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Review article

Brownfield-related studies in the context of climate change: A comprehensive review and future prospects

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ABSTRACT

The global climate change events are expected to augment the vulnerability of persistent organic pollutants within the global brownfield areas to a certain extent, consequently heightening the risk crises faced by these brownfields amidst the backdrop of global environmental changes. However, studies addressing brownfield risks from the perspective of climate change have received limited attention. Nonetheless, the detrimental consequences of brownfield risks are intrinsically linked to strategies for mitigating and adapting to sustainable urban development, emphasizing the critical importance of their far-reaching implications. This relevance extends to concerns about environmental quality, safety, health risks, and the efficacy of chosen regeneration strategies, including potential secondary pollution risks. This comprehensive review systematically surveys pertinent articles published between 1998 and 2023. A selective analysis was conducted on 133 articles chosen for their thematic relevance. The findings reveal that: (1) Under the backdrop of the climate change process, brownfield restoration is necessitated to provide scientific and precise guidance. The integration of brownfield considerations with the dynamics of climate change has progressively evolved into a unified framework, gradually shaping a research paradigm characterized by "comprehensive + multi-scale + quantitative" methodologies; (2) Research themes coalesce into five prominent clusters: "Aggregation of Brownfield Problem Analysis", "Precision Enhancement of Brownfield Identification through Information Technology", "Diversification of Brownfield Reutilization Assessment", "Process-Oriented Approaches to Brownfield Restoration Strategies", and "Expansion of Ecological Service Functions in Brownfield Contexts"; (3) Application methodologies encompass five key facets: "Temporal and Spatial Distribution Patterns of Pollutants", "Mechanisms and Correlations of Pollution Effects", "Evaluation of Pollution Risks", "Assessment of Brownfield Restoration Strategies", and "Integration of Brownfield Regeneration with Spatial Planning". Future brownfield research from the climate change perspective is poised to reflect characteristics such as "High-Precision Prediction, Comprehensive Dimensionality, Full-Cycle Evaluation, Low-Risk Exposure, and Commitment to Sustainable Development".

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1. Introduction

The concept of brownfields emerged in the late 20th century. It is noteworthy that there is substantial variation in the definition of brownfields across countries, influenced by various factors such as deindustrialization, urbanization, population density, and socio-economic aspects [1,2]. Scholars have extensively researched brownfields in different countries. For instance, Scholar Dixon T [3] reviewed the brownfield policies in the UK and the emerging sustainable development agenda. Scholar Yu S [4] provided an overview of urban soil quality research, particularly the trace metal pollution in many Chinese brownfields. Scholar Perić A [5] reviewed the planning practices of brownfield regeneration in Europe based on specific experiences. Scholar Miyagawa T critically [6] examined Japan's brownfield policies from a risk governance perspective through a literature review. Consequently, brownfields are defined [7] as previously developed but currently unused land, also described [7,8] as areas affected by prior use or surrounding land influence, rendering them unusable without further intervention. It is important to note that the reuse types of brownfield sites depend more on the surrounding urbanization level and specific regional characteristics rather than their past use. Additionally, most described brownfield reuses take the form of soft reuse (53%). In this study, "brownfields" are defined as sites known or potentially contaminated due to human activities, requiring reuse based on site-specific risk assessments and remediation for intended purposes. In terms of brownfield regeneration methods, these can be primarily categorized as follows: environmental investigation and assessment, remediation of pollutants, land redevelopment and reuse, ecological restoration and greening, sustainable management and planning, and sustainable management and planning [9–12].

In the midst of the myriad uncertainties brought about by global climate change in the 21st century, the persistence of extreme weather and climate events adds further complexity and risk to the already intricate realm of brownfield issues. These factors not only influence the toxicity of pollutants, levels of exposure, and biological sensitivities [13] but also accelerate the migration and dispersion of pollutants [14,15]. They disrupt the effectiveness of initial site remediation plans and the long-term operation, management, and maintenance of restored sites. For instance, extreme weather events can inundate containment structures, damage monitoring equipment, intensify the leaching of pollutants, and adversely impact the long-term stability of restoration outcomes. Therefore, it becomes paramount to assess the long-term stability of residual pollutants in brownfields throughout sustainable remediation processes and ensure that they do not pose significant risks to the environment and human health. Despite the urgent need to assess the associated risks between brownfields and climate change, research examining the effects of climate change on pollutant migration and environmental restoration remains limited in quantity. While extensive investigations have been conducted from the perspectives of water resources [16–19], soil [20–22], plants [23–25], and airborne environments [26,27] regarding the impacts of climate change, there remains a dearth of research at multiscale spatial dimensions and a lack of integrated analysis involving ecological processes. Furthermore, scientific guidance is absent to facilitate interdisciplinary collaboration for sustainable remediation processes within risk and performance assessment frameworks.

The explosive growth in urban land use demands has elevated sustainable land remediation to a paramount environmental restoration objective and a pivotal driver in expediting brownfield reclamation processes [28,29]. From a climate change perspective, studying the interactions between brownfield site pollutants and relevant soil physicochemical properties offers the potential for earlier establishment, prediction, and profound understanding of their broader and more fundamental connections to environmental factors. Concurrently, an increasing number of researchers view brownfield redevelopment as a critical strategy to mitigate the adverse impacts of climate change [29,30]. With the revitalization of vast tracts of idle and abandoned land, brownfields are now regarded as potential resources within the realm of sustainable land management. These lands, once considered "discarded", have been endowed with limitless potential to serve urban ecosystems, including climate regulation services [31,32] (such as air pollution alleviation [33], carbon sequestration [34,35], urban heat mitigation [36–40], and support for rainwater management), habitat services, and cultural services [41,42]. Overall, their quantification in the brownfield redevelopment process can be attributed to three tiers of impact. The primary impact focuses on risk management associated with the removal of toxic pollutants in situ. The secondary impact shifts towards the comprehensive effects spanning the entire life cycle and restoration process [43,44]. The tertiary impact concerns the consequences arising from redeveloping polluted land [45,46]. For instance, in the assessment of greenhouse gas emissions from brownfields, the framework follows a three-tier impact pathway, which encompasses: 1) primary impacts (related to the physical state of brownfields); 2) secondary impacts (associated with remediation activities), and 3) tertiary impacts (linked to later-stage effects) for calculating carbon emissions reduction equivalents resulting from brownfield redevelopment in a city [47]. The multifaceted nature of brownfield redevelopment underscores the intricate interplay between environmental restoration, sustainable urban planning, and climate change mitigation, necessitating a comprehensive approach to guide policy formulation and brownfield regeneration practices.

Neglecting the influence of climate change on the entire restoration process can adversely impact the outcomes of remediation efforts. This consideration can be approached from two perspectives: (1) how climate change affects the restoration process and (2) how climate change impacts restoration technologies. Firstly, brownfield restoration is a time-consuming, resource-intensive, and costly undertaking [48]. Unreasonable soil remediation can potentially trigger a series of public health crises, concurrently resulting in substantial carbon dioxide emissions [49]. The proliferation of brownfields in inner-city and industrial outskirts not only diminishes urban living quality but also poses significant environmental issues and health risks, particularly for vulnerable populations at the urban fringes. Therefore, within the context of climate change, brownfield restoration technologies should to some extent integrate resilient techniques that combine mitigation and adaptability. Simultaneously, brownfield redevelopment must consider central urban growth, density, and mixed land use to align with an encompassing sustainable developmental vision. To effectively address the impact of climate change, adaptation and mitigation need to be treated equally [50]. Tailored climate adaptation strategies for contaminated brownfields become especially pivotal. Nature-based solutions (NBS), compared to traditional physical and chemical remediation techniques, offer broader prospects for achieving sustainable urban rejuvenation. NBS not only maximizes the overall net benefits for societal, economic, and environmental sustainability but also holds the potential to supersede traditional remediation methods. Conventional techniques not only demand substantial energy and resource inputs but also risk land function loss and secondary pollution [51]. The nexus of brownfield regeneration, climate change adaptation, and sustainable urban development underscores the imperative of holistic approaches that capitalize on natural solutions. Achieving these integrative goals is pivotal to ensuring a resilient and environmentally conscientious future while navigating the challenges posed by urbanization and climate uncertainty.

As more scholars recognize the crucial ecological, economic, and societal value of transforming brownfields into green spaces [52–55], empirical and review literature addressing brownfield restoration, urban regeneration, and their spatial relationship have witnessed rapid growth in recent years. In the empirical research domain, more significant research interest has been directed towards large urban areas, often overshadowing climate change studies in medium and small cities. In the realm of review literature, scholars have explored various aspects, including the construction of interdisciplinary frameworks for brownfield-related studies [56,57], comparative assessments of regional brownfield restoration methods [58], brownfield redevelopment potential [59], resilience [60], emphasis on the significance of natural-based brownfield restoration (NBS) and green sustainable restoration methods in the re-remediation process, spatial planning, and post-revival benefits assessment [51]. However, there remains a lack of research that employs bibliometric analysis and visualization techniques to deeply delve into the risks and opportunities of brownfield regeneration under climate change scenarios, exploring the intersections between brownfields and climate change, encompassing risk and opportunity, as well as a comprehensive review of relevant literature on sustainable resilient adaptive strategies.

Therefore, this paper centres its investigation on these themes and endeavours to address the following questions: (1) What is the evolutionary trajectory of the current research landscape, key issues (focusing on edge cities and informal urban areas), and future research application scenarios in this domain? (2) How can the characteristics of pollutant migration in different types of brownfields under climate change scenarios, methods for environmental risk assessment, green-resilient restoration frameworks and strategies be scientifically evaluated and established? (3) In what ways and using which methods can the potential of brownfield restoration under various scenarios quantitatively contribute to climate change mitigation and adaptation efforts? This study seeks to aid in addressing pivotal domains and issues within the future brownfield restoration process by formulating timely response strategies, thereby promoting enhanced planning practices for the times ahead.

2. Materials and methods

2.1. Data source and screening

This study utilized the Web of Science (WOS) Core Collection platform's SCI and SSCI literature as the data source. Relevant research literature from all periods was selected, employing the search query TS = (brownfield or "brown land" or "brown ground" or "industrial and mining area" or "abandoned land" or "waste land" or "contaminated soil") AND TS = ("climate change" or "climate mitigation*" or "climate adaptation*" or "extreme weather" or "climate risk" or "global warming"). A total of 226 articles were retrieved. Following manual exclusion and removal of articles with lower relevance, a total of 133 articles were obtained for subsequent analysis. The search was conducted up to July 5, 2023.

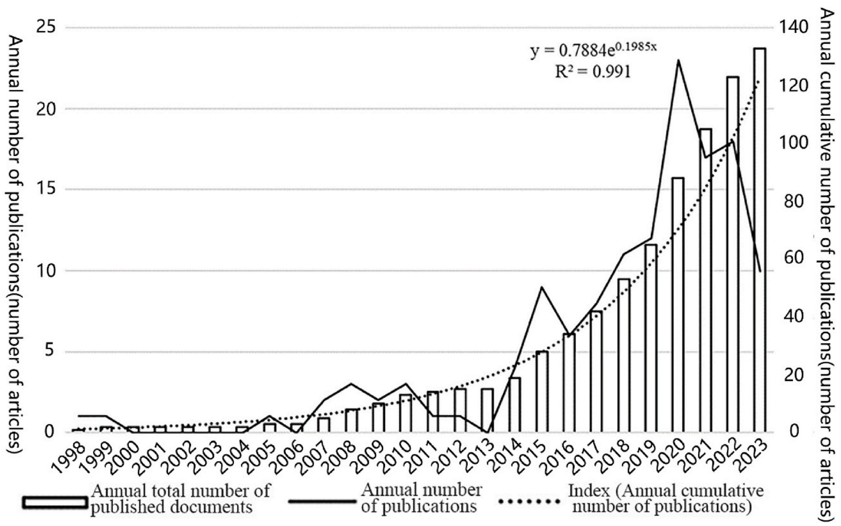

Fig. 1. Annual distribution of publications in brownfield research related to climate change processes.

2.2. Data analysis method

Scientometric analysis is a cutting-edge technique based on extensive bibliometric data to map the evolution and measure the impact of research in specific disciplines [61]. Currently, scientometrics has been widely employed for evaluating scientific contributions, capturing trends in the forefront of disciplines, and visualizing these trends. It quantitatively analyzes published literature to objectively depict the core structure, historical development, and future research trajectories of relevant scientific studies [62–67]. The VosViewer software, developed by van Eck and Waltman [68], is utilized for analyzing bibliometric data obtained from the Web of Science (WOS) database. Data in CSV format is imported into the central unit of the VosViewer software for analysis. The software's built-in keyword co-occurrence and co-authorship analysis tools are employed to generate corresponding networks. CiteSpace is a versatile, temporal, and dynamic citation visualization analysis software.

3. Results

3.1. Descriptive statistical analysis of the research literature

The 133 papers utilized in this study originated from 623 authors affiliated with 300 institutions across 41 countries. These papers were published in 88 different journals and cited a total of 9664 references from 3381 journals. Fig. 1 illustrates a significant increase in the number of relevant articles published from 1998 to 2023. The earliest recorded publication incorporating climate change factors into brownfield restoration dates back to 1998 [69]. By comparing the potential issues of pollutant accumulation and migration before and after land use changes, this publication underscored the complex diversity of restoration site conditions under varying climate change impacts in different years. Subsequently, the cost-effectiveness and method effectiveness of different-stage remediation techniques were quantified by constructing a life-cycle management framework and conducting a life-cycle assessment, thereby extending the scope of potential impacts on the environment and human health risks beyond the restoration phase [70,71]. This study pioneeringly identified key core issues in the brownfield restoration process under global climate change scenarios – the multifaceted potential impacts (ecological, economic, social) brought by the continuous and dynamic interaction between pollutants and environmental factors throughout the entire lifecycle. As climate and environmental concerns progressively become focal points in various research domains, the issues of brownfield restoration under climate change processes have garnered increasing attention from scholars. Green restoration technologies [72–75], risk management strategies [23,76], and nature-based solutions (NBS) [51,77], proposed to adapt and mitigate global climate change impacts, have emerged as multifaceted strategies in this research area in recent years. Through an analysis of journal sources, the journal "Science of the Total Environment" from Elsevier stands as a leading publication in this research field (Table 1).

3.2. Analysis of research stages and evolutionary paths

Cluster analysis was conducted on key terms related to brownfield restoration under climate change processes, revealing a three-stage evolution in the research trajectory (Fig. 2). Specifically, the first stage focused on the intrinsic characteristics of brownfields, encompassing studies on toxicology testing of brownfield soil pollutants and site-specific strategies. Although this stage recognized the series of impacts of one-dimensional environmental changes on contaminated soil, a direct link between climate change and brownfield restoration had not yet been established. In the second stage, systematic brownfield restoration frameworks were developed, encompassing dynamic and comprehensive consideration of the impacts of climate change events on various polluted sites across multiple environmental factors. The intense shifts in environmental factors triggered by climate change prompted a realization of their profound impact on brownfield restoration. In the third stage, there was a growing recognition of the potential and value of adaptive and mitigative brownfield restoration strategies within the context of climate change scenarios. The integration of climate change and brownfield restoration became an inseparable consideration in a holistic manner.

In the first stage, based on the "pressure-state-response" dual-drive mechanism, differential associations between various pollutants and single-factor environmental parameters under different environmental conditions were analyzed. However, this approach overlooked the interconnected influences among multiple environmental parameters [78], often emphasizing the physicochemical characteristics of pollutants themselves while neglecting the spatial relationships between pollutants and sites. Nevertheless, collectively,

Table 1
Top nine journal sources in the field of brownfield research under climate change processes.

Ranking	Journal sources name	Circulation	Total citations	Average citations
1	Science of the total environment	11	119	10.82
2	Environmental science and pollution research	6	173	28.83
3	Journal of environmental management	4	210	52.50
4	Journal of cleaner production	4	86	21.50
5	Chemosphere	4	73	18.25
6	Agriculture Ecosystems & Environment	4	72	18
7	Journal of soils and sediments	4	39	9.75
8	Sustainability	4	19	4.75
9	International journal of phytoremediation	3	1	0.33

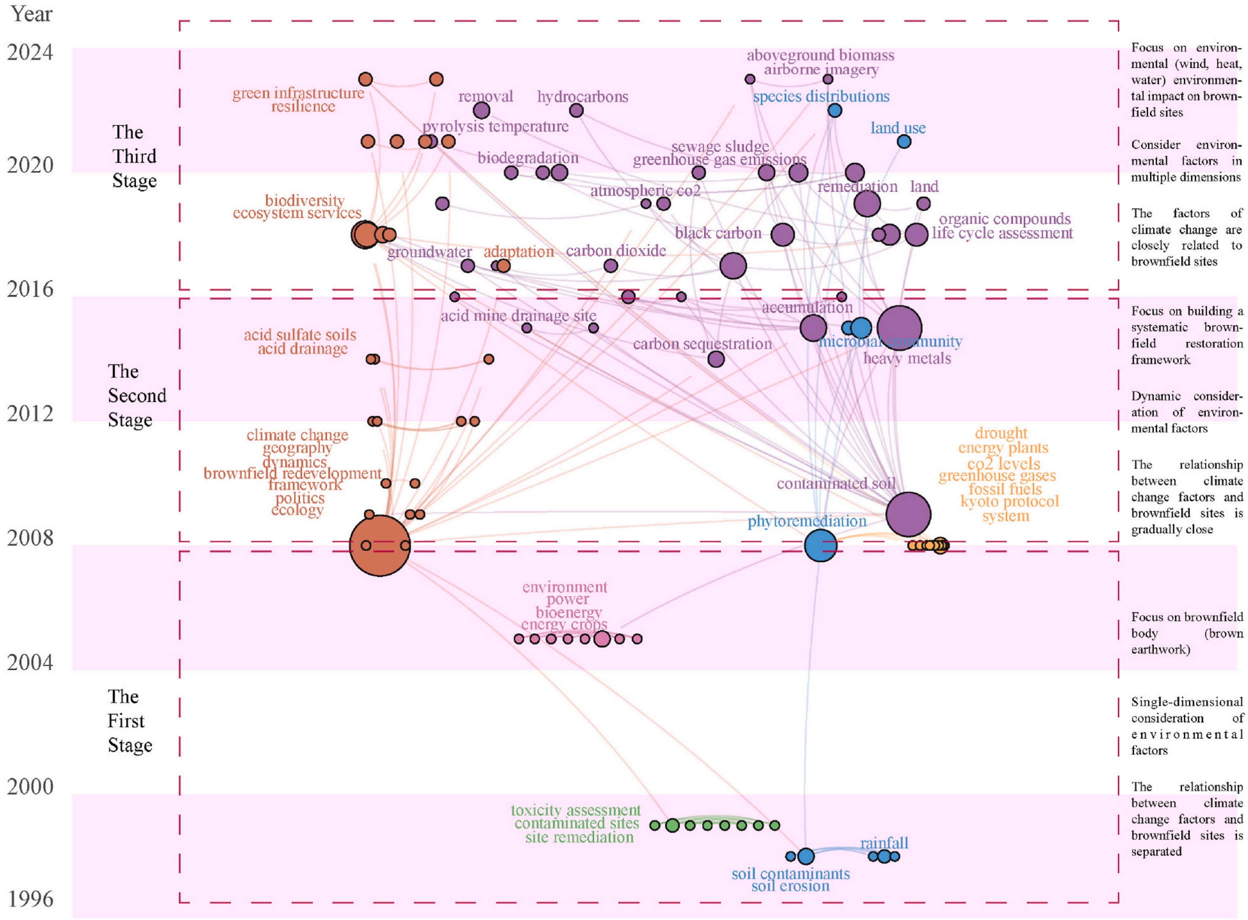

Fig. 2. Temporal and spatial distribution map of brownfield-related research under the climate change context (1998–2023).

these efforts laid a solid foundation for constructing environmental pollution simulation and prediction models in the subsequent stage. In the second stage, a gradual integration of multiple environmental factors led to the development of a systematic brownfield restoration framework. Attempts were made to combine digital models to analyze the spatiotemporal distribution and periodic evolution of pollutants. This approach provided strong technical support and spatial basis for understanding the migration and transport patterns of pollutants at individual brownfield sites under various climate change scenarios, and for proposing strategies of joint prevention and control. In the third stage, aided by advancements in remote sensing technology [79,80] and the introduction of artificial intelligence algorithms [34,81,82], scientific identification of the spatial distribution [83] and patterns [84,85] of potential brownfield clusters under climate change impacts were achieved. Monitoring and predicting changes in pollutant concentrations [86,87] and spatial exposure characteristics [88–90] also became possible, laying a theoretical foundation for precise governance and adaptive brownfield restoration strategies. Simultaneously, the focus shifted from “pollutants” to “populations and spaces”. This transition allowed the proposal of adaptive pollution prevention and control strategies considering the size, zoning, and gradation of population exposure [91]. By incorporating population needs, efficient subsequent spatial utilization methods and deriving multi-dimensional spatial value [92], the study gradually formed a research framework of “comprehensive + multi-scale + quantitative” in guiding brownfield restoration under the process of climate change.

3.3. Analysis of research keywords and hotspots

The keyword co-occurrence temporal map generated by CiteSpace in the context of brownfield restoration research under climate change illustrates the emergence of eleven clusters in this research domain (Fig. 3). These clusters include urban adaptation and climate change mitigation sustainable development framework, adsorption, global climate warming and sustainable governance, soil erosion, solid waste composting, microbial communities and bioremediation technology, multi-scenario environment, life-cycle assessment, geographical information and geological environment, renewable energy potential, and sediment (Fig. 4). Upon summarization, these clustered keywords can be categorized into five main themes: brownfield problem analysis clustering, precision identification aided by information technology, multidimensional evaluation of brownfield reuse, process-oriented brownfield restoration strategies, and extension of brownfield ecological service functions.

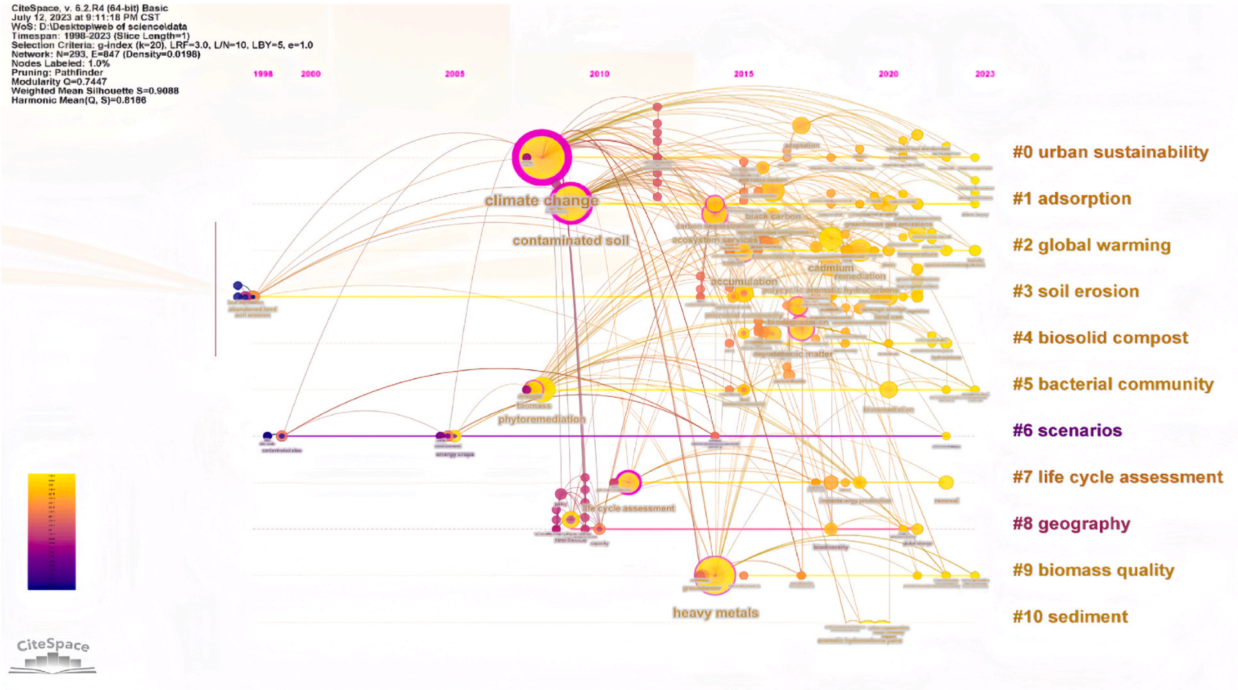

Fig. 3. Analysis of annual variation and clustering of key keywords in brownfield research related to climate change processes (1998–2023).

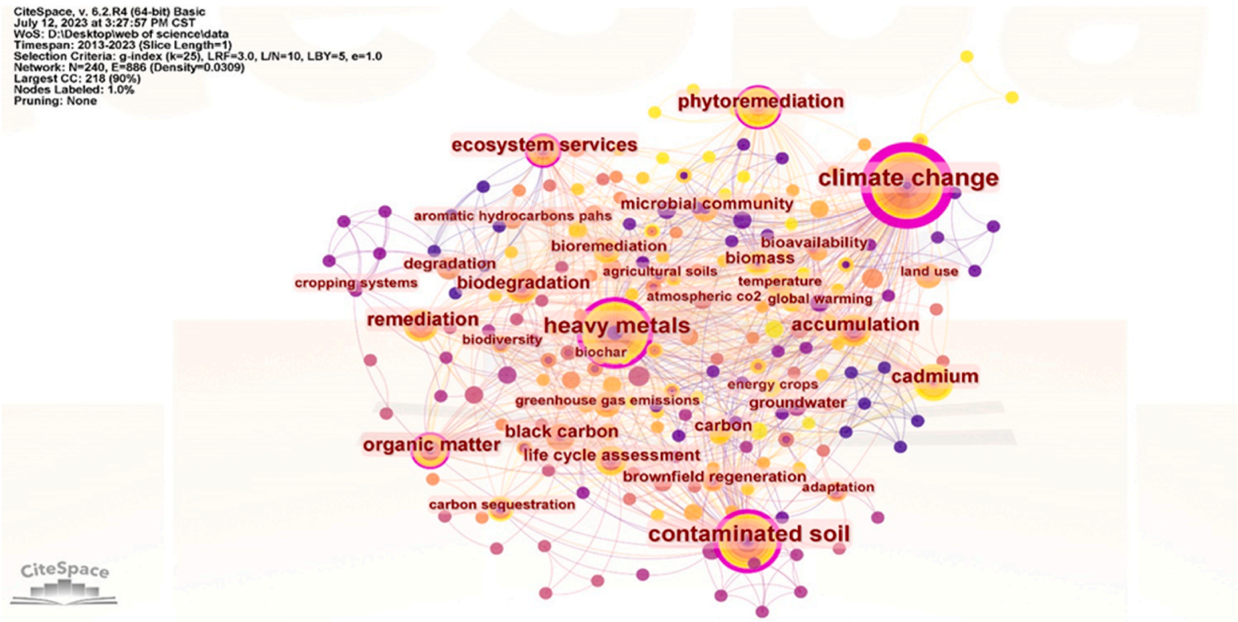

Fig. 4. Co-occurrence network of key keywords in brownfield research related to climate change processes (1998–2023).

3.3.1. Spatial focus: cluster analysis of brownfield problem analysis

This trajectory, represented by the keywords "brownfield soils – on-site brownfield sites – informal green spaces [59] – regional green space network – sustainable urban land use patterns", serves as a spatial evolution clue. The research focus has transitioned from dispersed individual brownfield sites to a comprehensive urban green space network, forming a research cluster known as the "urban brownfield zone". The attention has gradually shifted from the pollutants themselves to the sites and then to the spatial aspect of brownfield clusters, further exploring potential brownfield identification [83], urban brownfield regeneration spatial patterns [93,94], different brownfield greening transformation strategies and their potential impacts on the entire green space system, and the city's adaptability to climate change [31]. This attention change highlights the advantages of brownfields in urban land sustainability and circular utilization. For instance, brownfields, as a crucial component of urban "grey" infrastructure, integrate with "green" infrastructure to play a significant role in enhancing comprehensive rainwater and sewage control technologies, coordinating regional flood control with urban stormwater management, and improving urban resilience [95,96]. Simultaneously, brownfields, as essential components of urban ecological networks, influence the connectivity potential of specific nodes within the network. They serve as critical stepping stones for maintaining the connectivity of protective corridors and contribute significantly to the integrity and continuity of urban ecological processes [97]. In summary, under the context of climate change, integrating brownfields into the urban spatial system can shape adaptive and resilient spatial planning and management strategies and frameworks, mitigating the impact of climate change on urban development.

3.3.2. Methodological progression: precision identification of brownfield using information technology assistance

This trajectory is delineated by the keywords "plot sampling – numerical models – remote sensing monitoring – neural network models". It involves the analysis, simulation, and prediction of variables across three dimensions: time, space, and spatiotemporal. Notably, remote sensing technology exhibits features of "large coverage area + multi-temporal time series + low data acquisition time cost" for pollution monitoring in large-scale urban brownfields. Neural network models, on the other hand, exhibit attributes of "high data processing efficiency + accurate trend prediction + broad coverage of influencing factors". For instance, in the temporal dimension, Sophie [98] utilized Earth observation service data from Sentinel-1 and Sentinel-2 time series to monitor seasonal variations in newly developed brownfield site environments. Navrátil [99,100] constructed an agricultural brownfield identification database based on land use image data for analyzing agricultural brownfield changes over time. In the spatial dimension, Kadioglu and Daniels (2008) [101] combined GPR and EM-61 data to identify shapes and burial depths of shallow hazardous objects beneath brownfields. Morio and Finkel (2011) [102] employed "flow-guided interpolation" to identify large-scale brownfields. Ferrara [103] employed MIVI multispectral infrared and visible light imaging sensors for remote detection of the spatial distribution of potential environmental hazards and pollution in brownfield sites. Furthermore, scholars [103] combined satellite spectral data with machine learning to enhance the prediction accuracy of unsampled points in brownfield soil surveys. In the spatiotemporal dimension, scholars [104] utilized a method integrating crowdsourced datasets and traditional datasets to measure the dynamic information of brownfield plots at a fine spatiotemporal scale. The integration of presence and background data with a machine learning (PBL) model was employed to evaluate the suitability of large-scale brownfield reconstruction. Overall, the utilization of remote sensing information and neural network modelling has enhanced the accuracy of pollutant measurement, feature extraction, and identification system construction in brownfield recognition, along with improved accessibility to multi-source and multi-temporal data. Certainly, we also need to consider that certain brownfields do not represent vast areas or extensive industrial sites with a multitude of samples suitable for applying geostatistics and Machine Learning techniques [105,106]. In the future, identifying brownfields with specific spatial locations, properties, and characteristics will require further exploration and research into alternative approaches.

3.3.3. Multi-benefit assessment oriented: diversified evaluation of brownfield reutilization

This trajectory is defined by the keywords "elimination of pollutant threat factors – pre-use evaluation of site utilization – cost-benefit evaluation – multi-factor-driven site regeneration – multi-population demands – multi-functional benefit value – multi-level impacts" as spatial evolution cues. As government authorities increasingly recognize that converting brownfields into alternative land-use supplies effectively conserves land resources, a broader and more profound connection has been established between brownfields and cities or communities [107,108] (spatial science and social theory). Real-world brownfield greening projects should not only consider ecosystem service values but also factor in cost-effectiveness for a holistic assessment of broader benefits [109–112], which involves evaluating its priority utilization value and sequence from economic, ecological, and societal perspectives [113], and preemptively constructing an assessment framework of ecosystem service value for post-greening brownfields from a systemic standpoint [53]. For instance, developed multi-criteria decision analysis prioritization tools (MCDA) [114,115] based on a sustainable development framework have re-evaluated multi-scale brownfield vulnerable areas, risk assessments, and regeneration potential and value [114,116–126] from different angles. The approach has transitioned from direct ranking comparisons to layered aggregation-based multi-attribute decision comparisons. For example, the Timbre Brownfield Prioritization Tool assesses brownfields in terms of categorization and priority regeneration benefits from stakeholders' perspectives, thereby supporting diverse investors in managing different combinations of brownfields. Multi-criteria genetic algorithms determine optimal land use allocation based on stakeholder preferences and limitations associated with land use categories [127]. Currently, this clustering is gradually evolving towards "multi-dimensional regeneration factors + coordinated participation of multiple stakeholders + maximization of multi-party benefits".

3.3.4. Dynamic evolution: process-oriented approach to brownfield remediation strategies

This trajectory is defined by the keywords "pollutant migration outcomes – pollutant migration influencing factors – pollutant migration process – process-integrated remediation methods" as the main evolution line. As the potential migration impacts of pollutants under climate change scenarios become apparent, scholars have gradually focused on the logic of pollutant migration from environmental change characterization to ecological processes and underlying ecological functions. The research scope has expanded to explore the interaction mechanisms between factors influencing pollutant migration processes and climate change factors. It also emphasizes intervention-focused pollutant migration simulation analysis, predictive modelling, and comparative studies on the effectiveness of process-integrated remediation methods. From the perspective of intervening in pollutant migration processes, under the complex and changing conditions of climate change scenarios in brownfield restoration, pollutant migration behavior and bioavailability are not only related to their total quantity but also depend on the different transformation processes caused by their chemical forms, which is especially true for their original forms upon entry. Different forms and types of heavy metals can have varying environmental effects and directly impact their toxicity, migration, and cycling in the natural environment [128,129]. Currently, process-based simulation models related to pollutant migration have been widely developed and used, such as the Groundwater Modeling System [130,131], the Extended Environmental Multimedia Modeling System [132], and Hydrus [133–136]. These models allow for finer visualization of pollutant plumes [137] and effective integration of pollution data with multiple auxiliary information sources. They encompass the management, presentation, and analysis of different data related to industrial pollution sites, such as hydrogeological characteristics, pollution information, and risk assessment. For instance, scholars utilized the Hydrus-3D model's flow and solute transport modules to simulate the historical arsenic pollution process over 48 years in a brownfield site in northern China, which included three-dimensional migration and accumulation processes of soluble and adsorbed arsenic, spatial-temporal distribution, and migration trends. This provided a more accurate risk assessment foundation [138]. Regarding process-integrated remediation strategies, considering climate change's full lifecycle impact on pollutant migration processes has become a necessary step in assessing remediation schemes. For example, some researchers [139] simulated pollutant migration pathways using the REMChlor model, then assessed the adaptation capacity of different plant remediation systems to climate change recovery under various sea-level rise scenarios using SimaPro 8.0 LCA software. This led to a systematic assessment of the lifecycle impacts [140]. The remediation approach of Natural-Based Solutions (NBS) is intricately intertwined with a procedural and dynamic restoration process to a certain extent. It involves fully tapping into nature's inherent problem-solving potential within NBS [51,141], striving to enhance the overall environmental resilience and adaptability through dynamic adjustments. Unlike traditional physical and chemical remediation techniques that inevitably lead to secondary pollution during environmental shifts [142], NBS focuses on mitigating pollution during the process and leveraging natural degradation as a restorative force. These solutions introduce a more diverse range of natural features and processes into the brownfield restoration process through locally suitable, resource-efficient, and systematic intervention measures. For instance, techniques such as phytoremediation [143], biochar stabilization [144], and green synthesis-based nanoremediation [145,146] typically possess lower environmental footprints due to their reduced material and energy consumption, often with carbon sequestration potential. Overall, both the intervention-focused pollutant migration and process-integrated remediation methods offer valuable insights for controlling and intervening in pollutant migration on contaminated sites, as well as for constructing potential barriers.

3.3.5. Unlocking multi-functional potential: extending ecological services in brownfield redevelopment

This trajectory is delineated by the keywords "site restoration – soft reuse [147] – circular land management – potential ecological potential assessment – sustainable energy contribution – climate change mitigation potential" as the spatial evolution cues. The provision of ecosystem services through brownfield greening depends on factors such as location, area, shape, restoration methods, greening patterns, vegetation coverage, and community arrangement. As the scarcity of urban green space fails to meet the growing demand for green areas among urban populations, the transformation of abandoned and vacant land is seen as the most favourable approach to addressing the shortage of green spaces in urban landscape planning. Simultaneously, brownfields provide solutions for urban public health [148] and enhance urban ecosystem service capacity [149–152]. For instance, regarding sustainable energy contribution, brownfield sites have the potential to rapidly deploy renewable energy sources. Scholar Soji Adelaja [153] conducted a study using Michigan as an example to explore renewable energy production in brownfields. Based on estimates of brownfield land capacity in the region, the total available energy potential of Michigan's brownfields is estimated to be equivalent to 43% of Michigan's residential electricity consumption. Scholar Briana [154] proposed a GIS model for evaluating the energy production potential of a series of specific locations, including brownfields, closed landfills, and abandoned mining areas. In the context of climate change mitigation potential, especially when brownfields are developed into green spaces, redevelopment efforts also significantly reduce greenhouse gas emissions [47]. Establishing different vegetation cover on urban abandoned land helps lower atmospheric CO2 concentrations. Tree canopy coverage directly stores and sequesters a considerable amount of CO2 through photosynthesis in above-ground and below-ground woody biomass and soil. In summary, the trajectory of brownfield redevelopment encompasses a range of interconnected themes including site restoration, soft reuse, circular land management, potential ecological assessments, sustainable energy contributions, and climate change mitigation potential. This multidimensional approach highlights the multifaceted benefits and potential of brownfield sites for enhancing urban sustainability, and public health and addressing climate change challenges. The most prominent and advocated aspect in recent years is the potential multiple benefits generated by NBS-based remediation of polluted areas [155,156]. Its significant contributory role towards the sustainable economic, ecological, and integrated comprehensive values of brownfields is highlighted [157–159]. Not only does it alleviate the risks of soil contamination, but it also provides additional advantages throughout the entire site remediation process. These benefits encompass mitigating climate change, enhancing mental health and well-being through contact with nature, managing rainwater, and conserving biodiversity, among others [160,161].

3.4. Analysis of scenario research applications

Currently, the application of climate change impact factors in brownfield pollution prevention and control is integrated throughout the three stages of the brownfield restoration process, namely the "pre-, mid-, and post-" stages. This integration spans the early-stage characterization of brownfield spatial and temporal distribution patterns and the influences on pollutant migration, the mid-stage assessment and prediction of brownfield pollutant migration, and the later-stage comprehensive process of urban brownfield regeneration strategies and prioritization.

3.4.1. Temporal and spatial integration: study of multi-scale pollutant distribution

Exploring the Spatiotemporal Distribution Patterns of Pollutants from the Perspective of Climate Change involves utilizing meteorological, remote sensing, atmospheric pollutant concentration, and socio-economic data. Techniques such as Visible and Near-Infrared Reflectance Spectroscopy (VNIR) coupled with Random Forest machine learning (RF) [162], Support Vector Machine (SVM), and Deep Neural Networks (DNN) [163] are applied to regional, urban, and neighbourhood environments. This research investigates pollutant distribution characteristics across various spatial and temporal scales, uncovering transmission pathways, rates, and the contributions of different factors. The findings reveal that brownfield pollutants exhibit characteristics of spatial “aggregation, heterogeneity, and strong migration" and temporal “seasonality, time series, and dynamism." The spatial distribution correlates significantly with the original land use type, layout structure, land development methods, human activity intensity, pollution history, and distance from emission sources. For instance, Chi Xu [164] employed Gas Chromatography coupled with Electron Capture Negative Ion Mass Spectrometry (GC × GC–ECNI–MS) to analyze the pollution status, spatial distribution, transport pathways, migration influencing factors, and ecological risk assessment of short-chain and medium-chain chlorinated paraffins in soil and sediment from electronic waste dismantling areas in China. Hongxia Li [165] investigated the spatial distribution and pollution sources of heavy metals and metalloids in coal mine brownfield soils, assessing the potential risks to ecosystems and human health. Huang [166] integrated remote sensing images with points of interest to analyze the intrinsic mechanism of spatial-temporal patterns of industrial expansion and regeneration reuse from the perspective of Potential Environmental Risk (PER).

3.4.2. Element coupling: analysis of pollutant influencing factors

A combination of multivariate linear regression and spatial autocorrelation analysis is employed in the realm of pollution influence factor research, including meteorological data, soil pollution monitoring data, and socio-economic statistics. Innovative methodologies like spatial Durbin models and neural network models are constructed to explore the mechanical aspects of pollution from both natural and social dimensions. This approach uncovers heterogeneity patterns and draws conclusions on pollution impact mechanisms characterized by “comprehensiveness, complexity, dynamics, regionality, persistence, and latency”. In recent years, several models have been employed to examine the relationship between soil heavy metal pollution and human activities, such as Chemical Mass Balance (CMB), Positive Matrix Factorization (PMF), Absolute Principal Component Scores with Multiple Linear Regression (APCS/MLR), Potential Source Contribution Function (PSCF), UNMIX, and Principal Component Analysis (PCA) [167–173]. For example, Sha Huang [20] estimated soil heavy metal pollution levels using the Nemerow Pollution Index (Pn) and utilized detector statistical methods to assess the influence of eighteen environmental factors, including six natural factors (such as soil properties and surface topography) and twelve anthropogenic factors (such as industry, road networks, land use types, and landscape patterns). Scholars [174,175] employed the Geographical Detector model to identify the impact strength of different driving factors on soil heavy metal accumulation, quantifying the contribution of previously identified pollution sources to soil heavy metal accumulation through an attenuation function MLR multivariate linear regression model. Wu [176] examined the distribution of chlorinated paraffins in brownfield sites of chlorinated paraffin production plants and their impact on soil microbial communities.

3.4.3. Scenario simulation: multi-scenario pollution risk assessment

Amidst a cascade of environmental risk concerns brought about by climate change, toxic metals in soil have been confirmed to pose potential biological, ecological, and health risks [177–180]. As a result, spatial pollution risk assessment in brownfields has become an integral component of urban planning. Some scholars, utilizing diverse spatial data sources like meteorological data and land use, employ deterministic risk assessment models (DRA) [17], probabilistic risk assessment models (PRA) [181,182], methods like SBET (Simple Bioavailability Extraction Test) [183–185], ASTM models, and risk management tools such as SADA (Spatial Analysis and Decision Assistance) [186,187] to study pollution risk assessment across various spatial and temporal scales, alongside relevant societal impacts. For instance, SeidlM et al. [188] evaluated the leaching risk of trace metals, polycyclic aromatic hydrocarbons, and polychlorinated biphenyls in floodplain brownfields. Poggio L et al. [189] employed a risk-based source-pathway-receptor pollutant linkage framework to estimate human exposure risk from heavy metals in soil. Ahmad N et al. [190] constructed a preliminary risk assessment framework for industrial brownfield redevelopment and proposed methods for identifying and prioritizing potential risks in the early stages of industrial brownfield reuse projects. Han Q et al. [152] used Interpretive Structural Modelling (ISM) and Matrix Impact Cross-Reference Multiplication Applied to Classification (MICMAC) to reflect interrelationships between risks in brownfield redevelopment projects. Simultaneously, the exposure issue arising from brownfield pollution risk has garnered increasing social attention due to a series of environmental justice and health concerns. Research indicates a close correlation between brownfield pollution risk exposure and regional disparities in mortality and morbidity rates [191]. Presently, studies related to brownfield pollution risk assessment often exhibit characteristics of “large temporal and spatial scope, multi-scale research, and multi-scenario prediction”, yet there remains a relative lack of research focusing on diverse brownfield types, comprehensive pollution monitoring processes, and high precision investigations.

3.4.4. Quantitative multidimensional: assessment of brownfield remediation strategies

In the realm of brownfield restoration strategy assessment, common approaches encompass life cycle assessment (LCA), RAAS (Remedial Action Assessment System), REC (Risk Reduction, Environmental Merit, Costs), NORISC, WELCOME IMS (Integrated Management Strategy), and DARTS (Decision Aid for Remediation Technology Selection) [116,119,192,193]. These methods evaluate brownfield restoration strategies from three dimensions: social benefits, economic benefits, and environmental benefits. Concurrently, the use of the TRACI method [194] to assess environmental impacts, coupled with tools like Sustainable Brownfield Reconstruction (SBR) and SIPRIUS, aims to comparatively assess alternative reconstruction schemes post-implementation [195]. Quantitative and multidimensional assessment of soil restoration effectiveness is conducted by investigating pollution concentrations, impact extents, and related aspects. It's noteworthy that strategy selection becomes more intricate when dealing with multiple pollutants due to the influence of synergistic and antagonistic interactions among pollutants [196–198]. In the process of remediation, it is essential to concurrently consider the Correlation of co-contamination (organic and inorganic), as understanding the interplay and connections between these pollutants is crucial for effective remediation and management strategies. Organic and inorganic pollutants may interact, influencing the behavior of soil, water, or other elements in the environment. Understanding the relationships between them aids in better designing remediation methods suitable for different combinations of pollutants [140,199–201]. For instance, Libera A's study delved into the impact of climate-driven aquifer recharge on the sustainability-driven alteration of residual pollutants in soil and groundwater [202]. Lemming G utilized life cycle assessment (LCA) to evaluate the environmental impact of chloroethylene-contaminated site restoration, encompassing the infiltration of pollutants into groundwater and subsequent human toxicological effects through water consumption (primary impact assessment), as well as leaching risks from the restoration process [203]. Economic benefits of land resources were also integrated and applied in assessing the life cycle impact of two potential restoration schemes for idle brownfields in the Brussels region of Belgium. Currently, methods for soil pollution assessment are advancing towards being "concise and intuitive" while also "smart and dynamic". We also need to emphasize the application of the strategies, especially advanced analytics, of environmental forensics. It can be utilized to identify pollution sources, assess the degree of contamination, and monitor the effectiveness of remediation efforts. Through advanced analytical techniques such as chemical analysis, geochemistry, and biogeochemistry, pollutants can be identified, quantified, and tracked more accurately, aiding in determining the best remediation strategies and monitoring plans [204–206].

3.4.5. Optimal reconstruction: application in planning

The integration of human health risk assessment and geographical spatial analysis can offer more supportive ecological restoration strategies for urban brownfield revitalization. In the context of urban planning where brownfields are situated, reliance can primarily be placed on natural data, socio-economic data, etc. Methods such as multi-criteria genetic algorithms [207] can be employed to assess pollution's spatiotemporal mechanisms, influencing factors, and brownfield regeneration benefits. From the dimensions of urban spatial structure, form, and resilience, strategies can be formulated for brownfield pollution prevention and control, contributing to research on energy-efficient urban environmental optimization and low-carbon, low-pollution, and ecological reconstruction aspects. Critical factors for successful brownfield redevelopment undoubtedly encompass clear property rights, acceptable levels of purification, return on investment acceptable to stakeholders, and governmental incentive measures. In addition to political, economic, and procedural factors, geographical aspects play a crucial role. For instance, scholar Bohumil Frantál [94] employed variance analysis to explore the spatial patterns of urban redevelopment and used a detailed database model of existing and regenerated brownfields in Brno, Czech Republic, to identify significant geographical factors impacting urban brownfield regeneration. In another study [208], researchers examined the revitalization of the Leipzig Bavaria train station brownfield in Germany, evaluating the potential relationship between regulating microclimates through ecosystem services and the process of urban densification. ENVI-met modelling and a virtual reality display system were utilized to visualize the intricate connections among cities of varying densities. In conclusion, digitizing the management of urban spaces and conducting a scientific assessment of brownfield types have become integral components of current urban spatial planning and sustainable land use management.

4. Discussion

Research on brownfields under the influence of climate change is still in its developmental phase. Most recent reviews focusing on brownfields comprehensively integrate and correlate them with aspects such as remediation cost-effectiveness, urban economics, industrial development, and value assessment management [161,209–213]. Reviews specifically addressing brownfields within the context of climate change tend to concentrate more on restoration methods and the potential for climate adaptation [29,47,84,139,161]. Noteworthy is the alignment with other related review findings, highlighting that amid increasingly unstable climate scenarios, more scholars are directing future problem-solving efforts towards comprehensive exploration of the integrated value in brownfield restoration [112], along with considerations of entire lifecycle and sustainable restoration pathways [203], while also delineating the linkage between brownfields and urban spatial connections [59,159]. Differing from other related studies, this article accentuates the multifaceted impact and research emphasis of the climate change perspective on brownfields across various stages. Its goal is to establish a systematic framework for reviewing research theories and pathways, rather than treating climate change solely as a backdrop for study or a premise for simulated research discussions. For achieving more precise and scientific spatial planning in the future, further in-depth research will be required in predicting the accuracy of pollutant migration, assessing pollutant concentrations, brownfield regeneration evaluation cycles, and urban spatial planning applications.

4.1. Research prospect

Currently, digital models often rely on natural influencing factors, and the treated factors are relatively singular. The scenarios predicting pollutant migration in models still struggle to effectively simulate the vital ecological processes in real-world contexts, resulting in fragmented ecological insights. Simultaneously, the association between pollutant migration itself and health exposure risks has not yet been established, limiting its application in improved spatial planning and design. For instance, the vertical migration of trace metals, PAHs, and PCB pollutants caused by rainfall (unsaturated flow) and river floods (saturated flow), which leads to leaching risks, remains confined to vertical spatial transfer without providing favourable spatial planning insights on a horizontal level. Moreover, the predicted data results for pollutant migration still fail to achieve accurate spatial predictive capabilities. In the future, composite models incorporating natural, social, economic, and ecological elements should be developed, progressively transitioning from "low precision + static" to "high precision + dynamic" approaches.

4.1.1. High-accuracy prediction

Exploring the Spatiotemporal Distribution Patterns of Pollutants from the Perspective of Climate Change involves utilizing meteorological, remote sensing, atmospheric pollutant concentration, and socio-economic data. Techniques such as Visible [205,214,215] and Near-Infrared Reflectance Spectroscopy (VNIR) coupled with Random Forest machine learning (RF) [162], Support Vector Machine (SVM), and Deep Neural Networks (DNN) [163] are applied to regional, urban, and neighbourhood environments. This research investigates pollutant distribution characteristics across various spatial and temporal scales, uncovering transmission pathways, rates, and the contributions of different factors. The findings reveal that brownfield pollutants exhibit characteristics of spatial "aggregation, heterogeneity, and strong migration" and temporal "seasonality, time series, and dynamism". The spatial distribution correlates significantly with the original land use type, layout structure, land development methods, human activity intensity, pollution history, and distance from emission sources. For instance, Xu [164] employed Gas Chromatography coupled with Electron Capture Negative Ion Mass Spectrometry (GC × GC–ECNI–MS) to analyze the pollution status, spatial distribution, transport pathways, migration influencing factors, and ecological risk assessment of short-chain and medium-chain chlorinated paraffins in soil and sediment from electronic waste dismantling areas in China. Li [165] investigated the spatial distribution and pollution sources of heavy metals and metalloids in coal mine brownfield soils, assessing the potential risks to ecosystems and human health. Huang [166] integrated remote sensing images with points of interest to analyze the intrinsic mechanism of spatial-temporal patterns of industrial expansion and regeneration reuse from the perspective of Potential Environmental Risk (PER).

4.1.2. Comprehensive lifecycle assessment

Currently, research concerning pollutant-contaminated soil is transitioning from relying on data collected from relatively localized traditional ground monitoring stations with limited sampling to handling "land-atmosphere-human" multi-source data. This shift includes the application of information technology throughout the entire pollution control process, encompassing "prediction-evaluation-response" cycles. With the advancement of information technology, the validation of composite data sources assists researchers in identifying more accurate research paths, gradually breaking down barriers between different sites. This progression evolves from a "site-specific" approach to comprehensive planning and management of brownfield clusters and even newly formed green systems resulting from brownfield-to-green conversions. Additionally, it involves pre-assessing the sequence and comprehensive value of brownfield regeneration, scientifically guiding the order and strategies for climate change-adapted brownfield restoration, and maximizing the post-regeneration value of brownfields for urban development. For instance, scholars have proposed conceptual frameworks that combine Ecosystem Services (ESS) assessments, economic cost-benefit analyses, and spatial pattern analyses [53]. They have also developed an ecological potential assessment method for brownfield-to-green transformations, which considers both the ecological importance of brownfields and their ability to maintain urban green infrastructure connectivity (GI) [151]. However, these approaches have yet to fully address the implications of climate change-induced brownfield risks. Assessing brownfields in the context of climate change requires multidimensional and holistic analyses that take into account the comprehensive post-regeneration value and climate resilience.

4.1.3. Concept of sustainability

The ultimate vision for the application of brownfield pollutant risk prevention and control lies in establishing scientifically sound urban land use practices. In the future, this endeavour will be further advanced by utilizing information technology and analysing ecological environments and landscape patterns. Intelligent assessment of soil environmental pollutant capacities will be employed, and innovative simulations related to pollution-associated land use will be conducted. This will facilitate the achievement of optimized control over urban forms, urban structures, and development intensities within the context of the overarching goal of creating healthy cities. In pursuing this vision, information technology will play a pivotal role in enhancing our understanding of soil pollution dynamics and its interactions with urban planning. By harnessing the power of data analytics and predictive modelling, researchers and urban planners can gain deeper insights into the potential pathways of pollutant migration, hotspot areas, and their impacts on both human health and the environment. This integrated approach will enable the formulation of targeted strategies to mitigate pollution risks and guide the allocation of land for various purposes in a way that minimizes the exposure of residents to harmful pollutants. Moreover, the synergy between ecological considerations and landscape design will contribute to more sustainable and resilient urban environments. By intelligently assessing the pollution-carrying capacity of soils and simulating pollution-related land use scenarios, cities can better balance the need for development with environmental protection. This will not only enhance the overall quality of life for residents but also contribute to the long-term well-being of the urban ecosystem. In summary, the construction of a scientifically informed urban land use framework represents the ultimate aspiration of brownfield pollutant risk prevention and control efforts. Leveraging information technology, ecological insights, and intelligent simulations will pave the way for optimized urban planning that prioritizes both human health and environmental sustainability.

4.2. Research limitation

Due to the inherent mobility of soil pollutants and the complexity of the pollutants themselves, the analysis of brownfields under climate change remains fragmented and one-dimensional. It has yet to provide a comprehensive and scientifically guided reference for the spatial application of brownfield regeneration methods and strategies under the influence of climate change. Any deductive analysis of relevance requires consideration of spatial application in real-world scenarios. Furthermore, the challenges posed by climate-induced brownfield regeneration risks exacerbate the complexity of pollutant-related issues. As a result, our goal is not to eliminate all pollutant risks but rather a more risk-informed control of these risks within such a changing environment. In the future, it is recommended that monitoring and assessment tools consider existing datasets, policies, standards, and guidelines when establishing indicators and benchmarks. This approach will enhance the relevance and applicability of these tools in guiding decision-making processes related to brownfield regeneration. In the context of climate change, an integrated approach is needed to achieve a more holistic and multi-dimensional understanding of the complexities associated with brownfields; this approach should encompass not only the mobility of pollutants but also the interplay between climatic factors, ecological conditions, and human activities. By embracing such an approach, urban planners, environmental scientists, and policymakers can develop strategies that address the challenges posed by brownfield pollution and climate change in a synergistic manner. In conclusion, the analysis of brownfields under the influence of climate change requires a shift from isolated and one-dimensional perspectives to a comprehensive and integrated approach. This shift will enable the development of strategies that effectively address the complexities of pollutant migration and regeneration risks within the context of a changing climate. Through such a comprehensive approach, we can better inform decision-making processes and ensure the sustainable and resilient development of urban areas.

5. Conclusions

With the intensification of climate change processes, research on brownfield issues related to climate change has garnered increasing attention from scholars worldwide. In this study, a comprehensive overview of 133 relevant papers from the Web of Science Core Collection database for the years 1998–2023 was conducted using bibliometric analysis. The trends in publications and significant journals in the field were identified, and the most influential articles and high-frequency keywords were analyzed. Furthermore, the evolution of research topics in this field over time was examined, and future research directions and trends were discussed. Over the past 25 years in the relevant research field, the series of impacts of climate change scenarios on brownfield issues have gradually gained the attention of interdisciplinary scholars. Both aspects have been integrated and analyzed as a whole. The growth of related research can be divided into three distinct stages: the nascent stage (1996–2008), the enhancement stage (2008–2016), and the rapid development stage (2016–2023). Notably, prominent journals such as "Science of the Total Environment", "Environmental Science and Pollution Research", and "Journal of Environmental Management" have played critical roles in shaping the research landscape in this field. High-frequency keywords such as urban adaptation, climate change mitigation, sustainable development framework, geographic information, geological environment, multi-scenario environment, soil erosion, and renewable energy potential have emerged as prominent themes in the field.

The research in this domain can be roughly categorized into five main directions:

(1) Investigating the potential impacts of different brown-to-green strategies on the entire green space system and urban adaptation to climate change.
(2) Utilizing information technology to accurately identify brownfields and potential brownfields.
(3) Constructing a framework for the assessment of ecosystem service values of brownfield greening from a systemic perspective.
(4) Exploring the interaction mechanisms between factors influencing pollutant migration processes and climate change factors, focusing on pollutant migration simulation analysis and prediction during intervention processes, and studying the comparative benefits of integrated restoration methods.
(5) Exploring the ecosystem service potential and carbon reduction potential of brownfield redevelopment.

The evolution of research applications revolves around five key aspects:

(1) Spatiotemporal variation patterns of pollutants from the perspective of climate change.
(2) Mechanisms of pollutant action and heterogeneity.
(3) Assessment of pollutant risks at different spatial and temporal scales and their associated social impacts.
(4) Evaluation of brownfield restoration strategies from the dimensions of social, economic, and environmental benefits.
(5) Combining human health risk assessment with geographical spatial analysis to provide supportive ecological restoration strategies for urban brownfield redevelopment.

Looking ahead, future research should prioritize the study of pollutant migration processes and the spatial heterogeneity of brownfields from the perspective of climate change. Additionally, continued attention should be given to the priority sequence of brownfield regeneration under climate change, aiming to mitigate the various risks it brings. Lastly, emphasis should be placed on ecosystem services and the increased potential in post-regeneration brownfields, highlighting their significance for the long-term sustainability of urban development. By focusing on these research directions, scholars and practitioners can contribute to the advancement of knowledge and the implementation of urban brownfield regeneration, thereby addressing pressing brownfield risk issues and promoting the long-term sustainability of urban development.

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Data availability statement

Data and code used for the analysis is available from the corresponding authors upon request.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Yunshan Wan: Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Data curation. **Shuo Chen:** Writing – original draft, Validation, Formal analysis. **Jiaqi Liu:** Writing – original draft, Validation, Formal analysis. **Lin Jin:** Writing – review & editing, Validation, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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