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CORRESPONDENCE

Assessing phytoremediation strategies for gold mine tailings: a bibliometric and systemic review

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Abstract This study evaluates the effectiveness of phytoremediation strategies in mitigating the environmental impacts of gold mine tailings through a bibliometric and systematic review. Utilizing the PRISMA methodology, 45 primary research articles were selected and analyzed, highlighting key rends and insights in phytoremediation research. The review spans over two decades of research, with a notable annual growth rate of 2.81% and significant contributions from countries like Indonesia, Malaysia, and South Africa. Key findings emphasize the variability in phytoremediation success based on plant species, site conditions, and remediation techniques. Prominent plants identified include vetiver grass, Siam weed, and water hyacinth, which demonstrate significant potential in heavy metal uptake and soil stabilization. The study also underscores the importance of optimizing plant–microbe interactions and employing site-specific approaches to enhance remediation efficiency. Future research opportunities are identified, focusing on genetic engineering of plants, field trials, and integration of advanced monitoring technologies. Overall, this comprehensive review highlights the promising potential of phytoremediation as a

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sustainable and effective strategy for managing gold mine tailings, advocating for continued research and policy support to advance this green technology in environmental management.

Abstraite Diese Studie bewertet die Wirksamkeit von Phytosanierungsstrategien bei der Minderung der Umweltauswirkungen von Rückständen aus Goldminen durch eine bibliometrische und systematische Überprüfung. Unter Verwendung der PRISMA-Methodik wurden 45 primäre Forschungsartikel ausgewählt und analysiert, um wichtige Trends undErkenntnisse in der Phytosanierungsforschung aufzuzeigen. Die Überprüfung umfasst über zwei Jahrzehnte Forschung mit einer bemerkenswerten jährlichen Wachstumsrate von 2,81 % und bedeutenden Beiträgen aus Ländern wie Indonesien, Malaysia und Südafrika. Wichtige Ergebnisse betonen die Variabilität des Erfolgs von Phytosanierung in Abhängigkeit von Pflanzenarten, Standortbedingungen und Sanierungstechniken. Hervorgehobene Pflanzen sind unter anderem Vetivergras, Siamesisches Unkraut und Wasserhyazinthen, die ein erhebliches Potenzial für die Aufnahme von Schwermetallen und die Bodenstabilisierung zeigen. Die Studie unterstreicht auch die Bedeutung der Optimierung von Pflanzen-Mikroben-Interaktionen und der Anwendung standortspezifischer Ansätze zur Verbesserung der Sanierungseffizienz. Zukünftige Forschungsrichtungen konzentrieren sich auf die genetische Veränderung von Pflanzen, Feldversuche und die Integration fortschrittlicher Überwachungstechnologien. Insgesamt hebt diese umfassende Überprüfung das vielversprechende Potenzial der Phytosanierung als nachhaltige und effektive Strategie für den Umgang mit Rückständen aus Goldminen hervor und plädiert für eine kontinuierliche Forschung und politische Unterstützung, um diese grüne Technologie im Umweltmanagement voranzutreiben.

Abstraite Cette étude évalue l'efficacité des stratégies de phytoremédiation dans l'atténuation des impacts environnementaux des résidus de mines d'or à travers une revue bibliométrique et systématique. En utilisant la méthodologie PRISMA, 45 articles de recherche primaires ont été sélectionnés et analysés, mettant en évidence les tendances et les perspectives clés de la recherche sur la phytoremédiation. La revue couvre plus de deux décennies de recherche, avec un taux de croissance annuel notable de 2,81 % et des contributions significatives de pays comme l'Indonésie, la Malaisie et l'Afrique du Sud. Les résultats clés soulignent la variabilité du succès de la phytoremédiation selon les espèces végétales, les conditions du site et les techniques de remédiation. Les plantes mises en avant incluent la vétiver, la mauvaise herbe de Siam et la jacinthe d'eau, qui démontrent un potentiel significatif dans l'absorption des métaux lourds et la stabilisation des sols. L'étude souligne également l'importance d'optimiser les interactions plantes-microbes et d'adopter des approches spécifiques aux sites pour améliorer l'efficacité de la remédiation. Les opportunités de recherche future identifiées incluent l'ingénierie génétique des plantes, les essais sur le terrain et l'intégration de technologies de surveillance avancées. Globalement, cette revue exhaustive met en avant le potentiel prometteur de la phytoremédiation en tant que stratégie durable et efficace pour gérer les résidus de mines d'or, appelant à une recherche continue et à un soutien politique pour faire progresser cette technologie verte dans la gestion environnementale.

Abstracta Este estudio evalúa la eficacia de las estrategias de fitorremediación en mitigar los impactos ambientales de los residuos de minas de oro mediante una revisión bibliométrica y sistemática. Utilizando la metodología PRISMA, se seleccionaron y analizaron 45 artículos de investigación primarios, destacando las principales tendencias y perspectivas en la investigación sobre fitorremediación. La revisión abarca más de dos décadas de investigación, con una notable tasa de crecimiento anual del 2,81 % y contribuciones significativas de países como Indonesia, Malasia y Sudáfrica. Los hallazgos clave enfatizan la variabilidad en el éxito de la fitorremediación según las especies de plantas, las condiciones del sitio y las técnicas de remediación. Las plantas destacadas incluyen la hierba vetiver, la maleza de Siam y el jacinto de agua, que demuestran un potencial significativo en la absorción de metales pesados y la estabilización del suelo. El estudio también destaca la importancia de optimizar las interacciones planta-microbio y emplear enfoques específicos para el sitio para mejorar la eficiencia de la remediación. Se identifican oportunidades futuras de investigación centradas en la ingeniería genética de plantas, ensayos de campo y la integración de tecnologías avanzadas de monitoreo. En general, esta revisión integral destaca el prometedor potencial de la fitorremediación como una estrategia sostenible y efectiva para gestionar los residuos de minas de oro, abogando por una investigación continua y un apoyo político para avanzar en esta tecnología verde en la gestión ambiental.

Astratta Questo studio valuta l'efficacia delle strategie di fitorisanamento nel mitigare gli impatti ambientali dei residui delle miniere d'oro attraverso una revisione bibliometrica e sistematica. Utilizzando la metodologia PRISMA, sono stati selezionati e analizzati 45 articoli di ricerca primari, evidenziando le principali tendenze e intuizioni nella ricerca sul fitorisanamento. La revisione copre oltre due decenni di ricerca, con un tasso di crescita annuale notevole del 2,81% e contributi significativi da paesi come Indonesia, Malesia e Sudafrica. I risultati principali evidenziano la variabilità del successo del fitorisanamento in base alle specie vegetali, alle condizioni del sito e alle tecniche di risanamento. Le piante più rilevanti includono la vetiver, la siamese e il giacinto d'acqua, che dimostrano un potenziale significativo nell'assorbimento dei metalli pesanti e nella stabilizzazione del suolo. Lo studio sottolinea anche l'importanza di ottimizzare le interazioni pianta-microrganismo e di adottare approcci specifici per sito per migliorare l'efficienza del risanamento. Le opportunità di ricerca futura si concentrano sull'ingegneria genetica delle piante, le prove sul campo e l'integrazione di tecnologie avanzate di monitoraggio. Complessivamente, questa revisione completa evidenzia il promettente potenziale del fitorisanamento come strategia sostenibile ed efficace per gestire i residui delle miniere d'oro, sostenendo la ricerca continua e il supporto politico per avanzare questa tecnologia verde nella gestione ambientale.

Keywords Phytoremediation · Gold mine tailings · Bibliometric analysis · Environmental remediation · Heavy metals

Schlüsselwörter Phytosanierung · Goldminenrückstände · Bibliometrische Analyse · Umweltsanierung · Schwermetalle

Motsclés Résidus de mines d'or · Analyse bibliométrique · Remédiation environnementale · Métaux lourds

Palabrasclave Fitorremediación · Residuos de minas de oro · Análisis bibliométrico · Remediación ambiental · Metales pesados

Parolechiave Fitorisanamento · Residui di miniere d'oro · Analisi bibliometrica · Risanamento ambientale · Metallipesanti

Introduction

The increasing environmental concerns associated with gold mining activities have necessitated the development of sustainable remediation technologies to manage mine tailings and mitigate their adverse impacts on ecosystems (Araujo et al., 2022; Karaca et al., 2018; Xu et al., 2019). Gold mine tailings, which consist of fine-grained waste material left after the extraction of valuable minerals, often contain high concentrations of heavy metals such as arsenic (As), lead (Pb), and mercury (Hg) (Kastury et al., 2024), posing significant risks to soil and water quality (Hadzi et al., 2024), as well as to human and ecological health (Okewale & Grobler, 2023; Tibane & Mamba, 2023). Traditional methods of remediation, such as physical removal and chemical stabilization, are often costly and may not provide long-term solutions to contamination (Rajendran et al., 2022).

Phytoremediation, the use of plants to absorb, accumulate, and detoxify pollutants from contaminated environments, has emerged as a promising and cost-effective alternative for the remediation of heavy metal-contaminated soils (Ashraf et al., 2019; Khan et al., 2023; Lavanya et al., 2024; Xu et al., 2023). This green technology leverages the natural processes of certain plant species to stabilize, extract, and degrade contaminants, offering an environmentally friendly solution that also contributes to soil restoration and ecosystem recovery (Priya et al., 2023; Tan et al., 2023). Certain plants have demonstrated strong in-situ phytoremediation potential, effectively removing metals from industrial waste and offering a promising, publicly accepted approach for re-vegetating heavy-metal contaminated soils (Sharma et al., 2021a, 2021b).

Research over the past two decades has identified a variety of plant species capable of phytoremediation, each with unique traits that make them suitable for different types of contaminants and environmental conditions (Kafle et al., 2022). Key factors influencing the effectiveness of phytoremediation include the plant's growth rate, biomass production, root system architecture, and tolerance to high concentrations of heavy metals (Shen et al., 2022). Metal-accumulating plants demonstrate strong phytoremediation potential and can be valuable tools for the eco-restoration of polluted site (Sharma et al., 2020). Additionally, the interaction between plants and soil microorganisms, such as arbuscular mycorrhizal fungi (AMF), can significantly enhance the uptake and translocation of metals, further improving phytoremediation outcomes (Putra et al., 2022, 2024).

Despite the promising potential of phytoremediation, its practical application in the field, particularly in gold mine tailings, remains challenging. Factors such as soil composition, climate conditions, and the presence of multiple contaminants require site-specific strategies and extensive research to optimize remediation techniques (Kuppusamy et al., 2016). Moreover, integrating phytoremediation with other remediation methods, such as soil amendments and microbial inoculation, can enhance the efficiency and sustainability of the process (Liu et al., 2020).

This study aims to provide a comprehensive review of phytoremediation strategies for gold mine tailings, highlighting key research trends, effective plant species, and innovative techniques that have been developed over the past two decades. By analyzing the existing literature and identifying future research opportunities, this paper seeks to inform both scientific research and practical applications in the field of environmental remediation. The findings underscore the importance of continued research and collaboration to fully harness the potential of phytoremediation as a sustainable solution for managing gold mine tailings and protecting environmental health.

Methods

Eligibility criteria

The inclusion criteria for this systematic review and bibliometric analysis were: (1) studies that assess the effectiveness of phytoremediation in addressing gold mine tailings; (2) studies published in peer-reviewed journals between 1994 and 2024; (3) studies written in English. Exclusion criteria included: (1) studies not focused on phytoremediation of gold mine tailings; (2) non-peer-reviewed articles such as conference abstracts, editorials, and commentaries; (3) studies not available in full text. The studies were grouped based on their focus on phytoremediation techniques and outcomes for synthesis.

Information sources and search strategy

The main database utilized for this study was Scopus, renowned for its extensive collection of peer-reviewed scientific literature (Linnenluecke et al., 2020). Scopus was selected due to its rigorous indexing of quality journals across diverse disciplines, ensuring comprehensive coverage of relevant literature on phytoremediation strategies, which is vital for capturing significant research contributions in the field and supporting the robustness of our bibliometric analysis. The search strategy employed included keywords and Boolean operators to effectively combine terms: (gold AND mine AND tailings AND phytoremediation). Filters were applied to include only peer-reviewed journal articles published between 1994 and 2024, resulting in an initial yield of 55 documents. These documents underwent a rigorous selection process based on pre-established criteria to ensure their relevance to the research objectives. Additionally, supplementary studies were identified by reviewing the reference lists of included articles. The full search strategy and filters applied are detailed in Supplementary Fig. 1, and the search concluded on June 26, 2024, at 2:39 PM.

Selection process

Two reviewers independently evaluated the titles and abstracts of all retrieved records to assess eligibility. Full-text articles meeting the initial criteria were subsequently reviewed independently by the same reviewers for final inclusion. Discrepancies were resolved through consensus, involving a third reviewer when necessary. This process culminated in a final selection of 45 articles for detailed analysis. The study selection did not employ any automated tools. A visual representation illustrates the search and selection process. This systematic review and bibliometric analysis strictly adhered to the PRISMA guidelines, and the completion of the PRISMA checklist ensured comprehensive coverage of all relevant aspects, thereby enhancing the rigor and transparency of the research process.

Data collection process

Bibliometric analysis is a robust empirical method that utilizes quantitative techniques to derive insights from published literature across various disciplines (Ellegaard & Wallin, 2015). This study adopts a comprehensive approach, employing citation and geographic network analyses alongside rankings of influential countries and authors. Additionally, word cloud generation is utilized to identify prevailing themes within the literature. These methodologies collectively illuminate the evolution of research within the chosen field over time, highlighting significant and emerging themes within the specified period (Linnenluecke & Griffiths, 2013).

A pivotal aspect of bibliometric analysis involves visualizing the intricate networks formed by the extensive collection of extracted articles. This visualization is achieved through multidimensional scaling techniques, facilitating the exploration of interrelationships among publications. Various software tools, such as R packages, iGraph, VOSviewer, and Biblioshiny, are available for this purpose (Zupic & Čater, 2015). The advancement of web-based and electronic bibliographic and referencing tools has markedly improved the quality of bibliometric outputs, driven by ongoing innovation and enhanced accessibility (Allen et al., 2009).

In this study, VOSviewer is employed for its intuitive interface and clear visual representations, enabling the creation and depiction of author and country networks. Similarly, Biblioshiny, an extension of the Bibliometrix R package, is utilized to generate the prominent keyword cloud, effectively visualizing database clusters. The search and selection process is represented visually, providing a comprehensive overview of the methodology used in this research.

Data items

In conducting this bibliometric analysis, data were systematically gathered across several key domains to comprehensively explore the landscape of research on phytoremediation of gold mine tailings. Primary outcomes focused on publication trends, citation analysis, research themes, and collaborative networks. Publication trends were assessed by tracking annual publication counts related to the topic. Citation analysis evaluated the impact of each publication through citation counts, reflecting its recognition in the academic community. Research themes were identified using keyword analysis and thematic clustering to uncover prevalent topics addressed in the literature. Collaborative networks examined patterns of author and institutional collaboration, including co-authorship patterns and geographic distribution of research contributions.

In addition to these primary outcomes, data were collected on supplementary variables such as study characteristics, participant details, and funding sources. Study characteristics encompassed study type (e.g., empirical, review), specific focuses within phytoremediation of gold mine tailings, and publication year. Participant characteristics included information on plant species used and geographic locations studied. Information on funding sources was gathered to identify potential influences on research outcomes and conflicts of interest. In cases where data were missing or unclear, efforts were made to impute missing information based on available context or exclude studies with insufficient data from specific analyses. Authors were contacted for clarification when necessary, although responses were not always received. These rigorous steps aimed to ensure the completeness and accuracy of the data collected, supporting the robustness and reliability of the bibliometric analysis conducted.

Study risk of bias assessment

To evaluate the risk of bias in the studies included in this bibliometric analysis, we employed a specialized framework tailored for such analyses. This framework systematically assessed several dimensions: the quality and reliability of data sources, particularly focusing on the comprehensive and representative nature of the Scopus database. Each study underwent rigorous evaluation for its relevance to the research topic and the accuracy of its indexing. Transparency in the selection process was paramount, with clear inclusion and exclusion criteria meticulously documented and consistently applied to minimize selection bias. Potential reporting bias was scrutinized by examining the tendency of published studies to emphasize positive or statistically significant findings. To mitigate this, efforts were made to include grey literature and unpublished studies, ensuring a balanced representation of research outcomes. Two independent reviewers conducted thorough evaluations of each study, resolving any discrepancies through consensus or consultation with a third reviewer when necessary. This comprehensive approach aimed to identify and address potential biases effectively, thereby enhancing the reliability and robustness of the bibliometric analysis.

Effect measures

In this bibliometric analysis, the metrics used to assess each outcome were tailored to suit the study's objectives. To examine publication trends in phytoremediation of gold mine tailings, the focus was on analyzing the annual number of publications, providing insights into evolving research patterns over time. The effect measure utilized was the total count of publications per year. For citation analysis, the impact of research was evaluated through metrics such as the average number of citations per article and the total citations received by articles in the dataset. This approach aimed to gauge the scholarly influence and recognition of the research findings within the academic community. Research themes were identified using keyword analysis and thematic clustering techniques. The effect measures here included the frequency of keyword occurrences and the thematic clusters generated from the bibliometric analysis, revealing prevalent topics and trends in the literature on phytoremediation of gold mine tailings. Collaborative networks among authors and institutions were explored to understand patterns of cooperation in research endeavors. Measures such as the number of co-authors per article and the visualization of collaboration networks using tools like VOSviewer were employed. Effect measures encompassed the total number of collaborations and the geographic distribution of research contributions, shedding light on the global reach and collaborative dynamics within the field. These effect measures were integral to capturing comprehensive insights into publication trends, citation impacts, research themes, and collaborative networks, thereby enriching the depth and breadth of the bibliometric analysis conducted.

Synthesis methods

Studies included in this synthesis met predefined inclusion criteria and provided pertinent data for the specified outcomes. Characteristics of each study were systematically tabulated and compared. Data preparation involved categorizing and coding relevant information to identify recurring themes and patterns across studies. Results from individual studies were compiled and presented visually using thematic maps and word clouds generated via bibliometric analysis tools. Narrative synthesis techniques were employed to integrate findings across studies, summarizing and interpreting emerging patterns and themes in phytoremediation of gold mine tailings research. Bibliometric tools like VOSviewer and Biblioshiny facilitated the visualization of collaboration networks and thematic clusters within the literature. Subgroup analyses were conducted to explore potential variations in research outcomes, such as geographic differences and variations in plant species studied. Given the nature of the study, sensitivity analyses were not applicable as quantitative synthesis or meta-analysis was not performed. Instead, the robustness of thematic findings was bolstered through cross-referencing and triangulation of multiple sources of evidence. This comprehensive approach ensured a nuanced exploration of the literature, providing insights into collaborative dynamics, thematic trends, and geographic variations in research on phytoremediation of gold mine tailings (Fig. 1).

Result and discussion

Descriptive analysis

Study selection results

The PRISMA flow chart provides a comprehensive overview of the literature selection process for this systematic review on phytoremediation studies. The identification phase began with 55 records identified from databases and an additional 22 from registers, totaling 77 records. Notably, no records were removed prior to screening, indicating all identified

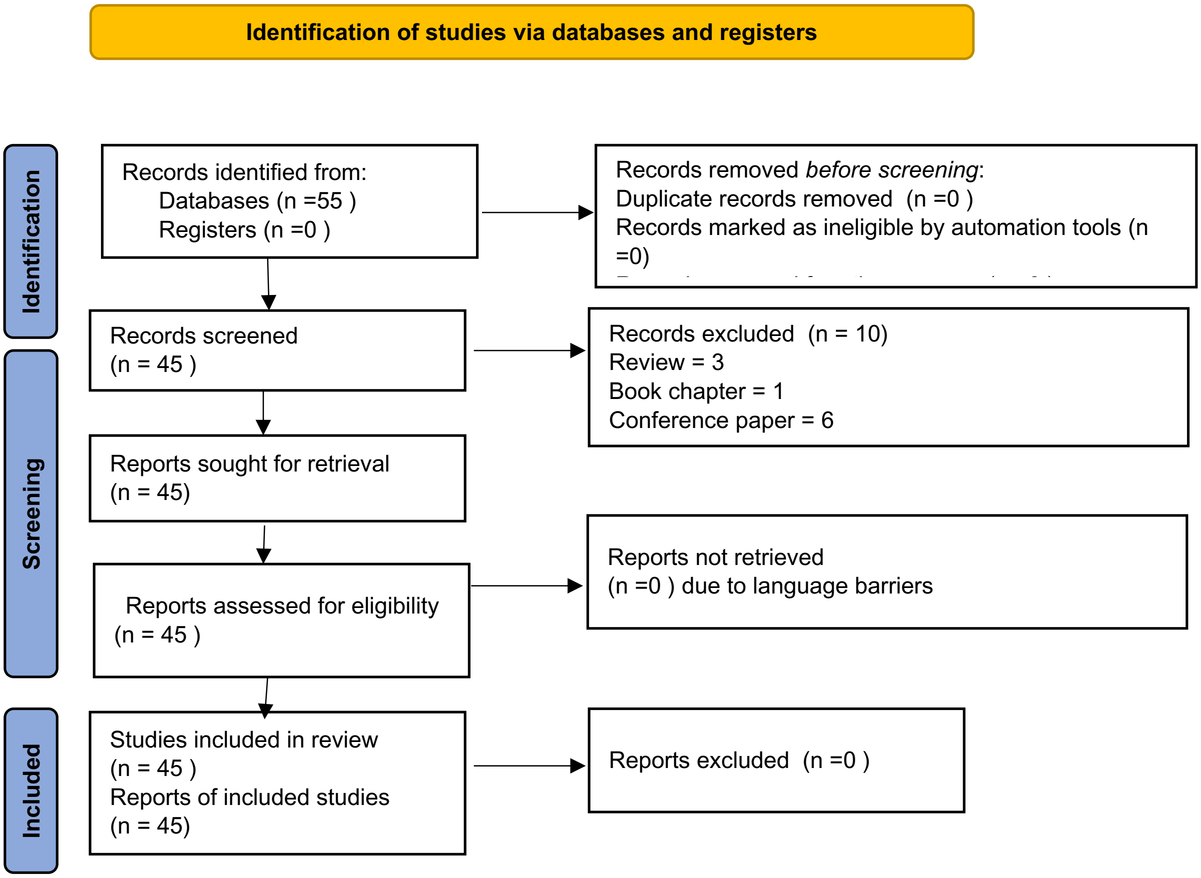

Fig. 1 Flow chart of the literature selection process according to PRISMA protocols

records were unique and initially met the inclusion criteria. During the screening phase, 45 records were screened. Of these, 10 records were excluded for specific reasons: 3 were review articles, 1 was a book chapter, and 6 were conference papers. These exclusions were necessary to ensure the dataset comprised only primary research articles that provide original data and findings on phytoremediation. Subsequently, 45 reports were sought for retrieval, and all were successfully retrieved, indicating an effective search and retrieval process. No reports were excluded at this stage, suggesting language barriers were not a significant issue, and all retrieved reports were in a language accessible to the reviewers. In the eligibility assessment phase, all 45 reports were deemed eligible for inclusion in the systematic review. No additional reports were excluded at this stage, ensuring that the final dataset was comprehensive and met the predefined inclusion criteria. In the final inclusion phase, all 45 studies were included in the review, providing a robust dataset for analysis. This comprehensive inclusion indicates that the screening and eligibility assessment processes were thorough and effective in identifying relevant studies. Overall, the systematic review process was meticulous, with clear criteria and rigorous screening ensuring the inclusion of high-quality, relevant studies. The absence of excluded records due to language barriers highlights the accessibility and inclusiveness of the selected studies. This systematic review provides a solid foundation for understanding the state of research in phytoremediation and offers insights into the effectiveness of various plants in removing heavy metals from contaminated soils. The detailed and structured approach used in this review ensures the findings are reliable and can inform future research and practical applications in the field of phytoremediation.

Trend in publication outputs and citations

The dataset spans publications from 1999 to 2024, indicating that research on phytoremediation has been conducted for over two decades. The number of sources contributing to this dataset is 33, including journals, books, and other publications, suggesting that this topic has extensive coverage in the scientific literature. A total of 45 documents were analyzed, providing a sufficiently large sample for systematic analysis. The average annual growth rate of these publications is 2.81%, indicating steady growth in phytoremediation research. The average age of the documents in this dataset is 6.78 years, indicating that the research included is relatively recent and relevant. The average number of citations per document is 20.36, demonstrating that these documents have a significant impact in their field. The total number of Keywords Plus (ID) used in the documents is 518, indicating a wide range of topics discussed in the literature, while the number of author-provided keywords (DE) is 145, showing the variety of terms used to describe their research. The total number of contributing authors is 156, indicating extensive collaboration in phytoremediation research. There is only one single-authored document, showing that this research is typically conducted collaboratively, with an average of 4.07 co-authors per document, indicating a high level of collaboration. The percentage of documents with international co-authorship is 13.33%, indicating significant international contributions to this research. All documents in this dataset are articles, reflecting a focus on formal scientific publications (Table 1).

Top authors' contributions to phytoremediation research for gold mine tailings

In our bibliometric analysis of phytoremediation research focused on mine tailings, we have identified several key contributors who have consistently published influential work in this field. The most prolific author is Sampanpanish P, with five publications, while Hamim H, Nuraini Y, and Setyaningsih L each have three publications. The details of author productivity are summarized in the accompanying table. These authors have significantly contributed to advancing the understanding of phytoremediation techniques, particularly in the context of heavy metal contamination in mine tailings (Fig. 2).

Table 1 Key information about datasets

Description	Results
Timespan	1999:2024
Sources (Journals, Books, etc.)	33
Documents	45
Annual growth rate %	2.81
Document average age	6.78
Average citations per doc	20.36
Keywords plus (ID)	518
Author's keywords (DE)	145
Authors	156
Authors of single-authored docs	1
Single-authored docs	1
Co-Authors per Doc	4.07
International co-authorships %	13.33
article	45

The productivity of researchers in the field of gold mine tailings phytoremediation over a specific period is visually represented. Each point on the graph represents a publication or scientific article produced by an author in a given year. The size of the points reflects the number of articles published, while the horizontal lines connecting the points from the same author indicate the consistency or variation in their productivity over time. This pattern offers valuable insights into individual researchers' contributions and how their engagement in this field has evolved over time.

Significant variation in the number of publications among researchers is evident, with some authors demonstrating high productivity, such as Sampanpanish P, who has made substantial contributions to the phytoremediation literature. On the other hand, other researchers may have fewer publications but still contribute to specific areas of study. This suggests that productivity in this field is not solely determined by the volume of publications but also by the quality and impact of the research produced.

However, there are periods where research activity declines, which may be attributed to various factors, including shifts in research focus, funding challenges, or resource limitations. These fluctuations underscore the importance of continuous funding and support for phytoremediation research to ensure that researchers can keep innovating and providing solutions to the environmental challenges posed by mine tailings.

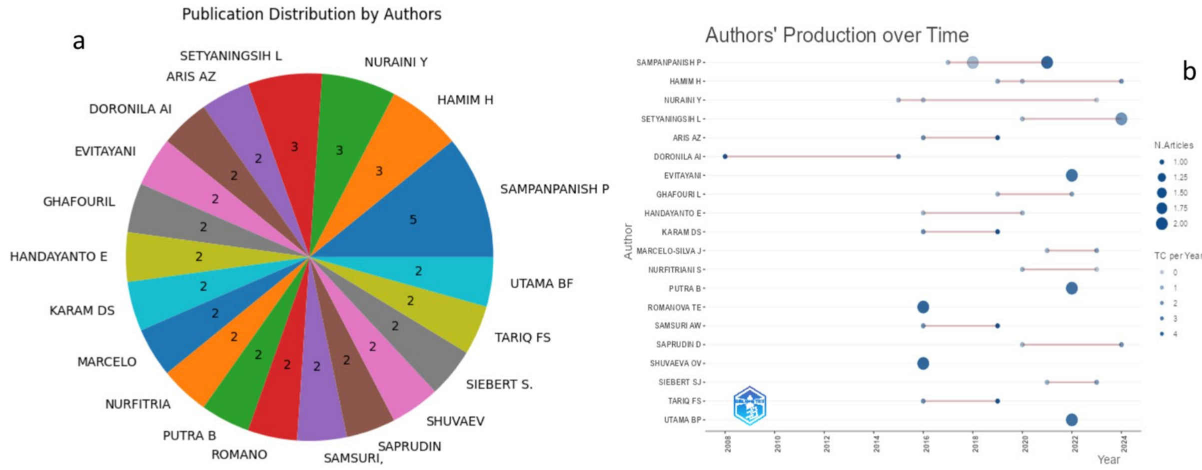

Fig. 2 Publication distribution by Authors (a) and authors' production over time in Phytoremediation of Gold Mine Tailings

Top countries in phytoremediation research for gold mine tailings

Indonesia leads global scientific production in phytoremediation research with 57 publications, reflecting the country's focus on addressing environmental challenges related to gold mining, particularly in artisanal operations, as summarized in the accompanying figure. South Africa follows, driven by the need to rehabilitate mining-impacted regions. China ranks third, with contributions focusing on innovative solutions for heavy metal contamination. Other key contributors include Brazil and the USA, both of which have large mining sectors. Australia and Thailand are also notable, reflecting their emphasis on mine rehabilitation and artisanal mining, respectively.

Emerging contributors like Malaysia, Mexico, and Ethiopia highlight the growing global interest in phytoremediation, particularly in developing countries where cost-effective, sustainable solutions are crucial. Contributions from countries like Iran, Ghana, and Philippines emphasize the broader geographic spread of research in this field. Overall, the distribution of publications shows that phytoremediation research is a global effort, with contributions from both developed and developing nations, highlighting its relevance in addressing the environmental impacts of gold mining worldwide (Fig. 3).

The data on the most cited countries in phytoremediation research for gold mine tailings highlights China's dominance, showcasing its significant investment in environmental remediation technologies. Australia follows, reflecting its focus on sustainable solutions for mine tailings due to its large mining industry. South Africa ranks third, driven by its need to address mining-related environmental issues. Other contributors include Korea, Austria, and Indonesia, with Indonesia's emerging role underscoring its growing participation in global research. Additionally, countries like Iraq, Denmark, Malaysia, and Thailand contribute, albeit on a smaller scale, expanding the geographic diversity of phytoremediation studies. This analysis demonstrates that while a few nations dominate in citation impact, many others play crucial roles in advancing the global understanding of phytoremediation as a solution for mining-related environmental problems, as shown in the visual representation of citation data.

A detailed visualization of scientific production over time from various countries engaged in research related to phytoremediation of gold mine tailings reveals several key trends. One of the most striking features of the data is the dominance of Indonesia, particularly from 2019 onwards. The country demonstrates a dramatic increase in publications, exceeding 40 scientific articles by 2024. This trend highlights Indonesia's emerging leadership in addressing environmental challenges related to gold mining, especially through the use of phytoremediation techniques. South Africa and China also show consistent contributions to this field, though at a lower level compared to Indonesia. Both countries exhibit steady

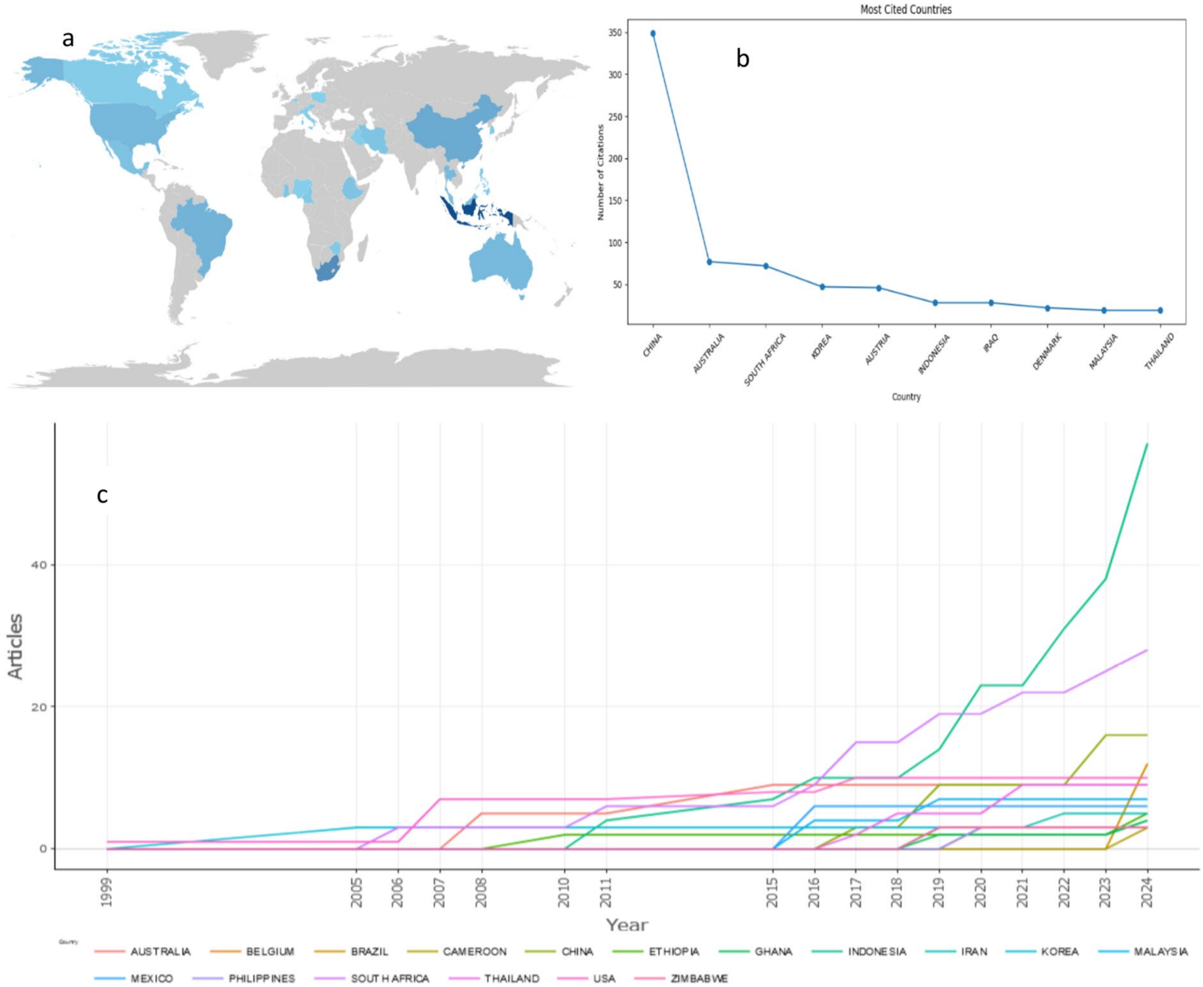

Fig. 3 Countries' Scientific Production **a**, Most Cited Countries **b**, and Countries' Production Over Time **c** in Phytoremediation Research for Gold Mine Tailings. Panel (a) displays the global distribution of scientific production, highlighting the leading countries by the number of publications in the field of phytoremediation for mine tailings. Panel (b) showcases the most cited countries, indicating which nations have produced research with the greatest global impact. Panel (c) illustrates the trends in scientific production over time, depicting how research output from various countries has evolved and increased throughout the years

growth, particularly after 2015. This steady increase suggests ongoing research efforts in these nations, focusing on sustainable solutions for environmental remediation. Other countries, such as Australia, Thailand, and Brazil, have been involved in phytoremediation research for a longer period, but their growth is more gradual. These nations contribute regularly to the field, though without the sharp increase seen in Indonesia, indicating steady but slower scientific output. The graph also reflects a global collaboration in this area of research. Contributions come from diverse regions, including Africa (South Africa, Ethiopia, Ghana), Asia (China, Thailand, Malaysia), and America (Brazil, USA, Mexico). This wide range of contributors underscores the international importance of phytoremediation research in mitigating the environmental impacts of gold mining. Finally, the upward trends in publication numbers, especially in the last decade, point to a growing international interest in phytoremediation as a sustainable solution for gold mine tailings. The collective efforts of these countries reflect a broader global movement towards environmentally-friendly mining practices and the restoration of affected ecosystems.

Analysis of key terms, authors, and co-authorship networks in phytoremediation research

The Sankey diagram presented illustrates the relationships between keywords (DE), authors (AU), and the countries of affiliation (AU_CO) within research focused on phytoremediation for gold mine tailings. The diagram highlights several key terms frequently encountered in the literature, such as "phytoremediation," "gold mine tailings," "arbuscular mycorrhizal fungi," "heavy metals," and "napier grass." These keywords reflect the primary focus areas within this field, emphasizing the utilization of plants to address heavy metal contamination in former gold mining areas. The specificity of these keywords aids in identifying critical topics that are commonly explored in phytoremediation research, providing a clear overview of current research trends and directions. The active contributors in this field come from various countries, with significant input from Indonesia, Malaysia, South Africa, Australia, Thailand, Iran, and the United States. Prominent authors such as "Samaprananish P," "Hamim H," "Saprudin D," and "Setyaningsih I" frequently appear in the literature, indicating their pivotal roles in phytoremediation research. The diagram also reveals collaboration patterns among researchers and the geographical distribution of studies, highlighting the substantial activity from Indonesian researchers. This underscores the relevance of phytoremediation research in countries with extensive mining activities and the need for sustainable solutions. Overall, the diagram provides comprehensive insights into the global research network in phytoremediation of gold mine tailings, delineating the main topics investigated and the geographical distribution of the researchers involved (Fig. 4).

Distribution of phytoremediation research articles by source and zone

The bar graph illustrates the distribution of articles across various scientific journals, highlighting the scholarly focus on phytoremediation strategies for gold mine tailings. This visual representation, segmented into three impact zones, underscores the concentration of research within high-impact journals such as the "International Journal of

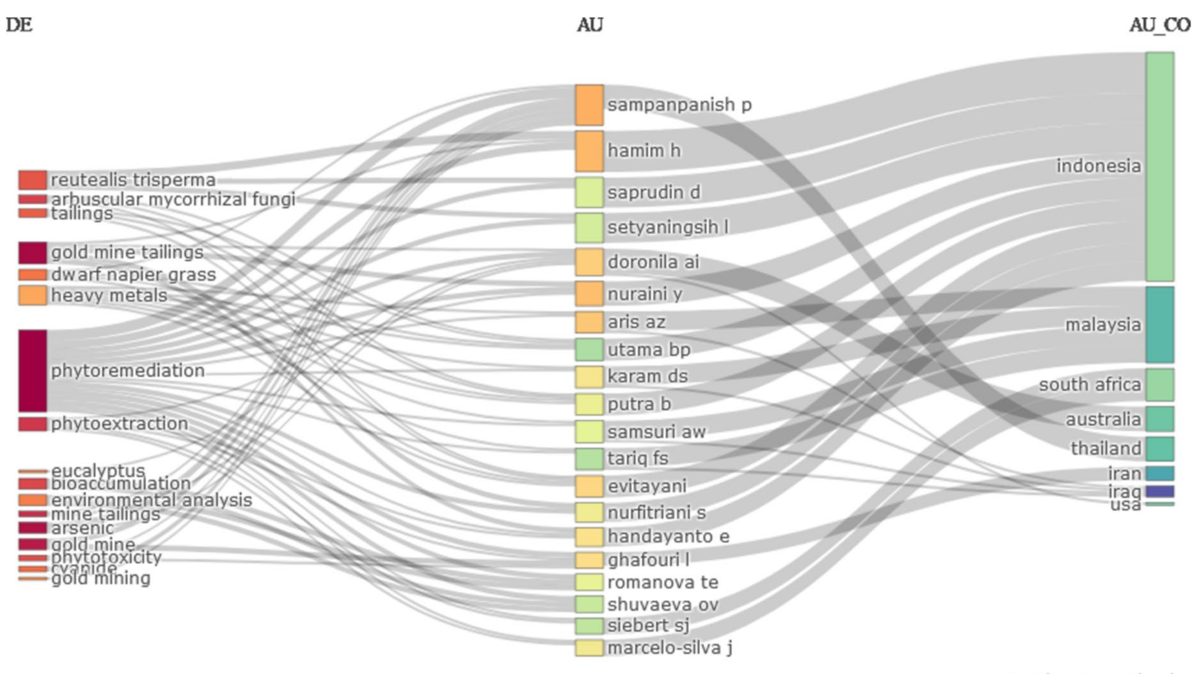

Fig. 4 Sankey diagram illustrating the relationships between keywords (DE), authors (AU), and countries of affiliation (AU_CO) in research focused on phytoremediation for gold mine tailings

Phytoremediation" and "Science of the Total Environment," which collectively indicate a robust interest and validation of phytoremediation methodologies in these top-tier platforms. The presence of numerous articles in Zone 1 journals demonstrates the critical recognition and dissemination of research findings in highly reputable sources, validating the importance of phytoremediation in mitigating environmental impacts of gold mining. Conversely, the inclusion of articles in Zone 2 and Zone 3 journals reflects a broader dissemination across diverse scientific communities, promoting a comprehensive understanding and interdisciplinary approach to phytoremediation. This bibliometric analysis, combined with meta-analytic insights, provides a holistic evaluation of phytoremediation efficacy, informing future research directions and policy frameworks for sustainable mine tailing management (Fig. 5).

Co-occurrence network of key terms in phytoremediation research

The co-occurrence network provides valuable insights into the current research landscape of phytoremediation strategies for gold mine tailings. The centrality of keywords like phytoremediation and bioremediation highlights the primary focus on using biological methods to remediate contaminated sites. The interconnectedness and dense clustering indicate a multidisciplinary approach, combining aspects of soil science, chemistry, and environmental monitoring. The visualization also points to key areas of ongoing research and potential gaps. For example, while heavy metals and soil pollutants are well-studied, there may be emerging areas such as specific plant responses or novel remediation techniques that are gaining attention but are not yet central. Overall, this network map serves as a useful tool for researchers to identify major themes, central topics, and emerging trends in the field of phytoremediation for gold mine tailings, guiding future research directions and collaborations (Fig. 6).

Distribution of phytoremediation research articles by institutional affiliation

The distribution of articles by affiliation highlights the institutions leading the research on phytoremediation strategies for gold mine tailings. It reflects the global interest and collaborative efforts required to tackle the environmental challenges posed by mining activities. The data suggests that institutions with

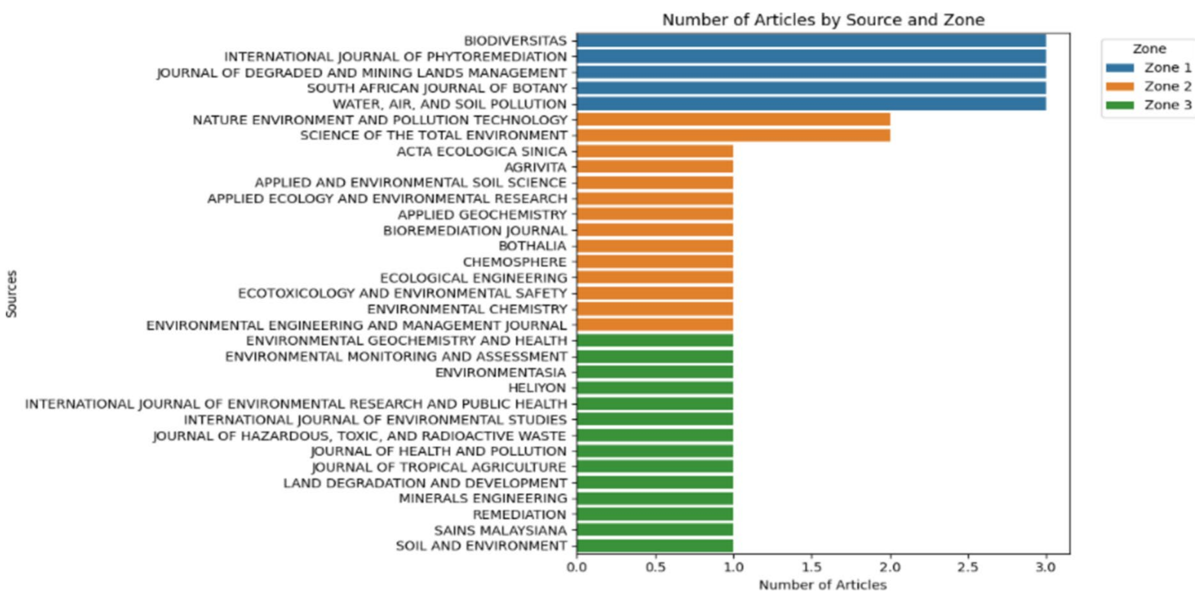

Fig. 5 Number of Articles by Source and Zone illustrates the distribution of articles across various journals related to phytoremediation strategies for gold mine tailings, highlighting the concentration of research efforts and publications within different scientific journals and their relative influence in the field

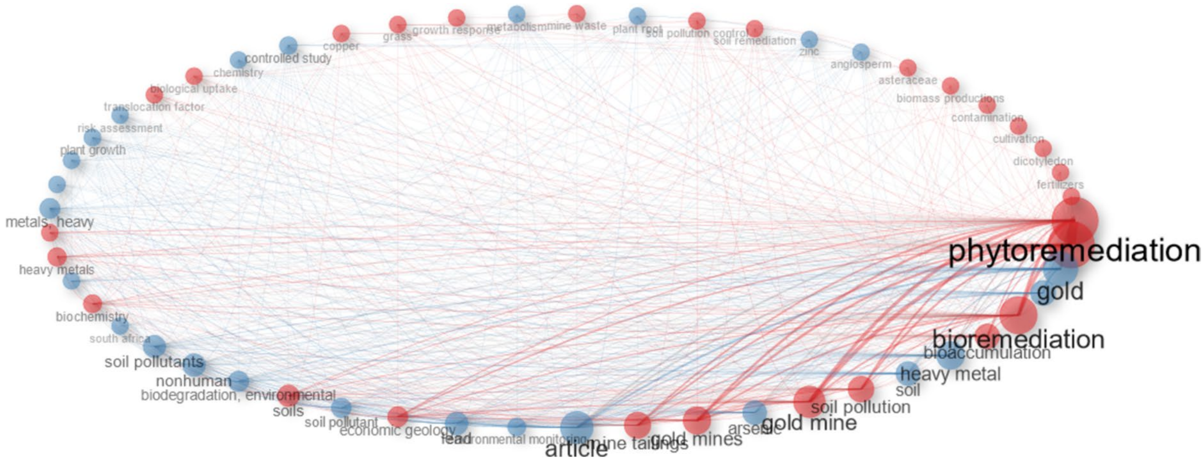

Fig. 6 Co-occurrence Network Visualization of Keywords Related to Phytoremediation Strategies for Gold Mine Tailings

strong technical and scientific backgrounds are at the forefront of this research, contributing significantly to developing effective phytoremediation methods. This insight can guide researchers and policymakers in identifying potential collaborators, understanding regional research strengths, and fostering international partnerships to enhance the impact and scope of phytoremediation strategies. It also underscores the importance of continued support and funding for institutions leading this critical research area, ensuring sustained progress and innovation in environmental remediation (Fig. 7).

The Instituto Tecnológico Vale leads with 12 articles, reflecting Brazil's increasing focus on sustainable mining and environmental remediation. Following closely are Brawijaya University and Universitas Airlangga from Indonesia, each contributing 9 publications and highlighting their efforts in addressing environmental issues related to artisanal mining through phytoremediation. IPB University in Indonesia and the University of the Witwatersrand in South Africa each contributed 7 articles, driven by the need for innovative solutions for land rehabilitation in regions with extensive mining. Other notable institutions include China's University of Science and Technology Beijing, North-West University in South Africa, and The University of Texas at El Paso, each with 6 articles, showcasing global collaboration in

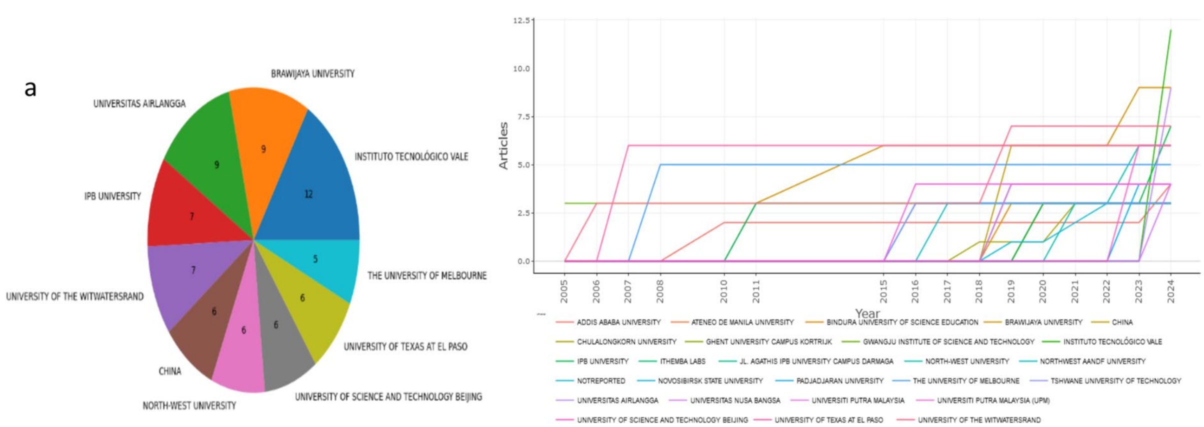

Fig. 7 **a** Illustrates the top affiliations contributing to phytoremediation research, highlighting key institutions and their publication counts. **b** presents the trends in affiliations' production over time

experimental and applied phytoremediation research. Lastly, The University of Melbourne contributed 5 articles, emphasizing its work on mine rehabilitation in Australia's unique contexts. This analysis underscores the diverse global contributions to phytoremediation research, which have been discussed in the manuscript to highlight the roles of key institutions.

Based on the **"Affiliations' Production over Time"** visual, the most prominent trend is the significant increase in contributions from **Instituto Tecnológico Vale**, particularly from 2019 onwards, reaching the highest number of publications by 2023. This reflects a growing focus on environmental remediation, especially in regions where mining activities are prominent. Other institutions, such as **Brawijaya University** and **Universitas Airlangga**, also show consistent contributions, particularly starting around 2014, which likely aligns with increased research funding and interest in phytoremediation solutions in Indonesia. Meanwhile, institutions like **IPB University** and **University of the Witwatersrand** have seen steady output, highlighting their ongoing efforts in contributing to this field.

Thematic map of phytoremediation research showing development and relevance of key themes

This thematic map provides insights into the structure and dynamics of the research on phytoremediation strategies for gold mine tailings. It highlights the core themes driving the field, such as the remediation of gold mine tailings and the associated biological and chemical processes. It also identifies niche areas where specialized research is being conducted and emerging themes that could represent future directions for the field. Researchers can use this map to identify well-established topics for collaboration and emerging areas that offer opportunities for pioneering research. It helps in understanding the overall landscape, guiding resource allocation, and setting strategic research priorities (Fig. 8).

Analysis of term frequency over time in phytoremediation research

The graph illustrates the cumulative occurrences of key terms related to phytoremediation research over time, spanning from 1999 to 2023. The terms tracked include "Bioaccumulation," "Bioremediation," "Gold," "Gold Mine," "Heavy Metal," "Mining," "Phytomremediation," "Soil," "Soil Pollution," and "Tailings." Each term's trajectory provides insights into the research trends and focal points within the field of phytoremediation. The term "Phytomremediation" shows the highest cumulative occurrences, indicating that it is the primary focus within the research domain. The steady rise in its mentions reflects the growing interest and

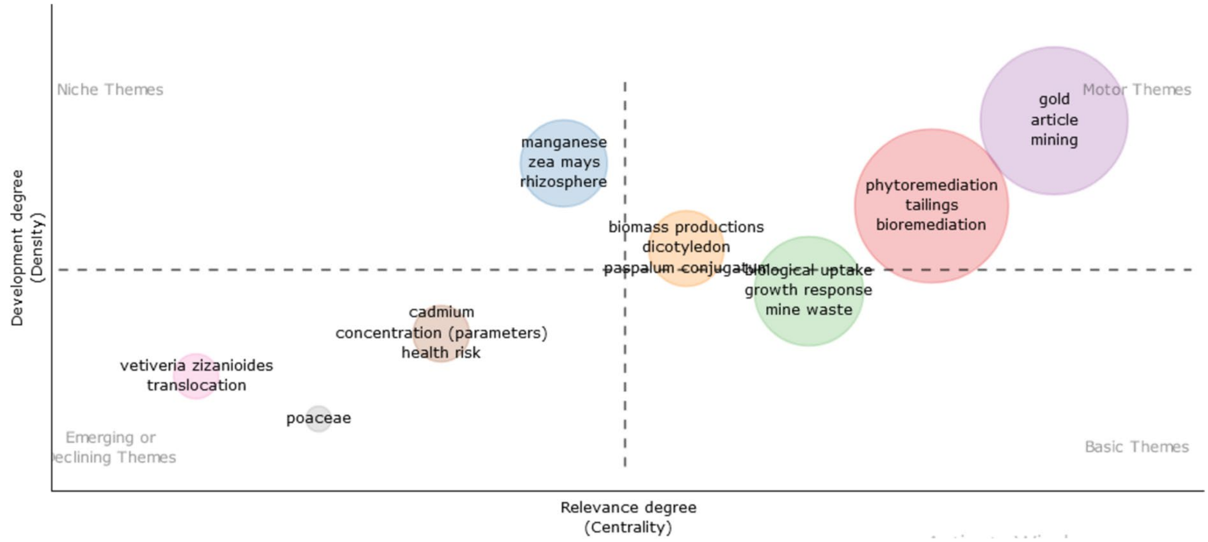

Fig. 8 Thematic Map of Research on Phytoremediation Strategies for Gold Mine Tailings

developments in this area over the years. Terms such as "Bioremediation," "Heavy Metal," and "Soil Pollution" also exhibit significant upward trends. These terms are crucial as they represent the primary pollutants and methodologies associated with phytoremediation. The terms "Gold" and "Gold Mine" show a noticeable increase in mentions, particularly after 2007. This suggests a growing interest in the application of phytoremediation techniques to mitigate pollution from gold mining activities, which is a significant environmental concern. "Bioaccumulation" and "Tailings" exhibit a more gradual increase in occurrences. Bioaccumulation is a critical process in phytoremediation where plants accumulate heavy metals, and tailings refer to the waste materials left after the extraction of valuable minerals, which are often targeted for remediation.

The overall steady growth in the occurrences of these terms suggests a broadening of research topics and an increasing depth of investigation into various aspects of phytoremediation and its applications. Post-2015, there is a marked increase in the occurrences of most terms, indicating a surge in research activities and publications related to phytoremediation. This could be attributed to heightened environmental awareness and the pressing need for sustainable remediation techniques (Fig. 9).

Citation classics

An overview of the top 25 most cited papers listed in the Scopus database and Google Scholar as of June 30, 2024, highlights significant contributions to the field. Frequently cited papers include those by Xiao et al. (2017), Wong et al. (1999), King et al. (2008), Chang et al. (2005), and Petelka et al. (2019). Among the most cited papers, contributions to the understanding of phytoremediation and its applications in environmental safety and pollution control predominate. For example, the top-cited paper by Xiao et al. (2017) in Ecotoxicology and Environmental Safety has garnered 335 citations in Scopus and 420 in Google Scholar, reflecting its significant impact with an annual citation rate of 41.88. This article likely addresses critical issues or breakthroughs in phytoremediation, making it a cornerstone in the field. Similarly, the paper by Wong et al. (1999) in Science of the Total Environment has 100 citations in Scopus and 161 in Google Scholar, demonstrating its enduring relevance since its publication in 1999 with a steady annual citation rate of 3.85.

Other notable papers include King et al.(2008) in science of the total environment, which has 77 citations in Scopus and 109 in Google Scholar, and Chang et al. (2005) in environmental geochemistry and health, with 46 citations in Scopus and 76

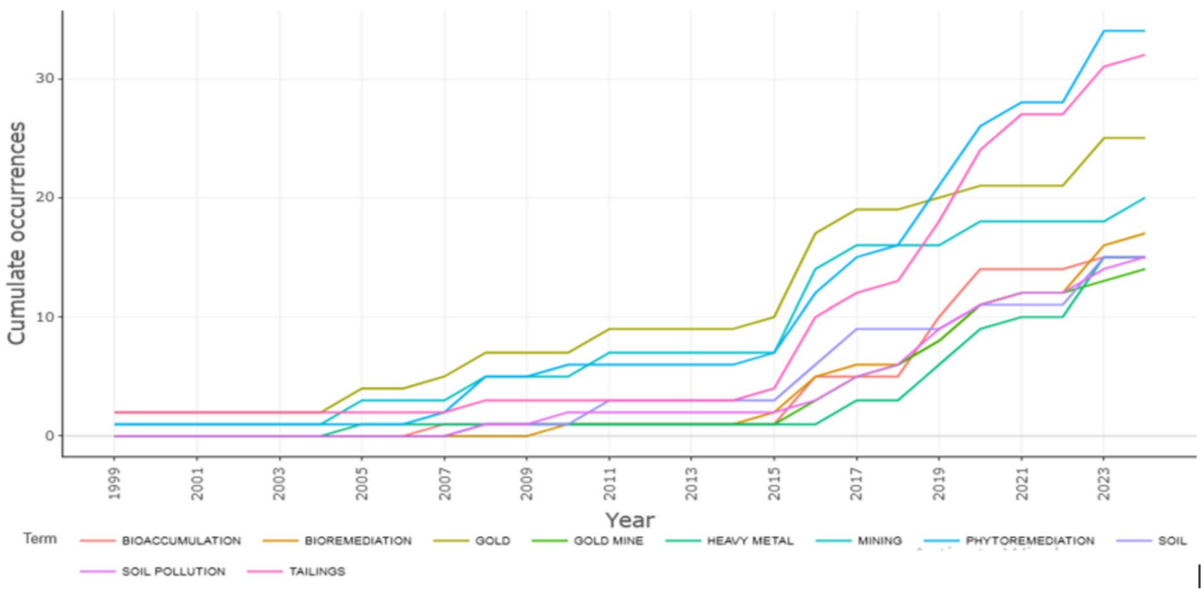

Fig. 9 Cumulative Occurrences of Key Terms in Phytoremediation Research (1999–2023)

in Google Scholar. These articles provide critical insights into the mechanisms and effectiveness of phytoremediation in various environmental contexts. Furthermore, the international journal of phytoremediation features multiple highly cited articles, such as those by Melato et al. (2016) and (Romanova et al. (2016), demonstrating the journal's importance in disseminating influential research in this domain. Overall, these highly cited papers highlight the advancements and key contributions to phytoremediation research, underscoring their importance in addressing environmental pollution and enhancing ecosystem health. The variations in citation counts between Scopus and Google Scholar also reflect differences in database coverage and indexing criteria, providing a comprehensive view of the impact of these seminal works.

The summarized studies provide a comprehensive overview of the potential of various plant species for phytoremediation of heavy metal-contaminated soils, particularly those impacted by gold mining activities. Phytoremediation is highlighted as an environmentally friendly, cost-effective, and efficient strategy to mitigate soil pollution and restore environmental health. Research has identified several plant species with strong potential for phytoremediation. For instance, *Erigeron canadensis*, *Digitaria ciliaris*, and *Solanum nigrum* have been recognized as suitable for mitigating heavy metal pollution (Xiao et al., 2017). Horsetails (*Equisetum rubiaceae* and *E. sylvaticum*) are effective in phytoremediation of arsenic and mercury-contaminated sites (Wong et al., 1999), while *Eucalyptus species*, such as *E. cladocalyx*, are ideal for long-term stabilization of arsenic-contaminated land (King et al., 2008). Poplar trees and Bracken ferns have shown potential for large-scale revegetation and arsenic accumulation (Chang et al., 2005).

Vetiver grass (*Chrysopogon zizanioides*) is particularly effective in adapting to gold mine tailings and can be used for the stabilization and phytoextraction of several heavy metals (Melato et al., 2016; Samsuri et al., 2019; Tariq et al., 2016). Water hyacinth has demonstrated a high ability to accumulate multiple heavy metals and efficiently translocate these elements (Romanova et al., 2016). *Typha domingensis* (cattail) and *Chrysopogon zizanioides* (vetiver) were also studied for their remediation capabilities, with Typha showing better adaptation and effectiveness (Compaore et al., 2020). Brassica species (e.g., *B. napus*) and *Celosia cristata* exhibited good potential for metal stabilization and recovery (González-Valdez et al., 2016), while Desert willow (*Chilopsis linearis*) showed enhanced gold uptake when treated with thiourea, indicating potential for phytomining (Rodríguez et al., 2007). Further, water hyacinth and pondweed were found effective in mercury accumulation, with pondweed being more practical for field applications (Romanova & Shuvaeva, 2016). Combining Mott dwarf Napier grass cultivation with electromagnetic field treatment improved arsenic remediation efficiency (Wanitsawatwichai & Sampanpanish, 2021). Native plants grown on waste dumps demonstrated the ability to accumulate and translocate multiple heavy metals, making them useful for polymetallic pollution phytoremediation (Fitamo & Leta, 2010). Furthermore, incorporating native plants into the broader treatment strategies for hazardous industrial wastewater presents a sustainable and innovative method for addressing pollution in contaminated areas (Sharma et al., 2021a, 2021b). Non-edible oil-producing plants like *Reutealis trisperma* showed high resistance and potential for gold mine tailing remediation (Nurafifah Andriya et al., 2019), and *Chromolaena odorata* grew well with organic amendments and FeSO4, enhancing Hg and Pb absorption (Lu et al., 2019).

The use of Bacillus species (e.g., *B. megaterium* and *B. pumilus*) was effective in bioremediation by solubilizing phosphorus and fixing nitrogen (Nuraini et al., 2015). In addition, bacterial-assisted phytoremediation has proven to be a successful method for treating metal-polluted wastewater from various sites (Sharma, 2021). *Pennisetum purpureum cv. Mott* (dwarf Napier grass) with AMF increased growth and reduced heavy metal contaminants (Putra et al., 2022). *Paspalum conjugatum*, combined with specific doses of NPK fertilizer, organic matter, and ammonium thiosulphate, was effective for phytoextraction in agricultural lands (Handayanto et al., 2016). Indigenous acacias showed significant AM fungal diversity, important for ecological restoration and soil health in gold and uranium mine tailings (Buck et al., 2019), while Heteropappusaltaicus demonstrated notable enrichment and transfer capabilities for Cd and Pb remediation near tailing dumps (Lu et al., 2019).

Effective phytoremediation strategies include selecting suitable plant species that naturally thrive in contaminated soils and have high metal accumulation and translocation capabilities, using soil amendments to enhance plant growth and metal uptake, leveraging mycorrhizal fungi inoculation to improve plant growth and metal uptake, and integrating multiple strategies such as electromagnetic field treatments and specific soil amendments to maximize remediation efficiency. These findings underscore the effectiveness of phytoremediation as a sustainable approach to managing heavy metal pollution in soils, particularly those impacted by mining activities. The use of specific plant species, along with tailored amendments and treatments, can significantly improve soil health and reduce environmental contamination.

Research highlights techniques such as phytoextraction and phytostabilization, along with the host plants utilized and the specific heavy metals targeted. Phytoextraction is illustrated by studies such as those by Romanova and Shuvaeva (2016) and Rodríguez et al. (2007), where plants like *Eichhornia crassipes* and *Chilopsis linearis* demonstrated a high capacity for accumulating heavy metals like Mo, Pb, and Au. The effectiveness of this technique varies based on plant species, soil conditions, and the type of metal involved. In contrast, phytostabilization, as seen in research by Compaore et al. (2020) and González-Valdez et al. (2016), involves plants like *Typha domingensis* and *Brassica napus* to stabilize heavy metals in the soil, effectively preventing their movement into the ecosystem.

Our analysis indicates that both phytoextraction and phytostabilization have distinct advantages. Phytoextraction focuses on the direct uptake of heavy metals, while phytostabilization aims at on-site containment. For example, *Vetiveria zizanioides*, used for phytostabilization, enhances soil quality in tailings but may not accumulate heavy metals as effectively as other species. The effectiveness of these techniques varies according to plant species, targeted heavy metals, and applied methods. Research suggests that plants like *Eichhornia crassipes* excel in phytoextraction, while *Typha domingensis* shows promise in phytostabilization. Additionally, combining both techniques can lead to optimal outcomes based on the specific conditions of the gold mine tailings (Table 2).

In this study, we have thoroughly analyzed the strengths and limitations of two primary phytoremediation techniques: phytoextraction and phytostabilization. **Phytoextraction** has proven to be highly effective in removing heavy metals such as lead (Pb), cadmium (Cd), and arsenic (As) from contaminated soils, as demonstrated by studies involving plants like *Eichhornia crassipes* and *Chilopsis linearis*. Additionally, this approach offers economic benefits through the recovery of valuable metals, making it a cost-effective alternative to traditional remediation methods. However, the success of phytoextraction heavily relies on selecting appropriate plant species with high metal accumulation capacity, which may not always be available (Chaney et al., 2020). Furthermore, various soil conditions, including pH, organic matter, and nutrient availability, can significantly influence the effectiveness of this technique. On the other hand, **phytostabilization** helps prevent soil erosion and reduces the risk of contaminant mobilization, thereby contributing to environmental protection. This method can also enhance soil health and fertility over time, benefiting plant growth and promoting ecosystem restoration. Despite these advantages, phytostabilization has its limitations; notably, it does not remove metals from the soil but merely immobilizes them. This may not be suitable for sites that require complete decontamination. Additionally, the success of this method depends on the ability of selected plants to thrive in contaminated conditions, which could limit its applicability.

In our study, we aim to provide a balanced perspective on each technique by analyzing these strengths and limitations in detail. We have incorporated a discussion section that addresses these points explicitly, allowing for a clearer understanding of how each approach can be effectively applied in the context of gold mine tailings. The discussion highlights how these strategies can be implemented to mitigate environmental damage caused by mining activities, focusing on several key areas. First, we outline how phytoremediation can effectively stabilize contaminated soils, enhance soil quality, and promote biodiversity, which is particularly important in regions where mining has led to significant land degradation. Additionally, we emphasize the economic advantages of using phytoremediation as a sustainable alternative to traditional remediation methods, noting that utilizing local plant species can reduce costs associated with chemical treatments and mechanical interventions. Furthermore, our strategies encourage local community engagement in restoration efforts, providing opportunities for education and participation in sustainable

Table 2 Top 25 citations according to Scopus and Google Scholar of Research on Phytoremediation Strategies for Gold Mine Tailings (Status: Jun 30, 2024)

References	DOI	Total Citations		Host plant	Findings	Phytoremediation Technique	Heavy metal
		scopus	scholar				
(Xiao et al., 2017)	10.1016/j.ecoenv.2017.03.002	335	420	(*Erigeron canadensis* L., *Digitaria ciliaris (Retz.) Koe*L.*, and Solanum nigrum* L.)	Three plants, namely *Erigeron canadensis* L., *Digitaria ciliaris* (Retz.) Koel., and *Solanum nigrum* L., were identified as suitable species for further phytoremediation efforts to mitigate heavy metal pollution	Phytoextraction	heavy metal
(Wong et al., 1999)	10.1016/S0048-9697(99)00021-2	100	161	horsetails (*Equisetum rubiaceae* and *E. sylvaticum*)	horsetails (*Equisetum rubiaceae* and *E. sylvaticum*) can be used in phytoremediation of sites contaminated with arsenic and mercury	Phytostabilization	As, Hg
(King et al., 2008)	10.1016/j.scitotenv.2008.07.054	77	109	*Eucalyptus cladocalyx*, *E. melliodora*, *E. polybractea*, *E. viridis*	*E. cladocalyx* ideal for long-term phytostabilisation of As-contaminated land	Phytostabilization	As
(Chang et al., 2005)	10.1007/s10653-005-0130-7	46	76	Poplar trees (*Populus davidiana*), Bracken ferns (*Pteridium aquilinum*)	Poplar trees potential for large scale revegetation, arsenic accumulations studied	Phytoextraction	As
(Petelka et al., 2019)	10.1007/s11270-019-4317-4	41	63	Various native plants	Plants assessed for heavy metal accumulation, *Aspilia africana* promising for Cu phytoextraction	Phytoextraction	Cu
(Melato et al., 2016)	10.1080/15226514.2015.1115963	32	38	Vetiver grass (*Chrysopogon zizanioides*)	Adapted well to gold mine tailings, restricted metal translocation to shoots	Phytostabilization	Heavy metal

Table 2 (continued)

References	DOI	Total Citations		Host plant	Findings	Phytoremediation Technique	Heavy metal
		scopus	scholar				
(Alcantara et al., 2015)	10.1016/j.mineng.2015.06.012	28	40	Various plants	*Brassica juncea* (Indian mustard), *Daucus carota* (carrot) grew successfully in the biosolids-mine tailings substrate combinations	Mixed	-
(Weiersbye et al., 2006)	10.4102/abc.v36i1.349	27	71	Various plants	Several plant families have been identified as potential agents for phytoremediation of tailings-contaminated lands. These families include *Poaceae* (107 species and subspecies), *Asteraceae* (81), *Fabaceae* (55), and *Anacardiaceae* (16). Species within these families, predominantly native and perennial plants, exhibit tolerance to acid mine drainage and salinity, making them suitable candidates for the phytoremediation of tailings and polluted soils	Mixed	-

Table 2 (continued)

References	DOI	Total Citations		Host plant	Findings	Phytoremediation Technique	Heavy metal
		scopus	scholar				
(Samsuri et al., 2019)	10.1016/j.apgeochem.2019.104366	23	34	vetiver grass (*Vetiveria zizanioides* L. Nash)	The results suggest that vetiver grass can be recommended for the stabilization of Zn and for the phytoextraction of Cr, Cu, and Mn from mine tailings	Phytoextraction	Cr, Cu, and Mn
(Orłowska et al., 2011)	10.1080/15226514.2010.495148	22	39	*Dodonaea viscosa*, *Andropogon eucomus*, *Imperata cylindrica*	The results suggest that the use of AMF, particularly those adapted to the specific conditions of gold tailings, can be an effective practical approach to the phytostabilization of alkaline gold tailings	Phytostabilization	-
(Romanova et al., 2016)	10.1080/15226514.2015.1073674	20	30	*Eichhornia crassipes*	Water hyacinth demonstrated high ability to accumulate Mo, Pb, and Ba and efficiently translocate Mo and Cd. As distance from tailings increases, concentration of Ag, Ba, and Pb in plant decreases, while amount of Mo does not drop significantly	Phytoextraction	Mo, Pb, Ba, Cd

Table 2 (continued)

References	DOI	Total Citations		Host plant	Findings	Phytoremediation Technique	Heavy metal
		scopus	scholar				
(Tariq et al., 2016)	10.1155/2016/4151898	17	27	Vetiver grass (*Vetiveria zizanioides*)	These findings suggest that both rice husk ash (RHA) and iron-coated rice husk ash (Fe-RHA) can influence the phytoavailability of heavy metals in vetiver grass grown in gold mine tailings, with specific effects varying depending on the type of amendment used.	Phytostabilization	Heavy metals
(Compaore et al., 2020)	10.1016/j.ecoleng.2020.106037	14	20	*Typha domingensis* (cattail) and *Chrysopogon zizanioides* (vetiver)	*Typha domingensis* (cattail) is considered a promising alternative for phytoremediation of gold mine tailing seepage, while *Chrysopogon zizanioides* (vetiver) showed very low growth rates and adaptation difficulties	Phytostabilization	Heavy metals
(González-Valdez et al., 2016)	10.1007/s11270-015-2724-8	14	19	*Brassica napus* L., *Brassica rapa* L., *Celosia cristata* L., *Tagetes erecta* L., *Calendula officinalis* L	*B. napus* showed high seed germination (66%), tolerance, growth, and total dry mass accumulation (0.041 g). Both *B. napus* and *C. cristata* demonstrated good potential for stabilizing or recovering metals from mine tailings	Phytostabilization	Heavy metals

Table 2 (continued)

References	DOI	Total Citations		Host plant	Findings	Phytoremediation Technique	Heavy metal
		scopus	scholar				
(Rodríguez et al., 2007)	10.1071/EN06048	11	14	Desert willow (*Chilopsis linearis*)	These results suggest that using TU (*thiourea*) can effectively enhance gold uptake and translocation in *C. linearis*, making it a promising approach for phytomining gold from mine tailings	Phytoextraction	Au
(Romanova & Shuvaeva, 2016)	10.1007/s11270-016-2874-3	9	15	water hyacinth (WH) and pondweed (PW)	These findings suggest that both water hyacinth (WH) and pondweed (PW) are effective in accumulating mercury from water in gold mine tailing areas, with PW being more practical for field applications	Phytoextraction	Hg
(Wanitsawatwichai & Sampanpanish, 2021)	10.1016/j.heliyon.2021.e07736	8	10	Mott dwarf Napier grass	These findings suggest that combining Mott dwarf Napier grass cultivation with a 1 V/cm electromagnetic field treatment can enhance the remediation efficiency of As-contaminated mine tailings, with significant As accumulation occurring primarily in the roots	Phytostabilization	As

Table 2 (continued)

References	DOI	Total Citations		Host plant	Findings	Phytoremediation Technique	Heavy metal
		scopus	scholar				
(Fitamo & Leta, 2010)	10.1080/00207233.2010.513587	8	12	Native plants	Native plants grown on waste dumps can accumulate and translocate Cr, Ni, Co, Cu, Zn, Cd, and Pb, useful for phytoremediation of polymetallic pollution	Phytoextraction	Cr, Ni, Co, Cu, Zn, Cd, Pb
(Nurafifah Andriya et al., 2019)	10.13057/biodiv/d201025	7	9	four non-edible oil-producing plants (*Jatropha curcas*, *Ricinus communis*, *Reutealis trisperma*, and *Melia azedarach*)	These findings suggest that *Reutealis trisperma* shows the highest resistance and potential for phytoremediation of gold mine tailings among the four species studied	Phytostabilization	Heavy metals
(Hamzah et al., 2011)	-	6	19	*Chromolaena odorata*	These findings suggest that the use of organic amendments and FeSO4 can enhance the growth of *Chromolaena odorata* and its ability to absorb Hg and Pb from gold mine tailings, making it a potential candidate for phytoremediation in such environments	Phytoextraction	Hg, Pb

Table 2 (continued)

References	DOI	Total Citations		Host plant	Findings	Phytoremediation Technique	Heavy metal
		scopus	scholar				
(Nuraini et al., 2015)	10.17503/agrivita-2015-37-1-p001-007	6	16	undetected	These findings suggest that *Bacillus megaterium* and *Bacillus pumilus*, along with other identified microbial species, can be effective in the bioremediation of gold mine tailings by solubilizing phosphorus and fixing nitrogen, thereby potentially improving soil health in contaminated areas	Bioremediation	-
(Putra et al. 2022b)	10.13057/biodiv/d230151	6	4	*Pennisetum purpureum cv.* Mott	The study concluded that AMF effectively increased the growth of dwarf Napier grass and reduced heavy metal contaminants in gold mine tailings	Phytoextraction	Heavy metals
(Handayanto et al., 2016)	-	5	5	*P. conjugatum*	These findings suggest that *P. conjugatum*, combined with specific doses of NPK fertilizer, organic matter, and ammonium thiosulphate, is effective for phytoextraction and remediation of gold mine tailings in agricultural land	Phytoextraction	Heavy metals

Table 2 (continued)

References	DOI	Total Citations		Host plant	Findings	Phytoremediation Technique	Heavy metal
		scopus	scholar				
(Buck et al., 2019)	10.1016/j.sajb.2018.10.014	5	13	indigenous acacias (*Vachellia* and *Senegalia spp.*)	These findings suggest significant AM fungal diversity in the roots of indigenous acacias used for phytoremediation of gold and uranium mine tailings in the Free State, with important implications for ecological restoration and soil health	Phytostabilization	Au, U
(Lu et al., 2019)	10.15666/aeer/1705_1058710597	5	7	Bulrush (*Phragmites communis* (Cav.) Trin. ex Steud.), Capillary Wormwood (*Artemisia capillaris*), Heteropappusaltaicus (*Artemisia gmelinii*), and Stipa (*Stipa capillata* Linn.)	These results suggest that *Heteropappusaltaicus* can be effectively used for the remediation of soils contaminated with Cd and Pb near gold mining tailing dumps, due to its notable enrichment and transfer capabilities	Phytoextraction	Cd, Pb

This table provides an overview of the Citation Classics based on the Scopus database and Google Scholar. It highlights significant research findings on the use of various plant species for phytoremediation in contaminated mine tailings, demonstrating their capacity to accumulate and translocate heavy metals such as Pb, Cd, As, and Hg. The studies underscore the effectiveness of phytoremediation as a viable solution for mitigating soil pollution in mining areas practices. We also include suggestions for policymakers on integrating phytoremediation techniques into existing environmental management frameworks, ensuring that these strategies are not only practical but also supported by legislation. Lastly, we address the importance of continuous monitoring and assessment of phytoremediation projects to evaluate their effectiveness and adapt strategies as needed. Overall, these practical implications demonstrate how phytoremediation strategies can play a crucial role in managing the environmental impacts of gold mining, reinforcing the significance of our findings.

Content analysis

The network visualization illustrates the relationships and co-occurrences of key terms within the domain of phytoremediation research. Created using VOSviewer, this visualization reveals two distinct clusters, highlighting the thematic areas and interconnections among various research topics (Fig. 10).

Cluster 1 (red): phytoremediation and environmental impact of gold mining Cluster 1 focuses on the intersection of phytoremediation techniques and their application in addressing the environmental impacts of gold mining. Key terms associated with this cluster include their occurrences and link strength, providing a comprehensive overview of the relevant concepts within the research context (Table 3).

Arsenic contamination is a significant concern in gold mining areas. Research such as that by Boonmeerati and Sampanpanish (2021) demonstrates how specific plant–microbe interactions can enhance the uptake of arsenic from contaminated soils. Biodegradation refers to the breakdown of contaminants by biological means. Studies like "Arsenic, manganese, and cyanide removal in a tropical wetland system" by Sampanpanish (2018) explore how natural systems can be leveraged to degrade and remove contaminants from the environment. Biological uptake involves the absorption of contaminants by plants and other organisms. The study by Marfuah et al. (2023) highlights how endophytes can enhance the ability of plants to uptake heavy metals.

Biomass refers to the total mass of living organisms in a given area. Phytoremediation efforts often focus on maximizing biomass to enhance contaminant uptake, as seen in research on fast-growing plants like Siam weed (*Chromolaena odorata* L.) for phytoremediation of lead contaminated soil (Hamzah et al., 2011). Understanding the chemical processes involved in phytoremediation is crucial. Studies such as that by Chang et al. (2005) examine the chemical interactions between contaminants and plant tissues. Environmental monitoring is essential for assessing

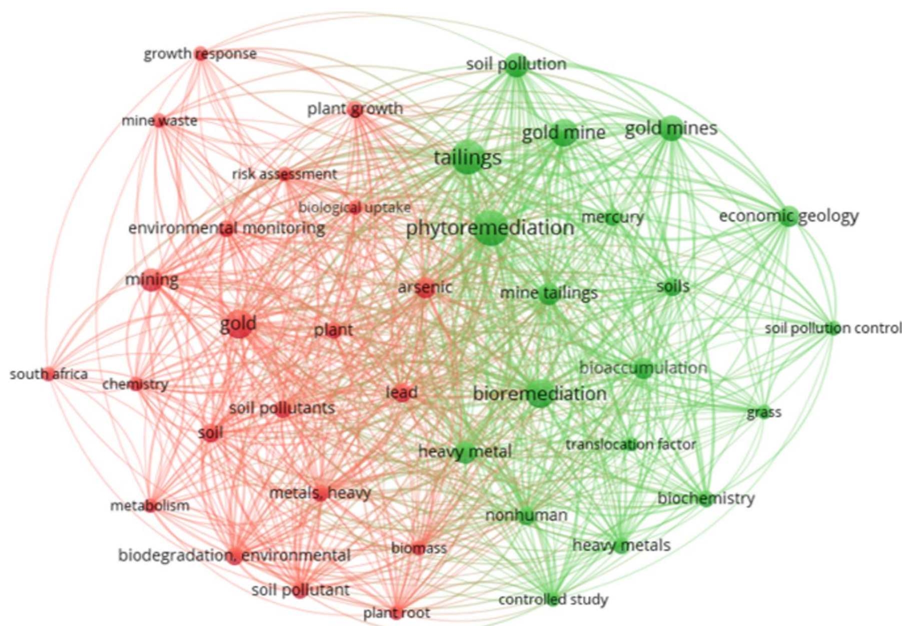

Fig. 10 Network Visualization in Phytoremediation Research

Table 3 Key terms and their occurrences in cluster 1: phytoremediation techniques and environmental impacts of gold mining

Key term	Occurrences	Total link strength	Key term	Occurrences	Total link strength
Arsenic	8	96	Mine waste	9	114
Biodegradation (environmental)	6	80	Mining	10	96
Biological uptake	8	90	Plant	5	49
Biomass	5	64	Plant growth	5	64
Chemistry	5	65	Plant root	5	90
Environmental monitoring	5	65	Risk assessment	5	90
Gold	15	143	Soil	7	94
Growth response	5	64	Soil pollutant	5	77
Lead	7	95	Soil pollutants	6	90
Metabolism	5	64	South Africa	5	64
Heavy metals	5	77			

the effectiveness of phytoremediation strategies. Continuous monitoring helps in understanding the long-term impacts and success of remediation efforts.

Gold mining is a major source of environmental contamination. Research like that by Sampanpanish (2018) addresses the need for remediation techniques to manage contaminants associated with gold extraction processes. The growth response of plants to contaminated environments is a key factor in phytoremediation. Studies often investigate how different plants grow in polluted soils and their ability to survive and remediate contaminants. Lead is a common pollutant in mining areas. Research such as that by Hamzah et al. (2011) focuses on using specific plants to reduce lead levels in the soil. Understanding the metabolic processes of plants and microorganisms helps in optimizing phytoremediation strategies. This includes studying how contaminants are transformed and detoxified within the organism.

Heavy metals like arsenic, lead, and mercury are common targets for phytoremediation. Research on the concentration and effects of heavy metals in plants helps in selecting suitable species for remediation projects. Mine waste is a significant environmental issue. Studies investigate methods for stabilizing and detoxifying mine waste using phytoremediation, reducing the long-term impact on the environment. The overall impact of mining on the environment includes soil, water, and air pollution. Phytoremediation offers a sustainable solution to mitigate these impacts, as highlighted in various studies within the dataset.The role of plants in phytoremediation is central. Research explores different plant species and their effectiveness in absorbing and detoxifying contaminants. Optimizing plant growth in contaminated soils is crucial for successful phytoremediation. Studies focus on factors that enhance or inhibit plant growth in polluted environments. The root system of plants plays a significant role in phytoremediation. Research investigates how root structures and functions contribute to the uptake and stabilization of contaminants. Risk assessment involves evaluating the potential hazards and benefits of phytoremediation projects. This includes studying the effectiveness and potential side effects of using certain plants for remediation.

Soil health is a primary concern in phytoremediation. Studies examine the impact of contaminants on soil properties and the ability of plants to restore soil health. Research focuses on identifying and managing various soil pollutants through phytoremediation, aiming to reduce their bioavailability and toxicity. Studies in specific regions like South Africa highlight the unique environmental challenges and phytoremediation strategies relevant to those areas. Notable findings from the dataset contribute to a deeper understanding of how phytoremediation techniques can mitigate the environmental impacts of gold mining. For instance, Marfuah et al. (2023) illustrates how endophyte inoculation can enhance metal uptake in plants, while Boonmeerati and Sampanpanish (2021) highlights the role of rhizobacteria and fertilizers in improving arsenic uptake in plants. Moreover, concentrations of arsenic and heavy metals in indigenous plants used in traditional medicine by Oyuela et al. (2017) examines how indigenous plants can be used to remediate heavy metals, and Siam weed (*Chromolaena odorata* L.) for phytoremediation of lead contaminated soil by Hamzah et al. (2011) showcases the potential of using fast-growing weeds for lead remediation. Additionally, arsenic, manganese, and cyanide removal in a tropical wetland system by Sampanpanish (2018) provides insights into the bioremediation of multiple contaminants in wetland systems. These studies highlight the importance of continued research in optimizing phytoremediation strategies for sustainable environmental management and protection.

Cluster 2 (green): broad applications of phytoremediation and bioremediation techniques Cluster 2 represents a comprehensive exploration of the broader applications of phytoremediation and bioremediation techniques. Key terms associated with this cluster, along with their occurrences and total link strength, provide a detailed summary of the primary concepts related to phytoremediation and bioremediation. This summary emphasizes the diverse strategies employed to address various environmental pollutants, reflecting the extensive data analyzed in this research (Table 4).

These terms highlight the diverse areas where phytoremediation and bioremediation strategies are applied, targeting different pollutants and illustrating various biological processes involved.

Bioaccumulation refers to the process by which plants and other organisms absorb contaminants from their surroundings and concentrate them in their tissues, crucial for optimizing plant selection for remediation purposes. Research such as that by Marfuah et al. (2023) demonstrates how endophyte inoculation can enhance metal uptake in plants. Biochemistry studies within plants and microorganisms aid in understanding how contaminants are absorbed, transformed, and detoxified, enhancing phytoremediation strategies. The study by Boonmeerati and Sampanpanish (2021) explores the biochemical interactions between plants and soil microbes that facilitate arsenic uptake. Bioremediation involves using biological agents to remove or neutralize contaminants. Studies like those by Sampanpanish (2018) showcase how natural systems can be leveraged to degrade and remove contaminants from the environment. Controlled studies systematically investigate the effectiveness of different phytoremediation techniques. Research by Hamzah et al. (2011) represents efforts to examine how specific plants can be used effectively in controlled environments.

Economic geology examines the impact of geological resources and mining activities on the environment, indicating the relevance of phytoremediation in these areas. The study by Sampanpanish (2018) highlights the environmental challenges posed by mining activities. Gold mining terms focus on addressing pollution from gold extraction processes. Research by Sampanpanish (2018) provides insights into remediation techniques specific to gold mining operations. Grasses are often used for their fast growth and

Table 4 Key terms and their occurrences in cluster 2: Applications of phytoremediation and bioremediation techniques

Key term	Occurrences	Total link strength	Key term	Occurrences	Total link strength
Bioaccumulation	8	90	Mercury	5	63
Biochemistry	5	64	Mine tailings	9	114
Bioremediation	16	162	Nonhuman	6	93
Controlled study	5	64	Phytoremediation	23	198
Economic geology	8	73	Soil pollution	11	104
Gold mine	14	132	Soil pollution control	5	65
Gold mines	12	116	Soils	7	94
Grass	5	64	Tailings	22	199
Heavy metal	9	115	Translocation factor	5	64
Heavy metals	7	95			

extensive root systems in phytoremediation. Studies by Hamzah et al. (2011) highlight the effectiveness of using grasses for lead remediation. Heavy metals, including mercury, are prevalent pollutants targeted by phytoremediation to reduce their bioavailability and toxicity. Research on the concentration and effects of heavy metals in plants, such as "Concentrations of arsenic and heavy metals in indigenous plants used in traditional medicine" by Chang et al. (2005) helps in selecting suitable species for remediation projects.

Mine tailings and other mining waste materials are significant targets for stabilization and detoxification. Research like Sampanpanish (2018) demonstrates methods for addressing these issues through bioremediation. Nonhuman studies highlight the importance of biological agents in environmental cleanup, emphasizing the role of plants and microorganisms in ecosystem restoration. Phytoremediation involves using plants to absorb, accumulate, and detoxify contaminants, central to this cluster. The extensive occurrence of this term in the dataset underscores its significance in environmental remediation. Soil pollution and control terms emphasize managing soil contamination through phytoremediation, restoring soil health. Research on soil quality guides appropriate remediation strategies. Soil health is a primary concern in phytoremediation. Studies examine the impact of contaminants on soil properties and the ability of plants to restore soil health. Tailings are major targets for phytoremediation, aiming to reduce their environmental impact. Research by Sampanpanish (2018) illustrates efforts to address these issues.

The translocation factor measures the ability of plants to transport absorbed contaminants, crucial for selecting effective plants for phytoremediation. Notable findings from the dataset reveal significant insights into the broader applications of phytoremediation and bioremediation techniques. For instance, Marfuah et al. (2023) illustrates how endophyte inoculation can enhance metal uptake in plants. Boonmeerati and Sampanpanish (2021) explores the role of rhizobacteria and fertilizers in improving arsenic uptake in plants. Additionally, by Oyuela Leguizamo et al. (2017) examines how indigenous plants can be used to remediate heavy metals. Research such as "Siam weed (*Chromolaena odorata* L.) for phytoremediation of lead contaminated soil" by Hamzah et al. (2011) highlights the potential of using fast-growing weeds for lead remediation. Moreover, "Arsenic, manganese, and cyanide removal in a tropical wetland system" by Sampanpanish (2018) provides insights into the bioremediation of multiple contaminants in wetland systems. These studies underscore the importance of continued research in optimizing phytoremediation and bioremediation strategies for sustainable environmental management and protection.

This cluster categorizes the phytoremediation strategies based on their specific techniques, including phytoextraction, phytostabilization, and phytodegradation. Each strategy was evaluated by assessing its effectiveness in heavy metal uptake, as well as the specific plant species utilized in various environmental contexts. Key performance indicators included metal accumulation rates, biomass production, and the interaction with beneficial soil microorganisms. This categorization and evaluation allow for a comprehensive understanding of which techniques are most effective under different conditions and contribute to the broader applications of phytoremediation.

Future research opportunities in phytoremediation The future research opportunities in Cluster 1, which focuses on phytoremediation and the environmental impact of gold mining, suggest several promising directions for enhancing the effectiveness of remediation techniques. One key area is the enhanced selection and genetic engineering of plants to improve their contaminant uptake and tolerance capabilities. This involves identifying plant species with superior traits and using genetic modification to enhance these traits. Additionally, techniques such as gamma radiation-induced mutation can be explored to develop plant varieties that are more tolerant to high levels of contaminants. Another important avenue is the mechanistic study of biological uptake, which aims to understand the pathways and genes involved in the absorption and detoxification processes at the molecular level. Conducting field trials and long-term monitoring is crucial for gathering data on the effectiveness and sustainability of phytoremediation techniques in real-world settings. Integrating phytoremediation with other remediation methods, such as chemical amendments and microbial treatments, can also enhance the overall efficiency of contaminant removal. Additionally, assessing the formation and impact of secondary contaminants resulting from phytoremediation processes and developing mitigation strategies is essential to ensure that the remediation process does not introduce new pollutants (Table 5).

This table provides an overview of future research opportunities in the field of phytoremediation and bioremediation, highlighting key areas for development based on the analysis of two distinct clusters of current research. Each opportunity includes a description to guide potential research directions and objectives.

Cluster 2 highlights the broad applications of phytoremediation and bioremediation techniques across various contexts and pollutants. Future research opportunities in this cluster include expanding the range of target contaminants to include emerging pollutants such as pharmaceuticals and nanomaterials, which are increasingly found in the environment. Optimizing plant–microbe interactions is another key area, as beneficial microbial communities can support plant growth and enhance contaminant degradation. Developing multifunctional plants capable of addressing multiple types of contaminants simultaneously and exploring polyculture systems can improve the efficiency and effectiveness of phytoremediation. Economic and social impact assessments are necessary to evaluate the feasibility and acceptance of phytoremediation projects, including cost–benefit analysis, job creation potential, and community engagement. Research on climate change adaptation is also critical, focusing on developing resilient plant species and strategies to withstand extreme weather conditions and changing environmental parameters. Lastly, integrating remote sensing and GIS technologies can enhance the monitoring and management of phytoremediation projects by providing real-time tracking of contaminant levels and plant health.

Table 5 Future research opportunities in phytoremediation and bioremediation

Cluster	Research opportunity	Description
Cluster 1	1. Enhanced Plant Selection and Genetic Engineering	Focus on identifying and developing plant species with superior contaminant uptake and tolerance capabilities, using genetic engineering and techniques such as gamma radiation-induced mutation
	2. Mechanistic Studies of Biological Uptake	Explore the pathways and genes involved in the uptake and detoxification processes at the molecular level
	3. Field Trials and Long-term Monitoring	Conduct large-scale field trials and long-term monitoring to gather data on the effectiveness and sustainability of phytoremediation techniques
	4. Combination of Phytoremediation with Other Remediation Techniques	Integrate phytoremediation with chemical amendments, microbial treatments, and physical stabilization to enhance efficiency
	5. Assessment of Secondary Contaminants	Investigate the potential formation and impact of secondary contaminants and develop mitigation strategies
Cluster 2	1. Expanding the Range of Target Contaminants	Broaden the range of contaminants that can be effectively addressed, including emerging pollutants such as pharmaceuticals and nanomaterials
	2. Optimization of Plant–Microbe Interactions	Identify beneficial microbial communities that can support plant growth and contaminant degradation
	3. Development of Multifunctional Plants	Create multifunctional plants capable of addressing multiple types of contaminants simultaneously, and explore polyculture systems
	4. Economic and Social Impact Assessments	Conduct economic and social impact assessments, including cost–benefit analysis, job creation potential, and community engagement
	5. Climate Change Adaptation	Develop resilient plant species and strategies to withstand extreme weather conditions and changing environmental parameters due to climate change
	6. Use of Remote Sensing and GIS Technologies	Integrate remote sensing and GIS technologies for real-time tracking of contaminant levels and plant health

Conclusion

In conclusion, this study demonstrates that phytoremediation offers significant potential as an effective and sustainable method for mitigating the environmental impacts of gold mine tailings. The success of phytoremediation varies widely based on plant species, site conditions, and remediation techniques, with promising results shown through the use of soil amendments, mycorrhizal inoculation, and combined approaches. Global research trends highlight substantial contributions from countries such as Indonesia, Malaysia, and South Africa, underscoring the need for continued research and site-specific strategies. To advance the field further, we recommend specific research directions based on identified gaps, including the enhancement of plant genetic engineering to improve contaminant uptake, the need for long-term field trials to assess the effectiveness and sustainability of various phytoremediation techniques, and the exploration of multifunctional plants that can target multiple contaminants. Additionally, studies should focus on optimizing plant–microbe interactions and integrating phytoremediation with other remediation methods to enhance overall efficiency. Finally, this study emphasizes the importance of assessing the economic and social impacts of phytoremediation strategies, as well as promoting community involvement in restoration efforts. By addressing these areas, we can fully realize the benefits of phytoremediation as a green technology in environmental management and contribute to the development of more effective strategies for managing gold mine tailings.

Author contributions Bela Putra: Writing e review & editing, Writing e original draft, Methodology, Investigation, Formal analysis, Conceptualization. M. Surachman: Writing e review & editing, Methodology, Formal analysis, Data curation. I. W. A. Darmawan: Writing e review & editing, Validation, Resources. S. Maulana: Writing e review & editing, Validation, Resources. Diana Sawen: Writing e review & editing. Rahmi Dianita: Writing e review & editing, Supervision. Irine I. Pratiwi: Writing e review & editing. Kostafiana Sawo: Validation, Supervision. Marsel Hambakodu: Funding acquisition, Conceptualization. S. Akhadiarto: Validation and Data curation. S. Bahar: Validation and Data curation. J. Sirat: Validation and editing. Ruslan A. Gopar: Writing e review & editing, Methodology, Investigation, Formal analysis. Suharlina: Writing e review & editing, Validation, Data curation.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interest The authors declare that they have no competing of interest.

Ethical approval Approval The author has read, understood, and has complied as applicable with the statement on “Ethical Responsibilities of Authors” as found in the Instructions for Authors.

References

Alcantara, H. J., Doronila, A. I., Nicolas, M., Ebbs, S. D., & Kolev, S. D. (2015). Growth of selected plant species in biosolids-amended mine tailings. *Minerals Engineering, 1*(80), 25–32. https://doi.org/10.1016/j.mineng.2015.06.012

Allen, L., Jones, C., Dolby, K., Lynn, D., & Walport, M. (2009). Looking for landmarks: The role of expert review and bibliometric analysis in evaluating scientific publication outputs. *PloS one., 4*(6), e5910.

Andriya, N., Nadya, H. H., Sulistijorini, & Triadiati. (2019). The phytoremediation potential of non-edible oil-producing plants for gold mine tailings. *Biodiversitas*. https://doi.org/10.13057/biodiv/d201025

Araujo, F. S., Taborda-Llano, I., Nunes, E. B., & Santos, R. M. (2022). Recycling and reuse of mine tailings: A review of advancements and their implications. *Geosciences, 12*(9), 319.

Ashraf, S., Ali, Q., Zahir, Z. A., Ashraf, S., & Asghar, H. N. (2019). Phytoremediation: Environmentally sustainable way for reclamation of heavy metal polluted soils. *Ecotoxicology and Environmental Safety, 174*, 714–727.

Boonmeerati, U., & Sampanpanish, P. (2021). Enhancing arsenic phytoextraction of dwarf Napier grass (*Pennisetum purpureum* cv. Mott) from gold mine tailings by electrokinetics remediation with phosphate and EDTA. *Journal of Hazardous, Toxic, and Radioactive Waste, 25*(4), 04021027.

Buck, M. T., Straker, C. J., Mavri-Damelin, D., & Weiersbye, I. M. (2019). Diversity of arbuscular mycorrhizal (AM) fungi colonising roots of Indigenous Vachellia and Senegalia trees on gold and uranium mine tailings in South Africa. *South African Journal of Botany, 121*, 34–44. https://doi.org/10.1016/j.sajb.2018.10.014

Chaney, R. L., Li, Y. M., Brown, S. L., Homer, F. A., Malik, M., Angle, J. S., Baker, A. J., Reeves, R. D., & Chin, M. (2020). Improving metal hyperaccumulator wild plants to develop commercial phytoextraction systems: approaches and progress. In Phytoremediation of contaminated soil and water.

Chang, P., Kim, J.-Y., & Kim, K.-W. (2005). Concentrations of arsenic and heavy metals in vegetation at two abandoned mine tailings in South Korea. *Environmental Geochemistry and Health, 27*(2), 109–119. https://doi.org/10.1007/s10653-005-0130-7

Compaore, W. F., Dumoulin, A., & Rousseau, D. P. L. (2020). Metal uptake by spontaneously grown typha domingensis and introduced chrysopogon zizanioides in a constructed wetland treating gold mine tailing storage facility seepage. *Ecological Engineering*. https://doi.org/10.1016/j.ecoleng.2020.106037

Ellegaard, O., & Wallin, J. A. (2015). The bibliometric analysis of scholarly production: How great is the impact? *Scientometrics*. https://doi.org/10.1007/s11192-015-1645-z

Fitamo, D., & Leta, S. (2010). Assessment of plants growing on gold mine wastes for their potential to remove heavy metals from contaminated soils. *International Journal of Environmental Studies, 67*(5), 705–724. https://doi.org/10.1080/00207233.2010.513587

González-Valdez, E., Alarcón, A., Ferrera-Cerrato, R., Vega-Carrillo, H. R., Maldonado-Vega, M., & Salas-Luévano, M. Á. (2016). Seed germination and seedling growth of five plant species for assessing potential strategies to stabilizing or recovering metals from mine tailings. *Water, Air, and Soil Pollution*. https://doi.org/10.1007/s11270-015-2724-8

Hadzi, G. Y., Essumang, D. K., & Ayoko, G. A. (2024). Assessment of contamination and potential ecological risks of heavy metals in riverine sediments from gold mining and pristine areas in Ghana. *Journal of Trace Elements and Minerals*. https://doi.org/10.1016/j.jtemin.2023.100109

Hamzah, A., Kusuma, Z., Utomo, W. H., & Guritno, B. (2011). Siam weed (*Chromolaena Odorata* L.) for phytoremediation of artisanal gold mine tailings. *Journal of Tropical Agriculture, 50*, 88–91.

Handayanto, E., Nuraini, Y., & Muddarisna, N. (2016). Optimization of plant species and chelating agents in phytoextraction of gold from small-scale gold mine tailings. *Nature Environment and Pollution Technology, 15*(3), 1083–1088.

Kafle, A., Timilsina, A., Gautam, A., Adhikari, K., Bhattarai, A., & Aryal, N. (2022). Phytoremediation: Mechanisms, plant selection and enhancement by natural and synthetic agents. *Environmental Advances, 8*, 100203.

Karaca, Oznur, Cameselle, Claudio, & Reddy, Krishna R. (2018). Mine tailing disposal sites: Contamination problems, remedial options and phytocaps for sustainable remediation. *Reviews in Environmental Science and Biotechnology, 17*(1), 205–228.

Kastury, F., Besedin, J., Betts, A. R., Asamoah, R., Herde, C., Netherway, P., Tully, J., Scheckel, K. G., & Juhasz, A. L. (2024). Arsenic, cadmium, lead, antimony bioaccessibility and relative bioavailability in legacy gold mining waste. *Journal of Hazardous Materials*. https://doi.org/10.1016/j.jhazmat.2024.133948

Khan, I. U., Qi, S. S., Gul, F., Manan, S., Rono, J. K., Naz, M., Shi, X. N., Zhang, H., Dai, Z. C., & Dao Lin, D. (2023). A green approach used for heavy metals 'phytoremediation' via invasive plant species to mitigate environmental pollution: A review. *Plants, 12*(4), 725.

King, D. J., Doronila, A. I., Feenstra, C., Baker, A. J. M., & Woodrow, I. E. (2008). Phytostabilisation of arsenical gold mine tailings using four eucalyptus species: Growth, arsenic uptake and availability after five years. *Science of the Total Environment, 406*(1–2), 35–42. https://doi.org/10.1016/j.scitotenv.2008.07.054

Kuppusamy, S., Palanisami, T., Megharaj, M., Venkateswarlu, K., & Naidu, R. (2016). In-situ remediation approaches for the management of contaminated sites: A comprehensive overview. *Reviews of Environmental Contamination and Toxicology, 236*, 1–15.

Lavanya, M. B., Viswanath, D. S., & Sivapullaiah, P. V. (2024). Phytoremediation: An eco-friendly approach for remediation of heavy metal-contaminated soils-A comprehensive review. *Environmental Nanotechnology, Monitoring & Management, 22*, 100975.

Leguizamo, M. A., Gómez, W. D., & Sarmiento, M. C. (2017). Native herbaceous plant species with potential use in phytoremediation of heavy metals, spotlight on wetlands—A review. *Chemosphere, 1*(168), 1230–47.

Linnenluecke, M. K., & Griffiths, A. (2013). Firms and sustainability: Mapping the intellectual origins and structure of the corporate sustainability field. *Global Environmental Change*. https://doi.org/10.1016/j.gloenvcha.2012.07.007

Linnenluecke, M. K., Marrone, M., & Singh, A. K. (2020). Conducting systematic literature reviews and bibliometric analyses. *Australian Journal of Management, 45*(2), 175–194.

Liu, S., Yang, B., Liang, Y., Xiao, Y., & Fang, J. (2020). Prospect of phytoremediation combined with other approaches for remediation of heavy metal-polluted soils. *Environmental Science and Pollution Research, 27*(14), 16069–16085.

Lu, N., Li, G., Han, J. C., Wang, H. Y., Yang, W., & Sun, Y. Y. (2019). Investigation of lead and cadmium contamination in mine soil and metal accumulation in selected plants growing in a gold mining area. *Applied Ecology and Environmental Research, 17*(5), 10587–10597. https://doi.org/10.15666/aeer/1705_1058710597

Marfuah, D. S., Hamim, H., Sulistyaningsih, Y. C., Surono, S., Setyaningsih, L., & Saprudin, D. (2023). Dark septate endophyte inoculation improved Pb phytoremediation of Jatropha curcas and Reutealis Trisperma on gold mine tailings. *Bioremediation Journal*. https://doi.org/10.1080/10889868.2023.2279194

Melato, F. A., Mokgalaka, N. S., & McCrindle, R. I. (2016). Adaptation and detoxification mechanisms of vetiver grass (*Chrysopogon zizanioides*) Growing on Gold Mine Tailings. *International Journal of Phytoremediation, 18*(5), 509–520. https://doi.org/10.1080/15226514.2015.1115963

Nuraini, Y., Arfarita, N., & Siswanto, B. (2015). Isolation and characteristic of nitrogen-fixing bacteria and phosphate-solubilizing bacteria from soil high in mercury in tailings and compost areas of artisanal gold mine.

Agrivita, 37(1), 1–7. https://doi.org/10.17503/agrivita-2015-37-1-p001-007

Okewale, I. A., & Grobler, H. (2023). Assessment of heavy metals in tailings and their implications on human health. *Geosystems and Geoenvironment*. https://doi.org/10.1016/j.geogeo.2023.100203

Orłowska, E., Orłowski, D., Mesjasz-Przybyłowicz, J., & Turnau, K. (2011). Role of mycorrhizal colonization in plant establishment on an alkaline gold mine tailing. *International Journal of Phytoremediation, 13*(2), 185–205. https://doi.org/10.1080/15226514.2010.495148

Petelka, J., Abraham, J., Bockreis, A., Deikumah, J. P., & Zerbe, S. (2019). Soil heavy metal(loid) pollution and phytoremediation potential of native plants on a former gold mine in ghana. *Water, Air, and Soil Pollution*. https://doi.org/10.1007/s11270-019-4317-4

Priya, A. K., Muruganandam, M., Ali, S. S., & Kornaros, M. (2023). Clean-up of heavy metals from contaminated soil by phytoremediation: A multidisciplinary and eco-friendly approach. *Toxics, 11*(5), 422.

Putra, B., Jayanegara, A., & Susanto, I. (2024). Unraveling the effects of arbuscular mycorrhizal fungi on plant growth, nutrient content, and heavy metal accumulation in the contaminated soil: A meta-analysis. *Applied Environmental Research*. https://doi.org/10.35762/AER.2024006

Putra, B., Warly, L., Evitayani, E., & Utama, B. P. (2022). The role of arbuscular mycorrhizal fungi in phytoremediation of heavy metals and their effect on the growth of *Pennisetum purpureum* cv. Mott on gold mine tailings in Muara Bungo, Jambi Indonesia. *Biodiversitas Journal of Biological Diversity, 23*(1), 478–85. https://doi.org/10.13057/biodiv/d230151

Rajendran, S., Priya, T. A. K., Khoo, K. S., Hoang, T. K. A., Ng, H. S., Munawaroh, H. S. H., Karaman, C., Orooji, Y., & Show, P. L. (2022). A critical review on various remediation approaches for heavy metal contaminants removal from contaminated soils. *Chemosphere*. https://doi.org/10.1016/j.chemosphere.2021.132369

Rodríguez, E., Peralta-Videa, J. R., Sánchez-Salcido, B., Parsons, J. G., Romero, J., & Gardea-Torresdey, J. L. (2007). Improving gold phytoextraction in desert willow (*Chilopsis linearis*) using Thiourea: A spectroscopic investigation. *Environmental Chemistry, 4*(2), 98–108. https://doi.org/10.1071/EN06048

Romanova, T. E., & Shuvaeva, O. V. (2016). Fractionation of mercury in water hyacinth and pondweed from contaminated area of gold mine tailing. *Water, Air, and Soil Pollution*. https://doi.org/10.1007/s11270-016-2874-3

Romanova, T. E., Shuvaeva, O. V., & Belchenko, L. A. (2016). Phytoextraction of trace elements by water hyacinth in contaminated area of gold mine tailing. *International journal of phytoremediation, 18*(2), 190–4. https://doi.org/10.1080/15226514.2015.1073674

Sampanpanish, P. (2018). Arsenic, manganese, and cyanide removal in a tailing storage facility for a gold mine using phytoremediation. *Remediation, 28*(3), 83–89. https://doi.org/10.1002/rem.21563

Samsuri, A. W., Tariq, F. S., Karam, D. S., Aris, A. Z., & Jamilu, G. (2019). The effects of rice husk ashes and inorganic fertilizers application rates on the phytoremediation of gold mine tailings by vetiver grass. *Applied Geochemistry*. https://doi.org/10.1016/j.apgeochem.2019.104366

Sharma, Pooja. (2021). Efficiency of bacteria and bacterial assisted phytoremediation of heavy metals: An update. *Bioresource Technology, 328*, 124835.

Sharma, P., Tripathi, S., & Chandra, R. (2020). Phytoremediation potential of heavy metal accumulator plants for waste management in the pulp and paper industry. *Heliyon*. https://doi.org/10.1016/j.heliyon.2020.e04559

Sharma, Pooja, Tripathi, Sonam, & Chandra, Ram. (2021). Highly efficient phytoremediation potential of metal and metalloids from the pulp paper industry waste employing *Eclipta alba* (L) and *Alternanthera philoxeroide* (L): Biosorption and pollution reduction. *Bioresource Technology*. https://doi.org/10.1016/j.biortech.2020.124147

Sharma, P., Tripathi, S., Purchase, D., & Chandra, R. (2021). Integrating phytoremediation into treatment of pulp and paper industry wastewater: Field observations of native plants for the detoxification of metals and their potential as part of a multidisciplinary strategy. *Journal of Environmental Chemical Engineering*. https://doi.org/10.1016/j.jece.2021.105547

Shen, X., Dai, M., Yang, J., Sun, L., Tan, X., Peng, C., Ali, I., & Naz, I. (2022). A critical review on the phytoremediation of heavy metals from environment: Performance and challenges. *Chemosphere, 291*, 132979.

Tan, H. W., Pang, Y. L., Lim, S., & Chong, W. C. (2023). A state-of-the-art of phytoremediation approach for sustainable management of heavy metals recovery. *Environmental Technology and Innovation*. https://doi.org/10.1016/j.eti.2023.103043

Tariq, F. S., Samsuri, A. W., Karam, D. S., & Aris, A. Z. (2016). Phytoremediation of gold mine tailings amended with iron-coated and uncoated rice husk ash by vetiver grass (*Vetiveria zizanioides* (Linn.) nash). *Applied and Environmental Soil Science*. https://doi.org/10.1155/2016/4151898

Tibane, L. V., & Mamba, D. (2023). Environmental risk assessment, principal component analysis, tracking the source of toxic heavy metals of solid gold mine waste tailings, South Africa. *Environmental Forensics*. https://doi.org/10.1080/15275922.2023.2172478

Wanitsawatwichai, K., & Sampanpanish, P. (2021). The combination of phytoremediation and electrokinetics remediation technology on arsenic contaminated remediation in tailing storage facilities from gold mine. *Heliyon*. https://doi.org/10.1016/j.heliyon.2021.e07736

Weiersbye, I. M., Witkowski, E. T. F., & Reichardt, M. (2006). Floristic composition of gold and uranium tailings dams, and adjacent polluted areas, on south Africa's deep-level mines. *Bothalia, 36*(1), 101–127. https://doi.org/10.4102/abc.v36i1.349

Wong, H. K. T., Gauthier, A., & Nriagu, J. O. (1999). Dispersion and toxicity of metals from abandoned gold mine tailings at Goldenville, Nova Scotia, Canada. *Science of the Total Environment, 228*(1), 35–47. https://doi.org/10.1016/S0048-9697(99)00021-2

Xiao, R., Wang, S., Li, R., Wang, J. J., & Zhang, Z. (2017). Soil heavy metal contamination and health risks associated with artisanal gold mining in Tongguan, Shaanxi,

China. *Ecotoxicology and Environmental Safety, 141*, 17–24. https://doi.org/10.1016/j.ecoenv.2017.03.002
Xu, D. M., Zhan, C. L., Liu, H. X., & Lin, H. Z. (2019). A critical review on environmental implications, recycling strategies, and ecological remediation for mine tailings. *Environmental Science and Pollution Research, 26*(35), 35657.
Xu, Z., dos Muchangos, L. S., Ito, L., & Tokai, A. (2023). Cost and health benefit analysis of remediation alternatives for the heavy-metal-contaminated agricultural land in a Pb–Zn mining town in China. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2023.136503
Zupic, I., & Čater, T. (2015). Bibliometric methods in management and organization. *Organizational Research Methods*. https://doi.org/10.1177/1094428114562629