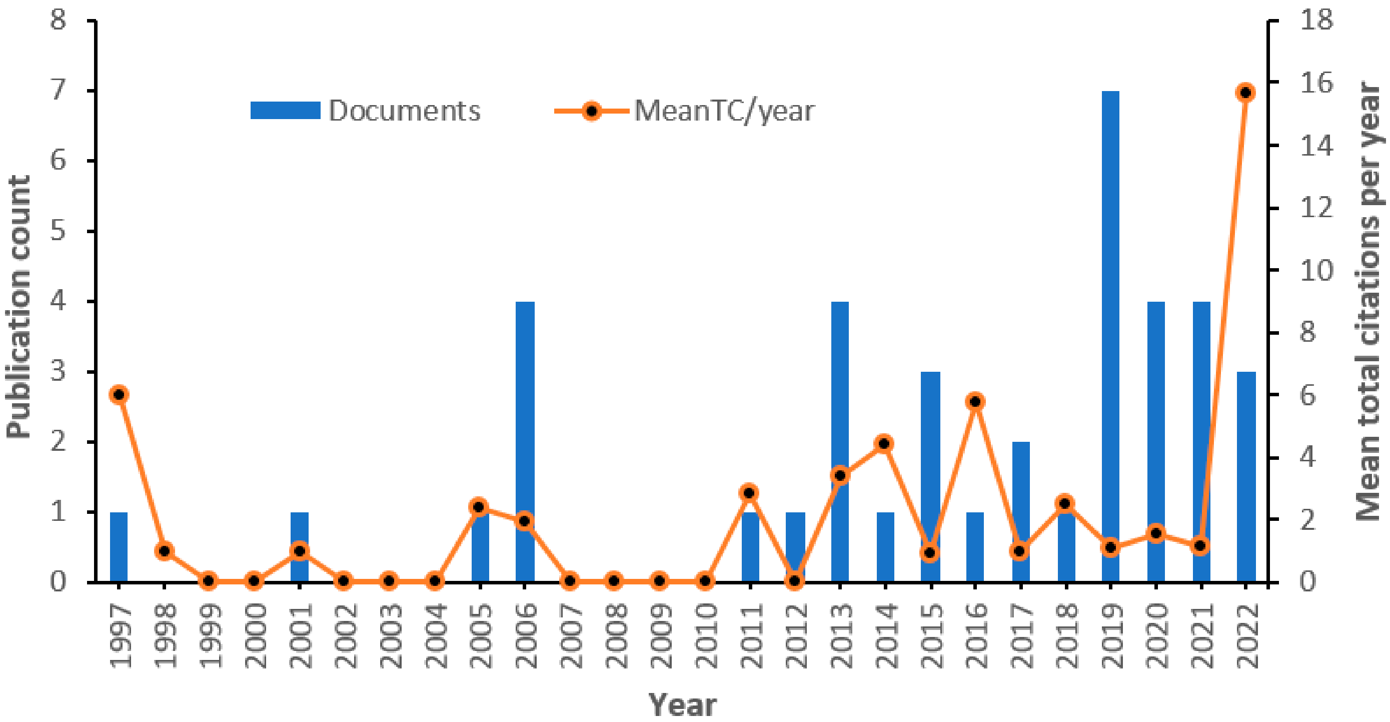
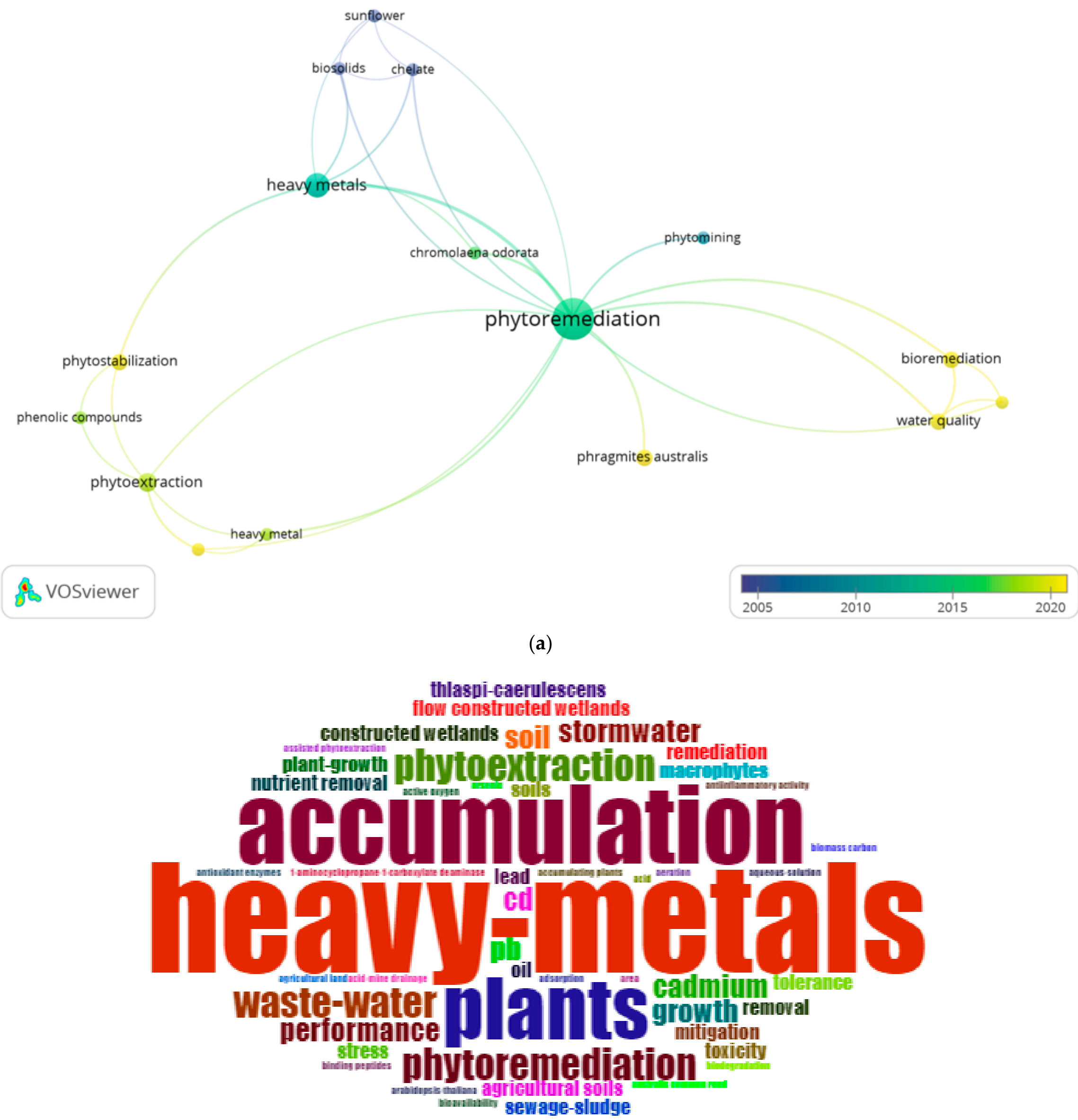


Figure 1. Annual publication and mean citation per annum on phytoremediation-related research in South Africa since inception to 2022.

3.2. Keywords Network Analysis

Keywords are the list of words that signify the focus of research within a specific area [25]. VOSviewer can be used to analyze the co-occurrence of authors' keywords. Using the fractional counting method, 127 keywords were identified. Fixing the minimum number of occurrences as two, only 16 keywords met the threshold, and the total strength of the co-occurrence links with other keywords was estimated. The keywords with the highest total link strength were selected. The result is presented in five clusters—Figure 2a. Keywords in the same cluster have closer links, and the nodes denote the number of times in which the keyword occurs.



(a)

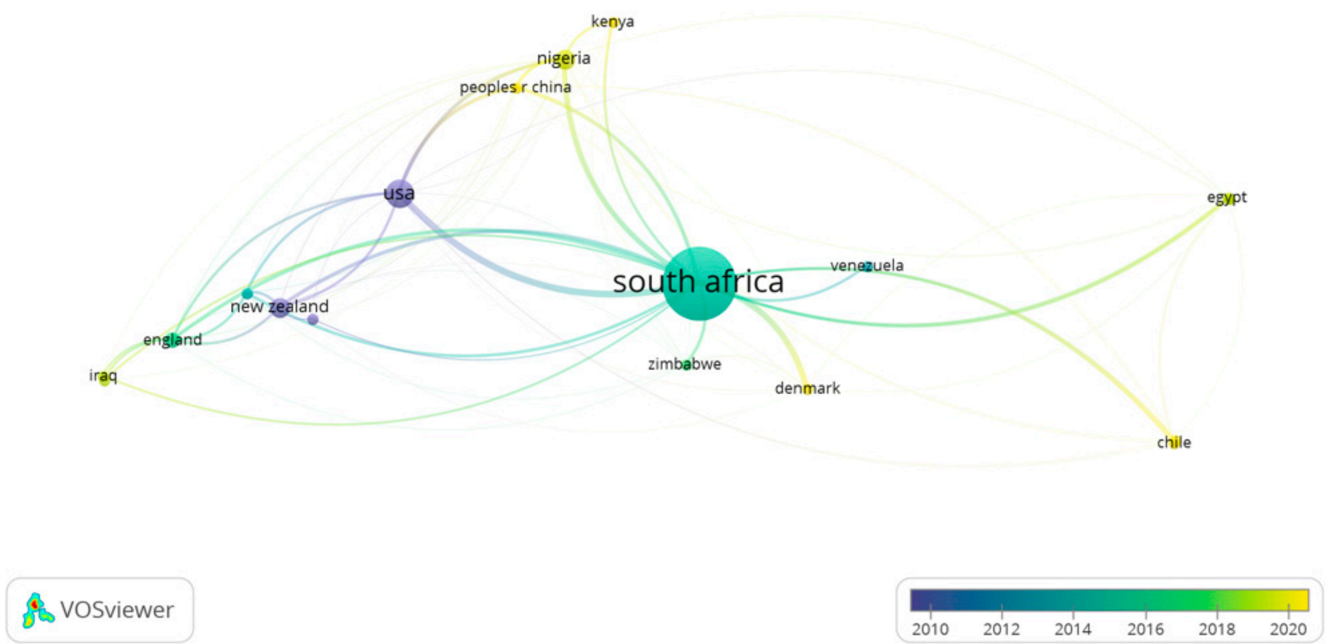
(b)

Figure 2. Co-occurrence of authors' keywords (**a**) and word cloud (**b**) in phytoremediation-related research in South Africa.

The lines representing the distance between two keywords are an indication of the connections of the terms. The keywords are divided into five clusters of 5, 4, 3, 3, and 1 items represented with a unique color to show their connectivity in the cluster [36]. Phytoremediation (nineteen occurrences, thirteen total link strength), heavy metals (seven occurrences, six total link strength), bioremediation (three occurrences, three total link strength), phytoextraction (four occurrences, three total link strength), and water quality (three occurrences, three total link strength) are the most prevalent keywords among authors. Many scholars have employed keywords to determine research outlook in various fields [25,27,37]. The keywords identified in this study pinpoint the research focus on the subject among scholars in South Africa since inception till 2022. Figure 2b shows the word cloud of frequently used words in phytoremediation-related research in South Africa.

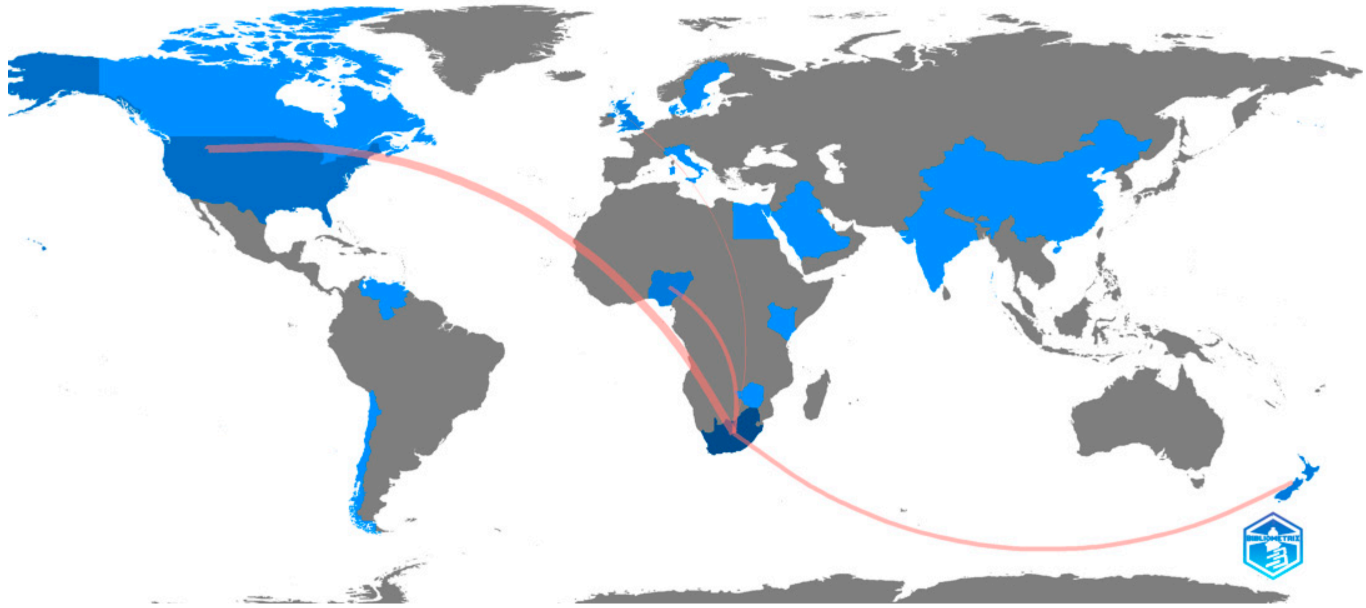
3.3. South Africa's Collaboration with Other Countries on Phytoremediation-Related Research

The VOSviewer software was used to identify and map countries collaborating with South Africa on phytoremediation-related research from inception to 2022. The fractional counting method was used for the analysis, and the maximum number of countries per document was 25. Eighteen countries were identified, and the total strength of South Africa's collaboration links with other countries was estimated. The mapped network grouped the 18 items into six clusters, with 78 links and 1682.41 total link strength. "Cluster 1 contains four countries", "Cluster 2 (four countries)", "Cluster 3 (three countries)", "Cluster 4 (three countries)", "Cluster 5 (two countries)", and "Cluster 6 (two countries)"—Figure 3a. Countries with the same color are closely linked and classified into the same cluster. In the country collaboration network analysis, the number of publications is directly proportional to the size of the circle on the map, and the thickness of the connecting line is also proportional to the scale of cooperation between the two connecting countries [38]. The size of the biggest circle in Figure 3a does not indicate South Africa as the foremost country in phytoremediation-related research globally. The geographical focus of this study was on South Africa to explore the collaborative network coverage of scholars in the field with scholars in other countries. The degree of collaboration between two countries is shown by the thickness of the connecting line, known as link strength. The USA has the highest link strength (453.09) with South Africa. The link strength between South Africa and Nigeria, England, the People's Republic of China, and New Zealand are 287.93, 229.00, 194.00, and 190.09, respectively. Figure 3b shows the country collaboration map with South Africa. This analysis provides information on current collaborators in the field and could provide insight for new researchers to identify prospective collaborators for future projects.



(**a**)

Figure 3. *Cont.*



(**b**)

Figure 3. Collaboration network of South African researchers with other countries (**a**) and the country collaboration map (**b**) in phytoremediation-related research in South Africa.

3.4. Relevant Authors' Collaboration Network

Partnership among authors, institutions, and countries can be measured using the collaborative network analysis. This can enhance academic exchange and expand the field of research, as well as show the veracity of academic communication in scientific research [33,39]. In this study, the fractional counting method in VOSviewer was used for the analysis of co-authorship of authors. The maximum number of authors per document was twenty-five, and the minimum number of documents per author was one. In total, 121 authors were identified, and the total strength of the co-authorship links with other authors was estimated. Only 13 of the 121 authors are connected and displayed below—Figure 4. The mapped network showing the 13 authors has 78 links and a total link strength of 6.50. Each of the 13 authors on the map has 44 citations.

Meanwhile, the publication output and citation impact of authors were analyzed as a function of h_index using biblioshiny in Rstudio. The h_index is a tool for measuring the quality of research publications in terms of productivity and citation impact of authors and journals [40,41]. The leading authors are KIRKHAM, MB (n = 5, h_index = 4, total citation = 183), LIPHADZI, MS (n = 5, h_index = 4, total citation = 183), BROOKS, RR (n = 2, h_index = 2, total citation = 184), ATAGANA, HI (n = 4, h_index = 2, total citation = 184), and BRINK, IC (n = 3, h_index = 2, total citation = 6)—Table 2. The most cited publications of Kirkham, MB and Liphadzi, MS focused on the technology to increase root growth of *Helianthus annuus* for enhanced phytoremediation of trace metals in polluted soil [42,43]. Although Kirkham, MB and Liphadzi, MS have the highest h_index, Brooks, RR, Howes, AW, and Robinson, BH have the highest total citations. Several factors, such as the quality of an article, year of publication, and accessibility of the article, among others, can influence the citation of an article. Hence, citation is an imperfect method of measuring authors' impact in a specific field of research [41,44].

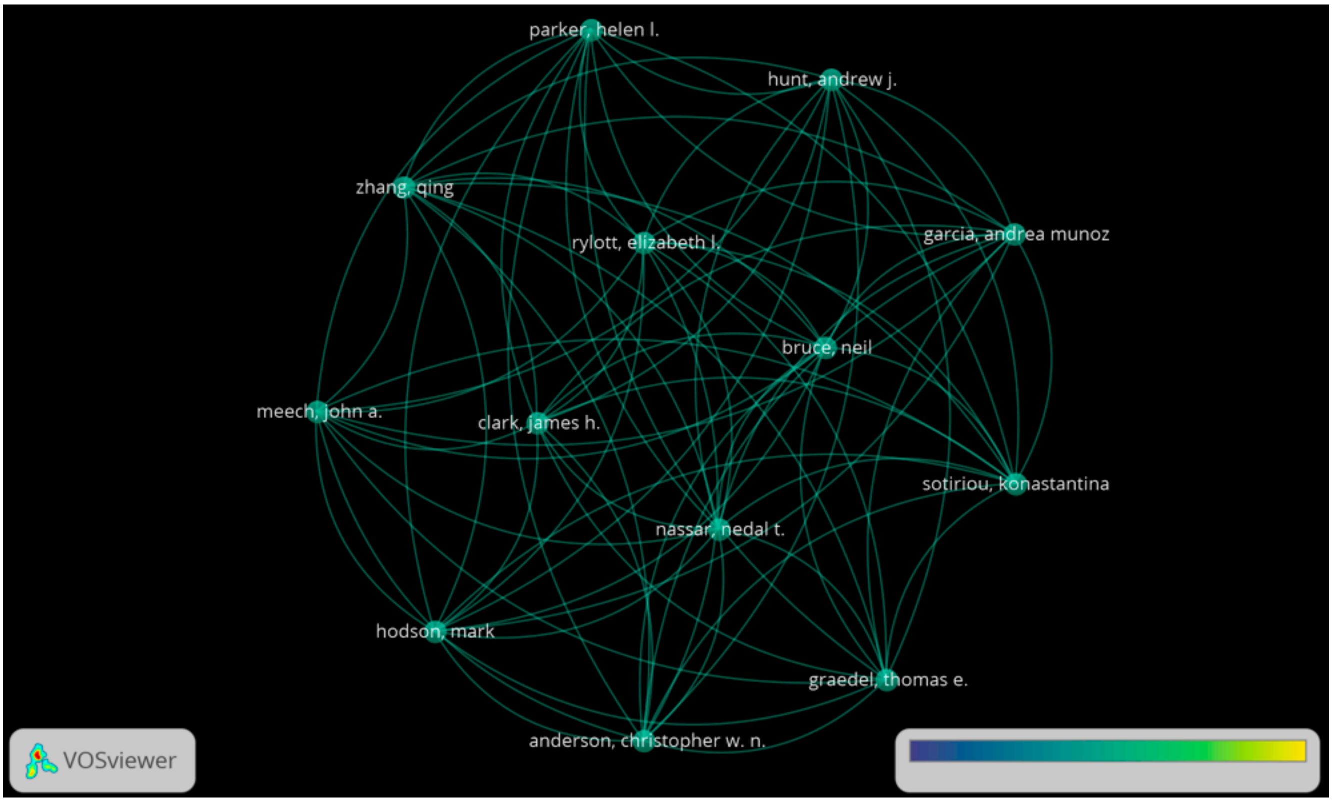


Figure 4. Collaboration of authors in phytoremediation-related research in South Africa.

Table 2. Top 20 authors in phytoremediation-related research in South Africa.

Authors	h_index	g_index	m_index	TC	NP	PY_start	AF
KIRKHAM MB	4	5	0.211	183	5	2005	2.33
LIPHADZI MS	4	5	0.211	183	5	2005	2.33
ATAGANA HI	2	4	0.154	53	4	2011	2.50
BRINK IC	2	2	0.4	6	3	2019	1.00
BROOKS RR	2	2	0.074	184	2	1997	0.45
DE WAAL J	2	2	0.4	6	3	2019	1.00
HOWES AW	2	2	0.074	184	2	1997	0.45
JACKLIN DM	2	2	0.4	6	3	2019	1.00
ROBINSON BH	2	2	0.074	184	2	1997	0.45
ABDEL-GAYED MES	1	1	0.2	15	1	2019	0.14
ABED SN	1	1	0.2	9	1	2019	0.33
ADENUGA DO	1	1	0.333	13	1	2021	0.33
AHMAD F	1	1	0.091	137	1	2013	0.33
ALMUKTAR SA	1	1	0.2	9	1	2019	0.33
ANDERSON CWN	1	1	0.1	44	1	2014	0.08
ANYASI RO	1	3	0.083	16	3	2012	1.50
ASEMOLOYE MD	1	1	0.5	75	1	2022	0.33
BABALOLA OO	1	1	0.091	137	1	2013	0.33
BADEJO AA	1	2	0.111	10	2	2015	0.45
BANDA MF	1	1	0.5	4	1	2022	0.25

TC: total citation; NP: number of publications; PY: publication year; AF: article fractionalized.

3.5. Relevant Journal Analysis

The retrieved data from WoS indicate that 39 documents were published in 30 sources—Table 1. In bibliometric analysis, journals and subject categories are tools that elucidate divisions of research scope in a particular topic [45]. In the current study, the publications on phytoremediation-related research in South Africa from inception to 2022 were divided into 20 WoS subject categories. The top categories are Environmental Sciences (*n* = 17, 43.59%), Water Resources (*n* = 8, 20.513%), Plant Sciences (*n* = 7, 17.949%), Agronomy (*n* = 3, 7.692%), and Engineering Chemical (*n* = 3, 7.692%). The most relevant journals on the subject are the *International Journal of Phytoremediation* (*n* = 4, IF = 4.003), the *South African Journal of Botany* (*n* = 4, IF = 3.111), *Water SA* (*n* = 4, IF = 1.586), *Applied Ecology and Environmental Research* (*n* = 1, IF = 0.816), and *Chemosphere* (*n* = 1, IF = 8.943)—Table 3. Although the *International Journal of Phytoremediation* has the highest number of publications (*n* = 4), the *Journal of Geochemical Exploration* has the highest total citation (161 citations), followed by *Reviews of Environmental Contamination and Toxicology*, vol 223 (137 citations) and the *South African Journal of Botany* (112 citations). The analysis of the most active journals indicates the studies in this field are environment-centered.

Table 3. Top 10 relevant journals on phytoremediation-related research in South Africa.

Journals	h_index	g_index	m_index	TC	NP	PY_start
INTERNATIONAL JOURNAL OF PHYTOREMEDIATION	3	4	0.333	38	4	2015
SOUTH AFRICAN JOURNAL OF BOTANY	3	4	0.158	112	4	2005
WATER SA	3	3	0.429	13	4	2017
APPLIED ECOLOGY AND ENVIRONMENTAL RESEARCH	1	1	0.2	5	1	2019
CHEMOSPHERE	1	1	0.5	75	1	2022
DESALINATION AND WATER TREATMENT	1	1	0.2	6	1	2019
ENVIRONMENTAL REVIEWS	1	1	0.091	11	1	2013
ENVIRONMENTAL SCIENCE AND POLLUTION RESEARCH	1	1	0.125	46	1	2016
ENVIRONMENTAL TECHNOLOGY	1	1	0.056	58	1	2006
GREEN PROCESSING AND SYNTHESIS	1	1	0.1	44	1	2014

TC: total citation; NP: number of publications; PY: publication year.

In addition, the relationship among journals was mapped in VOSviewer based on the shared references and total citations [33]. A fractional counting method with a minimum of a document in a journal was deployed for the bibliographic coupling of 30 journals involved in the publication of phytoremediation-related research in South Africa from inception to 2022. For each of the 30 article sources, the total strength of the coupling links with other sources was estimated, and the source with the greatest total link strength was selected. One of the article sources is not connected to the network; thus, the remaining 29 connected sources are shown in Figure 5. The mapped network has 137 links and 182.02 total link strength and is divided into five clusters represented with different colors. "Cluster 1 consists of eight items", "Cluster 2 (seven items)", "Cluster 3 (seven items)", "Cluster 4 (four items)", and "Cluster 5 (three items)". Among the three leading journals in terms of the number of publications and h_index, the *South African Journal of Botany* has the highest links of 16 and a total link strength of 35.55. The *Journal of Geochemical Exploration* has the highest total citation, with seven links and ten total link strengths. The high total citation of the only article on phytoremediation in the *Journal of Geochemical Exploration* may be a function of the year of publication (1997, the first published article on phytoremediation in South Africa) and the quality of the research, which focuses on the potential of *Berkhya coddii* plant for phytoremediation of nickel-contaminated soil. The study suggested a yield of 100 kg/ha of nickel is attainable in various sites [34].

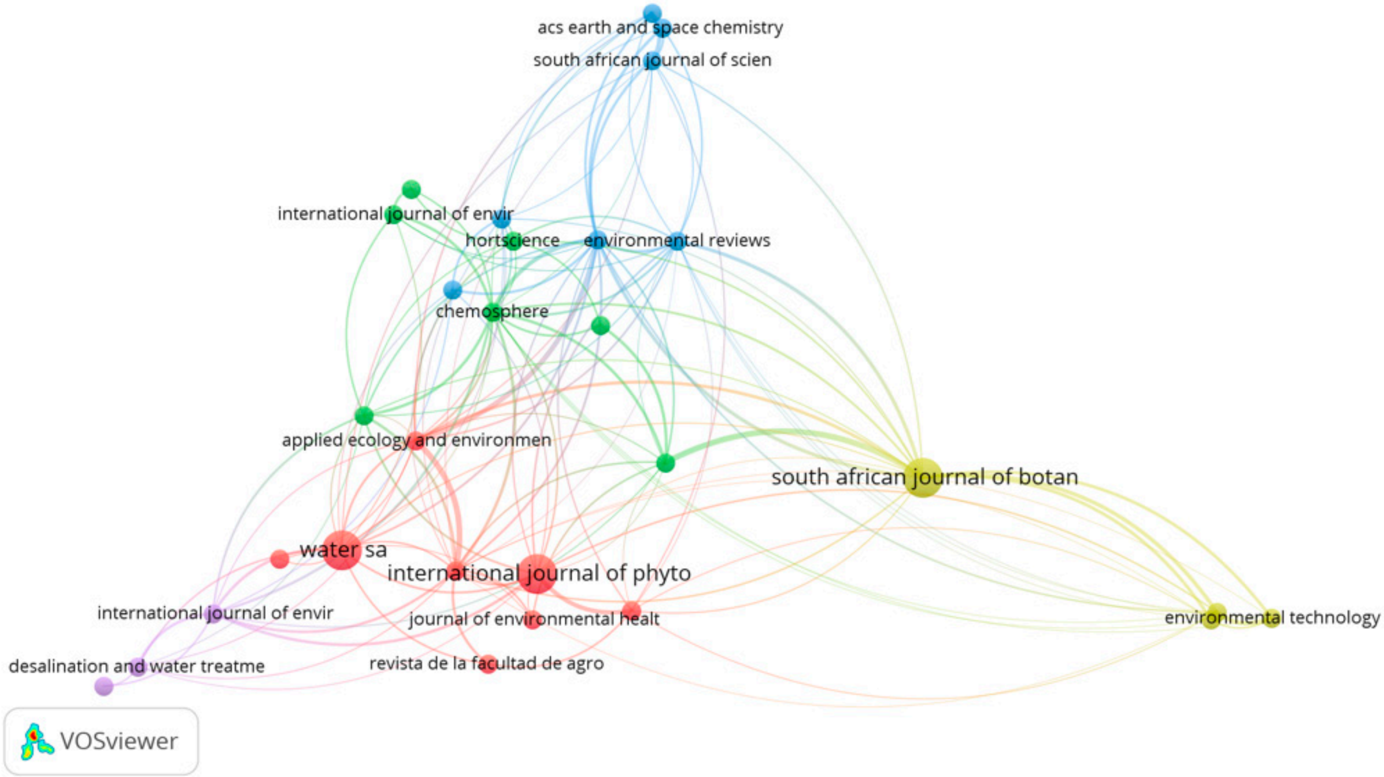


Figure 5. Bibliographic coupling analysis of journals.

3.6. Examples of Successful Phytoremediation Projects in South Africa

South Africa is a country contending with various environmental challenges, especially the impact of mining activities on the environment. In the pursuit of sustainable environmental management and remediation, the government of South Africa has come up with different environmental policies and regulations that aid the advancement and implementation of phytoremediation as an innovative tool for environmental restoration. The policy encourages research, investment, and implementation of phytoremediation technology in environmental remediation in South Africa [46,47]. This is made possible by providing incentives for research through grants and various funding mechanisms for the restoration of the environment [48]. Researchers in South Africa have taken advantage of these opportunities to promote phytoremediation technology. Some of the identified plant species for the restoration of contaminated environment in South Africa are shown in Table 4.

Table 4. Plant species in phytoremediation of the polluted environment in South Africa.

Method	Plant Species	Pollutants Removed	References
Phytostabilization and Phytoextraction	*Cyperus haspan*, *Schoenoplectus corymbosus*, *Typha capensis*, *Phragmites australis*, *Cynodon dactylon*, *Cyperus marginatus*, and *Juncus effusus*	Aluminium, Iron, and Manganese	[2]
Rhizofiltration	*Phragmites australis* and *Kyllinga nemoralis*	Cadmium, Chromium, Copper, Nickel, Lead, and Zinc	[8]
Rhizofiltration	*Phragmites australis*	Total kjeldahl Nitrogen	[9]
Phytoextraction	*Helianthus annuus*	Cd, Cu, Fe, Mn, Ni, Pb, and Zn	[42]
Phytoextraction	*Phragmites karka* and *Veteveria nigritana*	Fe, Mn, Pb, Mg, and Cr	[4]

Table 4. *Cont.*

Method	Plant Species	Pollutants Removed	References
Phytoextraction	*Chrysopogon zizanioides*	Chromium	[49]
Phytostabilization and Phytoextraction	*Salix mucronata*	Cadmium, Copper, and Lead	[15]
Phytoextraction	*Berkhya coddii*	Nickel	[34]
Phytoextraction	*Phragmites australis*	B, Cd, Cr, Cu, Mg, Ni, and Zn	[16]
Phytostabilization	*Helianthus annuus*	Cu	[50]
Phytoextraction	*Helianthus annuus*	Cd, Cu, Fe, Mn, Ni, Pb, and Zn	[43]
Phytoextraction	*Manihot esculenta*	Nickel	[51]
Phytoextraction	*Phragmites australis* and *Cyperus textilis*	Ammonia, Nitrate, Orthophosphate, and Glyphosate	[52]
Phytodegradation	*Chromolaena odorata*, *Aspilia Africana*, and *Uvaria chamae*	Arocol and Transformer Oil	[53]
Phycoremediation	*Chlorella vulgaris and Chlorella protothecoides*	Total Phosphates and Total Nitrogen	[54]
Phytoextraction	*Corchorus olitorius*	Lead	[55]
Phytoextraction	*Pennisetum clandestinum*	Cadmium	[56]
Phytostabilization and Phytoextraction	*Helichrysum splendidum*	Lead and Copper	[57]
Phytoextraction	*Chromolaena odorata*	Crude oil, Cd, Ni, and Zn	[58]
Phytoremediation	*Vetiveria zizanioides*	Zn, Mn, Ni, and Cu	[59]
Phytoextraction	*Eichhornia crassipes*	Phosphates and Nitrates	[22]

Eichhornia crassipes (water hyacinth) is an aquatic ornamental flower native to the Amazon Basin in South America and is now present in most continents. Although water hyacinth is considered an invasive aquatic plant, it has been used as a fertilizer and charcoal briquettes and in water treatment [60–62]. Reports have shown that the growth of water hyacinth in eutrophic water is beneficial. The plant consumes an enormous amount of nutrients (such as phosphorus, nitrogen, and potassium) from water, and a fraction of this is stored, while the leftovers are used for growth. Auchterlonie et al. [22] capitalized on the potential of water hyacinth as a remediation tool for the removal of phenols, heavy metals, and mirex, with restricted consequences on plants. Hartbeespoort Dam, located in the North West Province of South Africa, is polluted with acid mine drainage containing heavy metals [63]. The Auchterlonie et al. [22] report showed that water hyacinth grown in a vessel containing Hartbeespoort Dam water reduced the phosphate and nitrate concentrations by 93.8% and 87.8%, respectively, within 4 days. Consequently, *Eichhornia crassipes* can be deployed as a remediation tool for phytoextraction of nutrients without any harmful effects on plant health.

In addition, *Chrysopogon zizanioides* (vetiver grass) is a hyperaccumulator originally from India and is also found in South Africa [49,64]. Vetiver grass can grow up to a height of 5 ft, and its root is 7–13 ft deep. The stems are tall, and the leaves are somewhat rigid, thin, and long with brownish flowers [65,66]. Vetiver grass has been used in the treatment of industrial wastewater and soil reclamation in many countries [64,67]. Masinire et al. [49] reported the performance of vetiver grass in phytoextraction of chromium under hydroponic conditions. Their results indicated that grass density is proportional to the Cr(VI) removal efficiency. The experiment showed complete removal of Cr(VI) at a low concentration (5 ppm solution) in 26 days, while 82% removal was reported for the 30 ppm Cr(VI) solution in 30 days. The buildup of chromium in the vetiver leaves could make it suitable for extraction and recovery of the chromium. Therefore, vetiver grass can be used as a remediation tool for phytoextraction and/or phytostabilization of metals.

Furthermore, *Phragmites australis* and *Cyperus textilis* have been deployed for the reclamation of Renosterveld vegetation in the Western Cape Province of South Africa [52]. The contamination of Renosterveld vegetation and water bodies has been traced to the runoff from the excessive application of fertilizer and herbicide on agricultural land [68]. Rûens Silcrete Renosterveld is adjacent to the Breede River, which originates from the mountains of the Ceres basin, Western Cape, South Africa. The rate of deterioration of Rûens Silcrete Renosterveld vegetation is frightening. Thus, Jacklin et al. [52] investigated the performance of 14 indigenous wetland species occurring in Rûens Silcrete Renosterveld vegetation in a laboratory phytoremediation system. Their result indicated all wetland species had significant removal efficiencies for both herbicides and fertilizer than unvegetated soil. *Phragmites australis* and *Cyperus textilis* are the most effective species, with 95.87% and 96.42% removal, respectively. Therefore, these species can be considered for inclusion in vegetative buffer strips in river corridors.

4. Limitations

This study presents the mapping of phytoremediation research trends in South Africa from inception to 2022. However, the analysis might not give complete publications on the subject because our focus was on the articles indexed in the Web of Science without taking into account publications indexed in other scientific databases. Likewise, we may not have used up all likely keywords related to the phytoremediation research in South Africa within the specified period, and that may be a source of bias in our analysis. Additionally, some researchers might have collaborated with researchers from other institutions outside South Africa where the phytoremediation research took place, consequently influencing the number of publications connected to each affiliation in this study. Lastly, the focus of this study was to map the research trends on the topic; we did not analyze the contents of each publication to determine the scientific quality or otherwise of the articles. However, we presented three examples of phytoremediation research in South Africa.

5. Outlook of Phytoremediation in South Africa

This study reveals a slow but positive growth rate in publications. Notwithstanding the low annual growth rate of 4.49%, the research is published in high-impact journals, suggesting that the quality of studies remains commendable despite the limited volume. The prospect of further research is immense, especially considering the rich biodiversity and the availability of native hyperaccumulators uniquely suited to South African ecosystems. Indigenous species like *Berkheya coddii* and *Phragmites australis* have demonstrated efficacy in extracting heavy metals from contaminated soils, underlining the suitability of local species for phytoremediation projects.

Looking forward, several key aspects must be considered to fully harness the potential of phytoremediation in South Africa. Firstly, strategic investments in research and development are crucial. Governmental support, alongside incentives for private sector involvement, can increase the existing research base and drive innovations in phytoremediation techniques tailored to local environmental conditions. Secondly, enhancing international collaborations, particularly with leading nations like the USA, which currently holds the highest collaborative link strength with South Africa, could expedite knowledge transfer and the adoption of advanced methodologies.

Furthermore, phytoremediation aligns well with South Africa's commitment to sustainable development, as outlined in its National Development Plan and Green Economy Strategy. This alignment presents a distinct opportunity for mainstream phytoremediation as a cornerstone of environmental policy, especially in mining-impacted areas like Limpopo and Gauteng provinces, where the ecological and public health risks are most acute. Incorporating phytoremediation into national remediation frameworks could lead to large-scale restoration projects, thereby contributing to both ecological balance and socio-economic upliftment.

Finally, the future of phytoremediation in South Africa is promising but dependent upon improved research output, strategic collaborations, and policy integration. By capitalizing on its unique biodiversity and fostering a supportive research environment, South Africa can lead the way in pioneering phytoremediation technologies that not only restore degraded landscapes but also set a global benchmark for sustainable environmental management.

6. Conclusions

In the quest for green technologies to save the environment, the phytoremediation process has appeared as a potential candidate for tackling different kinds of environmental contamination. Hence, a bibliometric study was performed on the Web of Science to get a clear perspective of the situation of scientific production and collaboration on phytoremediation-related research in South Africa from inception to 2022. The study revealed 39 documents were published by 112 authors, and the annual publication rate is low (4.49%). Aid from the government and/or private sectors toward increasing research funds would improve the annual production rate. The USA has the highest collaboration network with South Africa, and the connection among authors was strong among a few authors. The most relevant journals on the subject are the *International Journal of Phytoremediation*, *South African Journal of Botany*, and *Water SA*. A short review of three selected articles revealed phytoremediation is effective in the remediation of polluted water and soil. We believe that with the plethora of indigenous plants in South Africa, researchers would be encouraged to explore phytoremediation techniques if the necessary support is provided by institutions and the government of South Africa. This might bring forth substantial output that will help the government in the restoration of land and water quality. Also, we believe new scholars in this field will find this study useful in discovering collaborators for future studies.

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