A decade of ecological and environmental research on the belt and road initiative: evolution and future directions

Gong, Y.; Wang, H.; Tzachor, A.; Fishman, T.; Ma, F.; Hou, L.; ... ; Tiunov, A.

Resources, Conservation & Recycling 217 (2025) 108217

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.sciencedirect.com/journal/resources-conservation-and-recycling

A decade of ecological and environmental research on the belt and road initiative: Evolution and future directions

Yongyue Gong [a], Heming Wang [a,b,*], Asaf Tzachor [c,d,**], Tomer Fishman [e], Fengmei Ma [b,f], Lingli Hou [e], Yao Wang [a], Wenju Sun [a], Yihan Song [a], Kai Fang [g,h,i], Wei-Qiang Chen [f,j,k], Yuri Mazei [l,m], Alexei Tiunov [n]

[a] *State Environmental Protection Key Laboratory of Eco-Industry, Northeastern University, Shenyang 110819, PR China*
[b] *Commonwealth Scientific and Industrial Research Organisation (CSIRO), Canberra, ACT 2601, Australia*
[c] *School of Sustainability, Reichman University (IDC Herzliya), Herzliya, Israel*
[d] *Centre for the Study of Existential Risk (CSER), University of Cambridge, Cambridge, UK*
[e] *Institute of Environmental Sciences (CML), Leiden University, 2333 CC Leiden, The Netherlands*
[f] *Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, PR China*
[g] *School of Public Affairs, Zhejiang University, 310058, Hangzhou, PR China*
[h] *Center of Social Welfare and Governance, Zhejiang University, 310058, Hangzhou, PR China*
[i] *Zhejiang Ecological Civilization Academy, 313300, Anji, PR China*
[j] *Xiamen Key Lab of Urban Metabolism, Xiamen, PR China*
[k] *University of Chinese Academy of Sciences, Beijing, PR China*
[l] *Lomonosov Moscow State University, Faculty of Biology, 119991 Moscow, Russia*
[m] *Shenzhen MSU-BIT University, Faculty of Biology, 518172 Shenzhen, PR China*
[n] *Severtsov Institute of Ecology and Evolution, Russian Academy of Sciences, 119071 Moscow, Russia*

ARTICLE INFO

Keywords:
Infrastructure
Environmental impact
Word embedding
Topic modeling
Natural language processing

ABSTRACT

The Belt and Road Initiative (BRI), launched in 2013, is an ambitious infrastructure project aimed at enhancing global trade and economic growth. Understanding the BRI's ecological and environmental impacts is crucial for achieving global sustainability. Despite a decade of BRI construction, research on its environmental impact remains fragmented with numerous understudied topics. This study seeks to uncover topical interconnections and trends by analyzing 735 publications on the BRI's eco-environmental impacts using natural language processing methods. The temporal trend of author keywords identifies 31 trending terms, 28 of which, including "renewable energy" and "institutional quality," emerged in 2019–2023. The topical interconnections reveal that CO_2-focused eco-environmental research is closely linked to themes of energy and economics. The results highlight the necessity of promoting cross-sector and international collaborations to mitigate eco-environmental impacts. Finally, we recommend leveraging digital technologies and institutional quality to support a greener BRI.

1. Introduction

China's Belt and Road Initiative (BRI) aims to promote "diversified, independent, balanced, and sustainable development" (Ascensão et al., 2018). The BRI, which includes the Silk Road Economic Belt and the 21st Century Maritime Silk Road (Wang et al., 2022), connects China with 151 countries. While the BRI approaches its second decade, participating nations have implemented extensive infrastructure projects and expanded trade networks (Hussain et al., 2020a). However, a significant portion of the BRI lies in ecologically sensitive regions—arid, semi-arid, or sub-humid areas (Zhang et al., 2021b), where large-scale infrastructure construction with weak environmental standards may pose complex environmental and ecological challenges, such as water shortages, biodiversity loss, land degradation and reduced ecosystem

* Corresponding author at: State Environmental Protection Key Laboratory of Eco-Industry, Northeastern University, Shenyang 110819, PR China; Commonwealth Scientific and Industrial Research Organisation (CSIRO), ACT 2601 Canberra, Australia.
** Corresponding author at: Reichman University (IDC Herzliya), School of Sustainability, Herzliya, Israel; University of Cambridge, Centre for the Study of Existential Risk (CSER), Cambridge, UK.
E-mail addresses: wangheming2006@gmail.com, wanghm@mail.neu.edu.cn (H. Wang), atzachor@runi.ac.il (A. Tzachor).

https://doi.org/10.1016/j.resconrec.2025.108217
Received 3 September 2024; Received in revised form 11 December 2024; Accepted 23 February 2025
Available online 1 March 2025

resilience (Fang et al., 2023; Nature Editorial, 2023; Tzachor et al., 2024; H. H. Wang et al., 2024). Additionally, these challenges may generate broader socio-economic and ecological impacts across interconnected systems. For example, the expansion of trade and transportation networks increases the risk of biological invasions in vulnerable ecosystems (Liu et al., 2019). These challenges underscore the critical need to study the BRI's environmental and ecological issues.

In response, extensive research has been conducted on the eco-environmental impacts of various BRI projects (Fang et al., 2021). For example, Lechner et al. (2018) and Narain et al. (2020) emphasized the importance of biodiversity conservation during BRI infrastructure construction. Muhammad et al. (2020) and Wei et al. (2021) examined the effects of economic activities (e.g., urbanization and trade) on air pollution. Lee and Roh (2023), Sheraz et al. (2022), and Tan et al. (2023) analyzed the impacts of innovation, digitalization capabilities, and government policies on sustainable performance. These studies highlight that understanding the BRI's ecological impacts is crucial for mitigating its environmental footprint and ensuring its long-term sustainability.

However, there are few literature reviews on the eco-environmental impacts of the BRI. Huang et al. (2022) reviewed the ecological and environmental challenges of the BRI, emphasizing the necessity for scientific data to ensure sustainable development and proposing future research directions. Teo et al. (2020) observed a predominance of Chinese authors and a focus on domestic routes in BRI-related research. They recommended greater international collaboration and increased attention to environmental impacts in developing countries. Additionally, Zhang et al. (2021b) systematically reviewed the BRI's ecological and environmental studies from four key aspects and 20 sub-aspects, noting a lack of comprehensive research on the evolution of environmental issues along the BRI. Specifically, while the early years of BRI research emphasized domestic infrastructure and development impacts, recent studies increasingly explore international collaboration, policy integration, and sustainability transitions.

Consequently, we have observed a persistent lack of bibliometric analysis in this area since this study was published three years ago, which continues to contribute to knowledge gaps. Indeed, bibliometric analysis may play an instrumental role in identifying research trends and hotspots, uncovering hidden connections between topics and sub-topics, and providing evidence-based guidance for future research. Word2vec is a potent tool for advanced bibliometric analysis, particularly in textual data mining, text classification, and discovering topic connections (Elnagar et al., 2020; Garg et al., 2018; Zhang et al., 2022b). For example, Zhu and Ren (2023) developed a six-step word embedding approach to enhance Word2vec modeling, which they used to decode research trends and connections between hot topics in *Resources, Conservation and Recycling* from 1989 to 2022. Similarly, Lee et al. (2020) employed a Word2vec approach to analyze a patent-product database, constructing a product landscape to identify technology opportunities across multiple domains.

Additionally, Top2vec, a topic modeling tool, can cluster documents within large-scale text corpora to uncover unexpected and valuable insights. For example, Ghasiya and Okamura (2021) applied Top2vec modeling to extract topic representations from 63,424 COVID-19-themed news articles. Smith et al. (2023) explored the interconnections between health and sustainable development goals using Top2vec and topic-cluster detection. Similarly, Chen et al. (2023a) employed Top2vec to analyze Twitter content, examining the differences in topics between users with attention-deficit/hyperactivity disorder (ADHD) and non-ADHD users.

As the BRI enters its second decade, this study aims to narrow knowledge gaps in the BRI's ecological and environmental research by systematically identifying the literature and analyzing the current state of the art in 735 publications on the subject. Namely, it explores topic development patterns and interconnections using normalized frequency, trend factors, keyword co-occurrence, semantic similarity, topic modeling, and topic-cluster detection methods. The trends found in author keywords guide our discussion on green development pathways within the BRI eco-environment. Furthermore, the study emphasizes the importance of digital technologies and institutional quality, which should be considered in future policymaking to support the development of a greener BRI.

2. Methods

Fig. 1 illustrates the research framework for this study. Our approach begins with the collection and processing of data. Once cleaned, the data is analyzed using general statistics and natural language processing techniques to uncover patterns and trends in BRI eco-environmental research. The analysis unfolds in three stages. First, we examine topic evolution and trends through author keywords, employing normalized frequency and trend factors. Next, we explore topic interconnections using keyword co-occurrence and Word2vec modeling, focusing on co-occurrence and semantic similarity. Finally, we integrate Top2vec results with trend factors to identify document-based topics and trends and conduct cluster detection. Each phase contributes to a comprehensive understanding of the research landscape.

2.1. Data collection and preprocessing

To ensure a comprehensive and accurate selection of relevant publications, we first identified suitable search terms related to the BRI from five older review articles on the initiative (Bashir et al., 2021; Cao and Alon, 2020; Panibratov et al., 2022; Teo et al., 2020; Zhang et al., 2021b). We combined these search terms using logical operators "OR" and "AND," along with wildcards, and conducted topic searches (field tag: "TS") using the Web of Science Core Collection database. This included six citation indexes: Science Citation Index Expanded, Social Science Citation Index, Conference Proceedings Citation Index – Science, Conference Proceeding Citation Index – Social Science & Humanities, Current Chemical Reactions, and Index Chemicus (accessed on 15 May 2024). The publication period was set from 2013 to 2023. The search string is as follows:

Topic search (TS) = ("One Belt One Road" OR "Silk Road Economic Belt" OR "Maritime Silk Road" OR "New Silk Road" OR "One Belt and One Road" OR "OBOR Initiative" OR "B&R Initiative" OR "Belt and Road" OR "Belt Road")

The next step is to filter literature related to the eco-environment using the "research areas" provided by the Web of Science (Web of Science Core Collection Help), the detailed information is provided in Supporting Information S1. This study simultaneously preprocessed the author keywords, title, and abstract, partially following Zhu et al. (2021). The detailed preprocessing steps are provided in Supporting Information S1.

2.2. Evolution and trends analyses

Tracking the evolution and trends of author keywords helps visualize changes in research hotspots in the BRI's eco-environmental studies from 2014 to 2023. We illustrate the trending patterns of research topics using normalized frequencies and trend factors.

Normalized frequencies allow for fair comparisons of topic popularity over different periods. The normalized frequency (F_{yrs}) represents the ratio of publications focused on an author keyword (f_{yrs}) to the total publications (N_{yrs}) within the same period (e.g., years i, …, j) (Eq. (1)). The normalized annual frequency (F_i) refers to the ratio of f_{yrs} and N_{yrs} in a given year (i), i.e., the ratio of f_i to N_i (Eq. (2)). This ratio is multiplied by 1000 to indicate the frequency of research on that keyword per 1000 publications within the specified period.

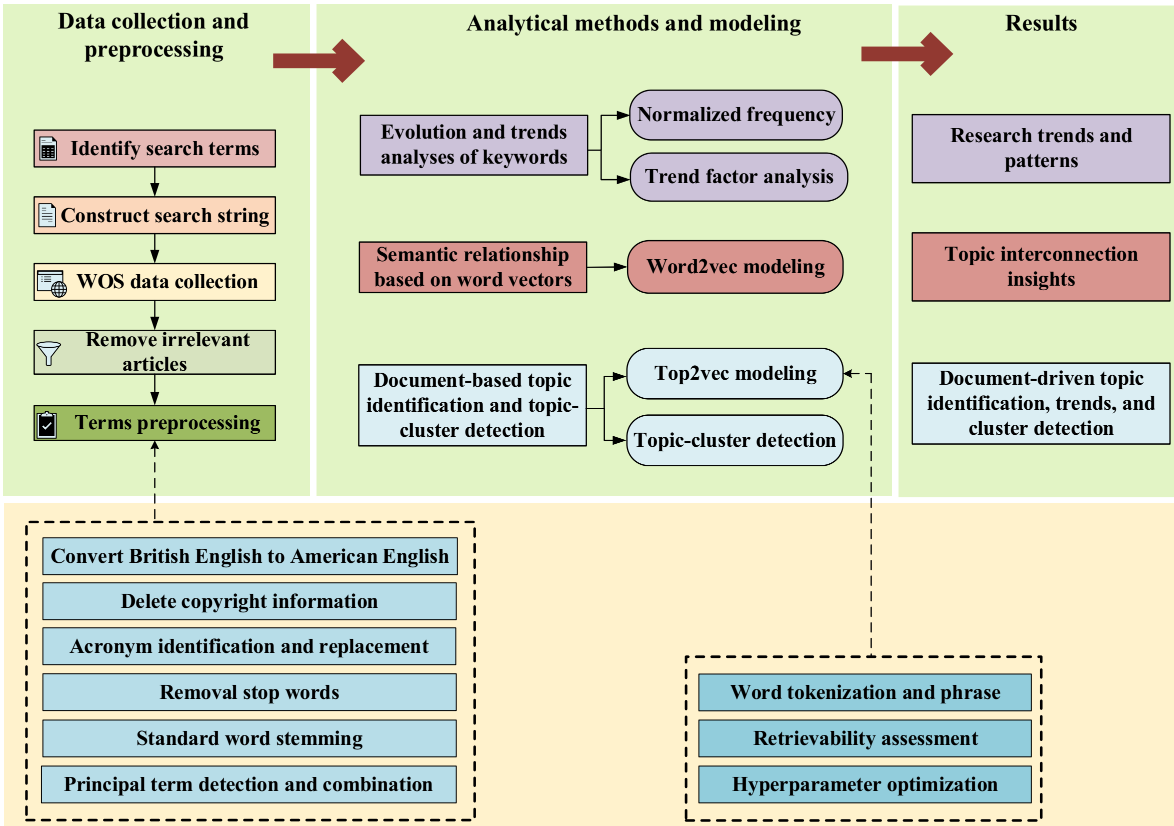


Fig. 1. The research framework for this study.

$$F_{yrs} = 1000 \times \frac{\sum_{yr=i}^{j} f_{yrs}}{\sum_{yr=i}^{j} N_{yrs}} (if\ i \neq j) = 1000 \times \frac{f_i}{N_i} (if\ i = j) \tag{1}$$

$$F_i = 1000 \times \frac{f_i}{N_i} (if\ i = j) \tag{2}$$

Additionally, we employed an intuitive approach—trend factors—to identify trending and emerging topics. Specifically, the decade of BRI publications was divided into two phases: the "early period" (2014–2018) and the "recent period" (2019–2023). This division helps determine trending topics. The trend factor is calculated as the logarithmic value of the ratio of normalized frequencies in the recent (F_{recent}) and early (F_{early}) periods (Eq. (3) and Eq. (4)) (Zhu and Ren, 2023). Theoretically, the range of trend factor values is $(-\infty, +\infty)$. A trend factor approaching positive infinity indicates that the topic (or keyword) has appeared only recently, while a trend factor nearing negative infinity signifies that the topic emerged earlier but has disappeared recently. A keyword is identified as increasingly trending when $TF_{2014-2018}^{2019-2023} \geq 0.4$ and $F_{recent} \geq 4$ (Zhu and Ren, 2023). A trend factor between -0.4 and 0.4 indicates stability, while $TF_{2014-2018}^{2019-2023} < -0.4$ represents a downward trend. For emerging topics, the "early period" is 2014–2020, and the "recent period" is 2021–2023. A keyword is identified as emerging term when $TF_{2014-2020}^{2021-2023} \geq 0.4$ and $F_{recent} \geq 4$. We use a bubble plot to represent the quantitative results of keyword temporal trends (frequency ≥ 5).

$$F_{early} = 1000 \times \frac{\sum_{2014}^{2018} f_{yrs}}{\sum_{2014}^{2018} N_{yrs}}\ and\ F_{recent} = 1000 \times \frac{\sum_{2019}^{2023} f_{yrs}}{\sum_{2019}^{2023} N_{yrs}} \tag{3}$$

$$Trend\ factor = TF_{early\ \ period}^{recent\ \ period} = \log\left(\frac{F_{recent}}{F_{early}}\right) \tag{4}$$

2.3. Word2vec modeling and analyses

Word2vec was used to reveal the interconnected nature of high-frequency terms. This powerful natural language processing tool captures the semantic relationships between keywords by creating a high-dimensional vector space model (Grand et al., 2022; Rosenthal et al., 2018; Tshitoyan et al., 2019). In this model, semantically related keywords are positioned closer in the vector space. The cosine similarity ($sim(\alpha, \beta)$) between two vectors (e.g., α and β) is commonly used to represent the semantic similarity between two words within a specific research scope, as shown in Eq. (5).

$$sim(\alpha, \beta) = \cos\theta = \frac{\alpha \cdot \beta}{\parallel \alpha \parallel \parallel \beta \parallel} \tag{5}$$

Word2vec-based analyses were conducted using the *Gensim* 4.3.2 package in Python 3.11.5 (Řehůřek and Sojka, 2010). After data preprocessing for titles and abstracts as described in Section 2.1, we performed "word tokenization and phrase," "retrievability assessment," and "hyperparameter optimization," according to Zhu and Ren (2023). We created a 270-dimensional Word2vec model (Skip-Gram) to calculate the cosine similarity between terms.

2.4. Top2vec modeling and analyses

Top2vec modeling was employed to identify document-based topics, classifying various documents into different topics. Top2vec is an unsupervised topic modeling technique that automatically detects topics by leveraging hierarchical clustering and vectorization to represent topics, documents, and words. This method facilitates the discovery of representative knowledge within large text datasets (Angelov, 2020), and is implemented in the *Top2vec* Python library.

Step 1 is "creating semantic embeddings," which generates higher-dimensional space vectors for words and documents using Word2vec and Doc2vec. Doc2vec can transform documents or sentences into vector representations (Budiarto et al., 2021). *Step 2* is "reducing the dimensionality" of the document vectors using Uniform Manifold Approximation and Projection (UMAP), which preserves the local and global structure of high-dimensional data. *Step 3* is "density-based clustering," where Hierarchical Density-Based Spatial Clustering of Applications with Noise (HDBSCAN) is used to find dense areas of documents and identify clusters in two dimensions. *Step 4* involves "determining topic vectors," calculating the arithmetic mean of all document vectors for each dense area. The words closest to the topic vector are defined as the topic words. Supporting Information S2 summarizes the documents corresponding to each topic.

To pinpoint hotspots of document-based topics, we calculated a trend factor for each topic (Fig. 5(b)). The chosen time points correspond to those used in the trend factor analyses of author keywords, with trend factor thresholds defined in the same way as for trending terms. The subsequent analysis will integrate Top2vec results with the temporal evolution of topics to examine their patterns.

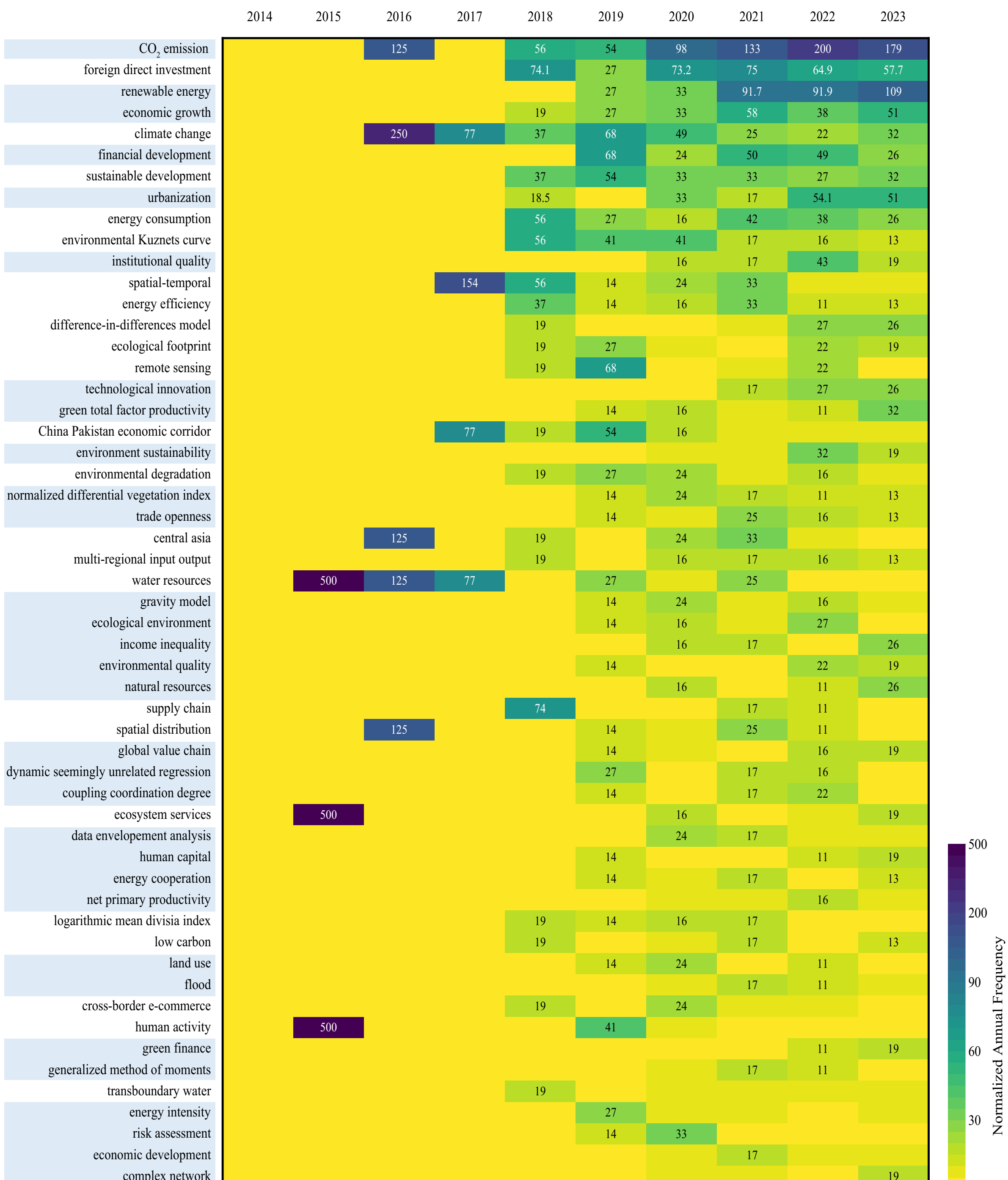


Fig. 2. Temporal trend of author keywords (frequency ≥ 5) based on normalized annual frequency. Note: The author keywords are arranged in descending order of total frequency, and trending terms are marked with a blue background. Author keywords with a normalized annual frequency ≥ 10 are labeled to highlight periods of higher frequencies (Zhu and Ren, 2023).

3. Results

3.1. Research trends and patterns

Understanding keyword trends and identifying trending and emerging terms are essential to tracing the evolution of the BRI's eco-environmental studies. Temporal trends of author keywords (frequency ≥ 5) are shown by their normalized annual frequency (Fig. 2). From 2015 to 2017, fewer than 15 publications were produced annually, primarily addressing climate change and water crises associated with infrastructure development during the early implementation of the initiative (Cai et al., 2016; Guan et al., 2017; Howard and Howard, 2016; Li et al., 2015; Zhou et al., 2017). In 2015, the normalized annual frequency of "water resources," "ecosystem services," and "human activity" was 500, as each keyword appeared once across two publications ($1/2 \times 1000$). From 2018, scientific attention shifted toward CO_2 emission, ecological footprint, economic growth (e.g., foreign direct investment, urbanization, supply chain, and financial development), and energy consumption/efficiency, focusing on their coordination and balance (Fan et al., 2019; Hu et al., 2020; Liu and Hao, 2018; Mahadevan and Sun, 2020; Sun et al., 2020). After 2020, most of the aforementioned topics remain central to scientific attention. Renewable energy projects have increasingly played a pivotal role in the BRI, alleviating energy shortages and reducing environmental pollution in countries along the initiative while promoting the adoption of green technologies (Gu and Zhou, 2020; Jing et al., 2020; Wu et al., 2020b). Green finance (Zhang et al., 2021a), renewable energy, and green total factor productivity (Li et al., 2022) have gradually strengthened the theme of "green efforts" in the BRI (Jing et al., 2020). Notably, green total factor productivity reflects both the extent of green economic growth and the coordination of economic and environmental development (Wang et al., 2024). Additionally, technological innovation and institutional quality are being leveraged to support a greener BRI (Adekoya et al., 2023; AL-Barakani et al., 2022; Khan et al., 2021; Wu et al., 2020a; Yasmeen et al., 2022). For example, technological advances in biomass energy applications have reduced energy consumption and improved energy efficiency, thereby reducing the ecological footprint of BRI countries and promoting sustainable development (Khan et al., 2023; Yasmeen et al., 2022). Improved institutional governance and comprehensive policies aim to foster cleaner industrial practices and ensure environmental sustainability (Jin and Huang, 2023; Yasmeen et al., 2022). Although green finance, technological innovation, and institutional quality were largely overlooked in early research on the BRI, the upward trend in normalized annual frequency indicates that scientific interest in these themes is likely to grow further in the future.

Trending and emerging terms were identified using trend factors. The trend factors (early period: 2014–2018, recent period: 2019–2023) for keywords (frequency ≥ 5) are detailed in the Supporting Information S2. The analysis identified 31 trending terms, with 28 of them absent from 2014 to 2018, except for CO_2 emission, urbanization, and economic growth. CO_2 emission was first introduced by Cai et al. (2016), who proposed policy recommendations for mitigating CO_2 emissions in the cement industry based on facility-level CO_2 intensities. This indicates that the interest in CO_2 emissions within the BRI stemmed from increased cement demand for infrastructure development. Fan et al. (2019) quantified the driving factors influencing CO_2 emissions in BRI countries, revealing that economic development and energy consumption are the primary drivers of carbon growth. Regarding urbanization, Yu and Lu (2018) investigated the relationship between urbanization and pollutant emissions in the Songhua River Basin, a significant transboundary water system under the BRI. Similarly, Liu and Hao (2018) examined the dynamic links among CO_2 emissions, energy consumption, and economic growth in countries along the BRI, suggesting that renewable energy contributes to long-term growth, particularly in energy-importing countries.

The 28 trending terms that emerged over the recent five years ($F_{early} = 0$), e.g., renewable energy, financial development, and institutional quality, should be acknowledged and addressed. Renewable energy was first mentioned in the BRI's eco-environmental area by Liu and Hao (2018), but it appeared as a primary research subject in the list of author keywords in Jing et al. (2020). This study analyzed China's renewable energy trade potential with BRI countries from 2007 to 2017, and highlighted related consequential factors such as GDP and total energy consumption. Wu et al. (2020a) examined the effect of China's outward direct investment on green total factor productivity in investment-receiving countries, emphasizing institutional quality's moderating role. Sheraz et al. (2022) introduced how financial development and renewable energy affect CO_2 emissions, with globalization and institutional quality serving as moderators. Overall, institutional quality is an important moderating factor for mitigating the environmental impact of financial development and energy trade and use.

Approximately 90% of the trending terms emerged in the latter half of the BRI decade, we have put a greater focus on emerging trends after 2020. The trend factors (early period: 2014–2020, recent period: 2021–2023) for keywords (frequency ≥ 5) are shown in Fig. 3. We identified 11 emerging terms, with technological innovation and green finance having the strongest emerging trends, as they have only entered the research landscape in the last three years. Khan et al. (2021) examined the effects of technological innovation, financial development, and foreign direct investment on renewable and non-renewable energy consumption and CO_2 emissions. Regarding green finance, Zhang et al. (2021a) and Luo and Zhang (2022) emphasized its fundamental role in promoting green economic growth and sustainable development through effective public spending, technological innovation, and environmental regulations within BRI regions. This role underscores the close relationship between green finance and technological innovation.

3.2. Topic interconnection insights

For a more granular analysis, we used keyword co-occurrence and Word2vec methods to investigate the association between keywords attributed to seven distinct categories (please refer to the legend of Fig. 4) from the perspectives of word frequency and numerical vectors, respectively (Fig. 4).

Keyword co-occurrence indicates that two keywords appear in the same paper's author keywords list and can reveal underlying topic patterns. High co-occurrence pairs highlight closely related research topics. Fig. 4(a) illustrates the co-occurrence of author keywords, with keywords categorized and color-coded. Thicker, darker edges signify higher co-occurrence, indicating that the two research topics are frequently studied together. The most common research topic pairs resulted from associations between any two of these aspects: CO_2 emission, the economy (e.g., economic growth, foreign direct investment, and urbanization), and energy (e.g., renewable energy and energy consumption). The top three co-occurring keyword pairs were CO_2 emission and economic growth (co-occurrence = 15), foreign direct investment (10), and renewable energy (10), respectively.

Word2vec is used to analyze the semantic connections between keywords, revealing underlying knowledge structures (Fig. 4(b)). CO_2 emission, located at the center of the maximum spanning tree, has been the focal point of the BRI's eco-environmental research. Eco-environmental studies (e.g., CO_2 emission, sustainable development, and environmental quality) are strongly associated with the economy (e.g., foreign direct investment, economic growth, and supply chain), energy and resources (e.g., renewable energy, energy consumption, and water resource), countries and regions (e.g., Asia, Indonesia, and country along the BRI), measures and governance (e.g., technological innovation and environmental regulation), natural disasters (e.g., drought), and quantitative indicators and methods (e.g., green total factor productivity and the environmental Kuznets curve).

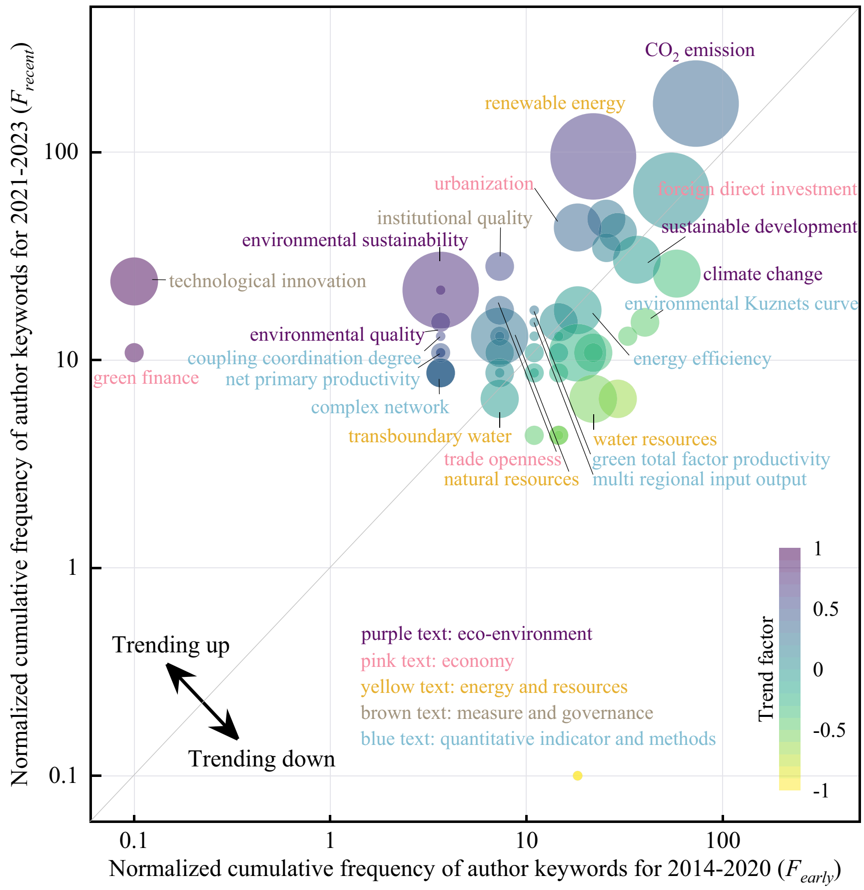


Fig. 3. Trend factors of author keywords (frequency ≥ 5). Note: The normalized cumulative frequencies in the early (2014–2020) and recent (2021–2023) periods (X-axis and Y-axis) determine the position of the bubbles. Due to using logarithmic coordinates, the bubbles along the Y-axis have been deliberately adjusted to placement at $X = 0.1$ for clearer visualization. The color of the bubbles indicates the value of the trend factor; bubbles in purple are more likely to exhibit an upward trend, while those in yellow suggest a downward trend. The size of each bubble represents the geospatial popularity of the author keywords, defined by the number of countries and regions researching them. For example, the keyword "renewable energy" is represented by a normalized cumulative frequency of 21.90 for 2014–2020 (X-axis coordinates) and 95.44 for 2021–2023 (Y-axis coordinates). The trend factor for this keyword is 0.64, which influences the bubble's color. The geospatial popularity is nine. The color of the bubble labels represents different categories that have been assigned manually by experts. The five categories are: eco-environment (purple), economy (pink), energy and resources (yellow), measure and governance (brown), and quantitative indicator and methods (blue).

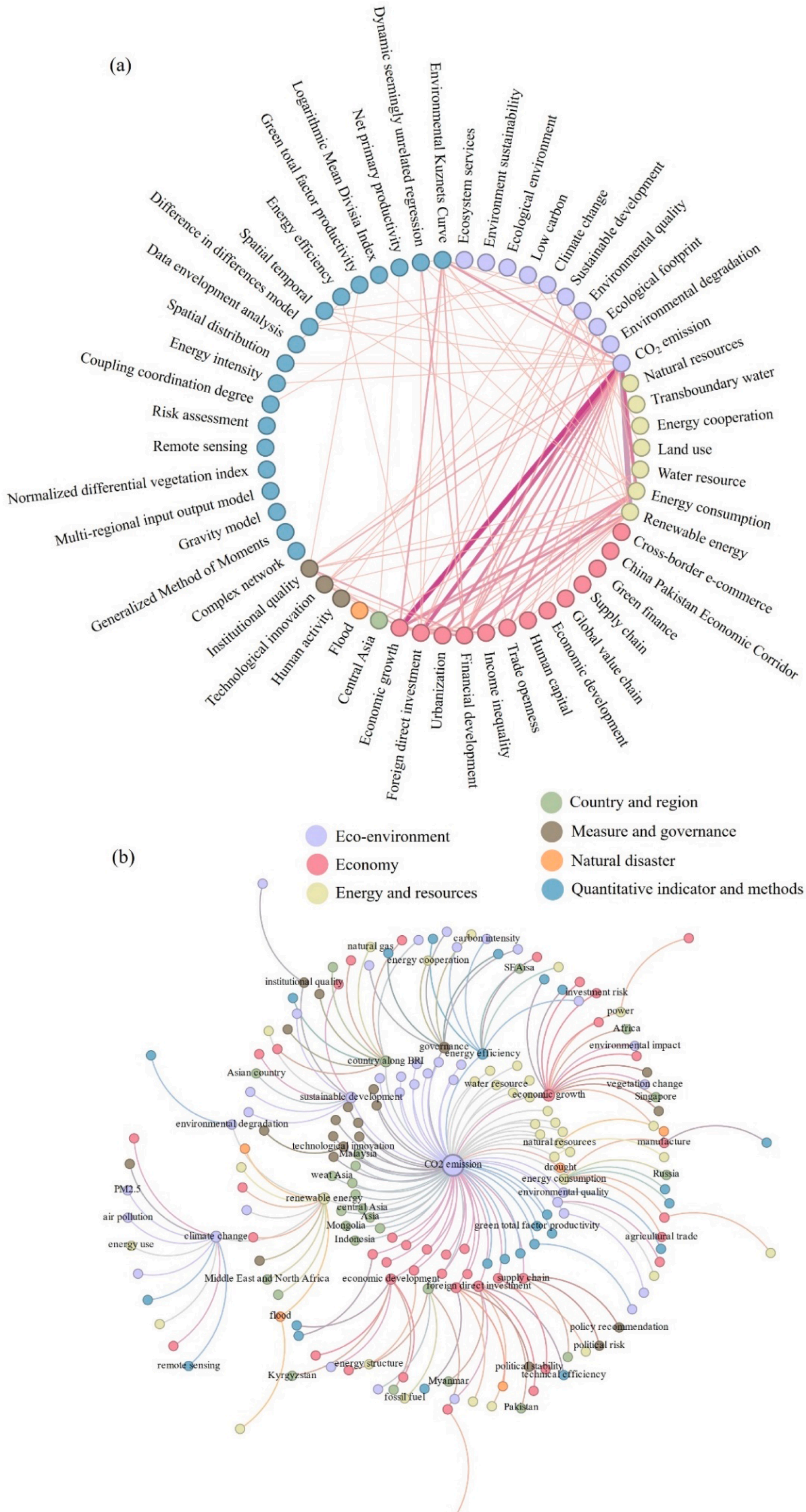
In addition, the economy is directly affected by policy and political stability, notably in Myanmar, Pakistan, Kyrgyzstan, Africa, Singapore, and northwest China. Renewable energy is closely linked to climate change and trade relations (e.g., bilateral trade and trade networks). The eco-environmental impacts of energy consumption in manufacturing, agricultural trade, and internal trade are also substantial. Countries and regions focusing on energy and resources include the Middle East, North Africa, Russia, and Southeast Asia.

3.3. Document-driven topic identification, trends, and topic-cluster detection

This study utilized Top2vec modeling to identify document-based topics and integrated trend factors to explore topic evolutionary patterns (Fig. 5). We also conducted topic-cluster detection to further refine new findings at the topic level. We identified 15 distinct topics and analyzed their evolutionary patterns, determining two trending topics: Topic 6, which assesses the coherence between different systems and the resource environment, and Topic 12, which quantifies ecological, environmental, and resource vulnerability or carrying capacity. We also identified one emerging topic, Topic 7, which is also trending, focusing on interactions among environmental sustainability, economic growth, and institutional quality. These topics are anticipated to dominate future research.

Trending topics highlight the interplay between human and natural systems, utilizing systems thinking to address complex problems. Topic 6 focuses on the coordination between eco-environmental and socio-economic systems, examining their spatial and temporal evolution (Bahtebay et al., 2021; Yang and Hu, 2019). For instance, Ariken et al. (2021) explored the impact of urbanization on the environment, noting how ecological degradation can hinder socioeconomic development. Topic 7 investigates environmental sustainability in the context of economic growth, institutional quality, and the adoption of renewable energy and technology. It suggests that sustainable development requires balancing these factors (Jiang et al., 2022; Muhammad and Long, 2021; Yasmeen et al., 2023). Topic 12 focuses on addressing ecological vulnerability and enhancing socio-ecological resilience in the BRI regions by improving governance, boosting economic capacity, and promoting sustainable resource management (Battamo et al., 2021; Chen et al., 2023b; Jin et al., 2021; Zhang et al., 2022a). These studies commonly use high-resolution geospatial data and temporal analysis to map and understand resilience and vulnerability patterns over time.

In addition, we have divided the 15 topics into three topic-clusters using the *Louvain* community detection algorithm in *Python* (Fig. 5 (a)). Each topic-cluster comprises 4 to 6 topics, highlighting key areas of scientific research related to the eco-environmental impacts of the BRI. Topic-cluster 1 focuses on comprehensive governance, optimization frameworks (Cheng et al., 2021; Sun et al., 2017), and risk management strategies (Duan et al., 2018; Hussain et al., 2020b; Wu et al., 2020b; Yuan et al., 2019) to achieve sustainable development and enhance



(caption on next page)

Fig. 4. Topic interconnections based on keywords. Note: (a) Co-occurrence of the author keywords (frequency $\geq$ 5) using the circos plot. Nodes represent author keywords, and each color indicates a category that has been assigned manually by experts. The seven categories are: eco-environment (purple), economy (pink), energy and resources (yellow), country and region (green), measure and governance (brown), natural disaster (orange), and quantitative indicator and methods (blue). (b) Topic interconnections are determined based on the Word2vec model for keywords (stemmed from Word2vec vocabulary, frequency $\geq$ 15). The links between nodes are represented using a maximum spanning tree, which is applied using *Kruskal's* algorithm (Kalyagin et al., 2022) to retain the main structure of the original network graph. A maximum spanning tree is a subgraph within an original undirected weighted graph that includes all nodes and maximizes the sum of edge weights while ensuring that all nodes are connected without forming loops. The weights of the edges represent the cosine similarity between two nodes (keywords), and the size of each node correlates with its degree. Keywords are categorized into seven groups, and the coloring rules are consistent with the circos plot above. For clarity, only some labels are displayed; however, this does not imply that unlabeled bubbles are unimportant.

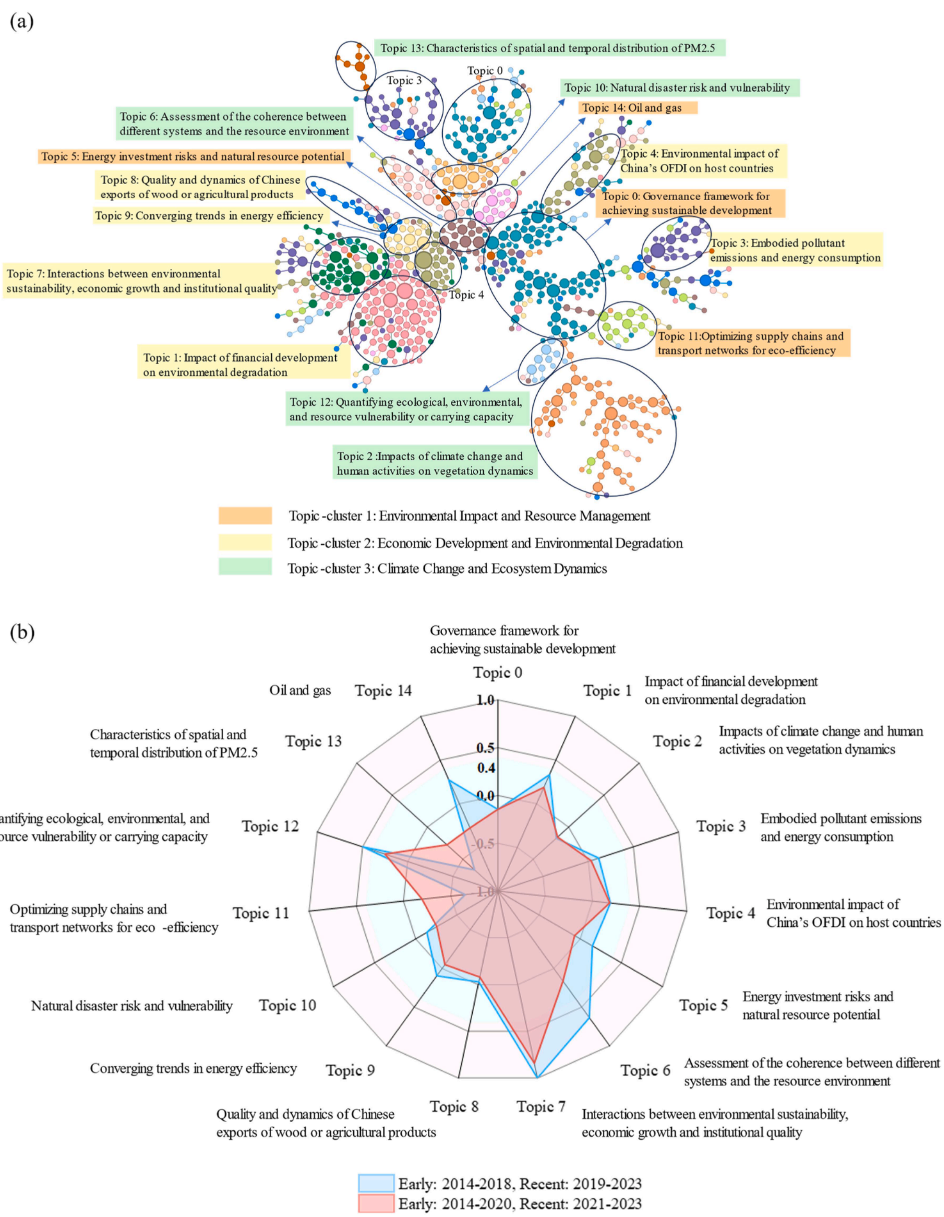


Fig. 5. Document-based topic identification, trends, and topic-cluster detection. Note: (a) Topic identification using Top2vec modeling at the document level. 735 documents were divided into 15 distinct topics, each containing between 17 and 128 documents. We summarize the top five topic words and document counts for the 15 identified topics in the Supporting Information S2. The links between the nodes (documents) are represented using a maximum spanning tree, which employs *Kruskal's* algorithm. This approach is chosen because it retains the main structure of the original network graph. A maximum spanning tree, defined as a tree within an undirected weighted graph, includes all nodes and maximizes the sum of edge weights to ensure connectivity among all nodes without forming loops. Nodes belonging to the same topic are displayed in the same color. The weights of the edges between nodes indicate the cosine similarity between the two documents. The size of the nodes correlates with their degree (Degree is the total number of edges connected to a node). There are three types of labels for topics, corresponding to the results of topic-cluster detection. Labels within the same topic-cluster are assigned the same color. (b) Trend factor analysis of each topic across different periods. The selection of periods aligns with those used in the trend factor analysis of the authors keywords, as detailed in Section 3.1. The scale of the axis represents the trend factor. Topic 7 first emerged in 2021 with a trend factor of positive infinity, and is positioned at coordinates equal to 1 on the graph for display clarity.

international energy cooperation (Zhao et al., 2021). Topic-cluster 2 has progressed from investigating the direct effects of economic growth and globalization on environmental degradation to analyzing the complex interactions among financial development, trade, investment, and sustainable practices within BRI regions (Huang et al., 2019; Lu et al., 2020; Peng et al., 2022, 2021; Qi et al., 2019; Zhang and Chen, 2022). Topic-cluster 3 focuses on the direct impacts of socioeconomic activities on ecosystems and the need for coordination among multiple systems (Ariken et al., 2021; Xu et al., 2021). This topic-cluster also uses advanced techniques and models to assess ecological risks, improve disaster resilience, and ensure balanced regional development (An et al., 2020; Duan et al., 2022; Fan et al., 2022; Fang et al., 2020; Jin et al., 2021). Collectively, these three topic-clusters offer a comprehensive framework for understanding and managing the interdependencies among economic development, environmental sustainability, and climate resilience. This framework advances both theoretical and practical approaches to achieving balanced and sustainable growth within the BRI regions.

4. Discussion

This study explores the topic evolution, trends, patterns, and interconnections in the research of eco-environmental impacts associated with- and related to- the BRI through general statistical analyses and natural language processing methods. Over the past decade, research has primarily focused on addressing the environmental implications of infrastructure development and on charting a green path forward. Our findings allow us to assess the evolution of suggestions for greening the BRI within the literature and to identify future challenges.

4.1. The green path of the BRI

To clearly illustrate the evolutionary trends of the decade of BRI-related eco-environmental studies, we broadly categorize research topics into three stages: environmental impacts of infrastructure (2014–2017), coordinated coupling of economy and environment (2018–2020), and green finance and technological innovation (2021–2023) (Fig. 6). The evolution of research topics is closely linked to policy changes and the international landscape.

The adoption of the Paris Agreement in 2015 heightened global attention to environmental protection within the BRI. During the BRI's initial phase (2014–2017), scientific research primarily examined the eco-environmental impacts of infrastructure construction and human activities, focusing on water resources, climate change, and CO_2 emissions. Additionally, while the BRI fostered economic growth in participating countries, transboundary water resource management in Central Asia emerged as an increasingly critical issue (Howard and Howard, 2016). In 2017, the Belt and Road Ecological and Environmental Cooperation Plan (China's Ministry of Ecology and Environment, 2017a) and the Guidance on Promoting Green Belt and Road (China's Ministry of Ecology and Environment, 2017b) integrated ecological and environmental protection into all aspects and stages of the BRI. These measures aimed to promote clean energy cooperation, develop a green investment and financing system, and drive technological innovation to achieve sustainable economic growth and environmental protection. As a result, scientific attention in 2019 shifted toward renewable energy research, focusing on institutional challenges in expanding clean energy projects (Chiyemura et al., 2023) and assessing renewable energy investment risks for countries along the BRI. Another key area of research emphasized the coordinated development of the ecological environment, economy, and energy to identify sustainable approaches for the BRI.

In 2020, China announced its targets to achieve peak carbon emissions by 2030 and carbon neutrality by 2060, further promoting low-carbon development within the BRI. Technological innovation and enhanced institutional frameworks have played pivotal roles in strengthening the resilience and sustainability of the green BRI. In 2021, the Initiative for Belt and Road Partnership on Green Development emphasized international cooperation to balance the economic, social, and environmental dimensions, promoting low-carbon, green, and sustainable economic recovery in the post-pandemic era. These initiatives encouraged the development of green financial instruments. However, scientific research on green finance only began in 2022. It is anticipated that this field will expand, requiring ongoing exploration of standards and the roles of mechanisms such as green bonds and green investment and financing. These policies have significantly enhanced collaborations across countries, sectors, and public-private partnerships in green infrastructure, energy, and finance.

4.2. Policy implications

Examining the evolution trends and topic interconnections of ecological and environmental research related to the BRI offers insights for policymaking. Research on CO_2 emissions and renewable energy has received significant attention, with their normalized annual frequency showing a consistent upward trend. Accordingly, policies should focus on enhancing cross-border carbon market regulations and optimizing the structure of renewable energy trade, ensuring the effective adoption

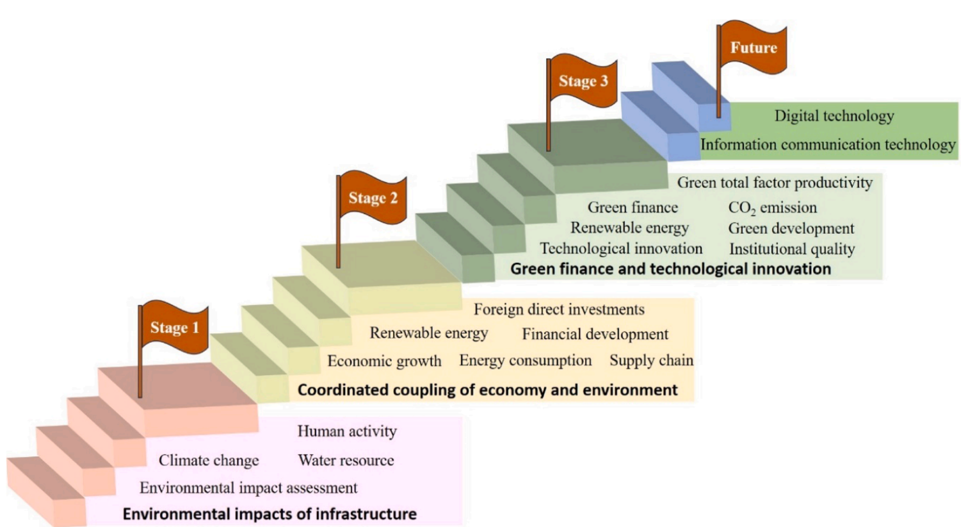


Fig. 6. Research focus trends over a decade of BRI related eco-environmental studies.

of green energy and products in environmentally vulnerable BRI countries. For enterprises engaged in the BRI, detailed incentive mechanisms for clean energy and comprehensive policies for waste management and resource recovery should be developed.

Financial development and institutional quality are identified as emerging terms (Fig. 2 and Fig. 3). The strong connection between CO_2 emissions and topics such as financial development and institutional quality (Fig. 4) seems to signify a very important step toward unifying environment-finance-energy-institute topics. Institutional quality serves as an important moderating tool, however, there is no consensus on the empirical results on the institutional-environmental quality relationship. Sheraz et al. (2022) revealed that a 1% increase in institutional quality leads to a 0.0624% increase in long-term CO_2 emissions across BRI countries, with potentially more significant short-term impacts. Strict environmental regulations and institutions can mitigate the environmental burden caused by financial development and promote the adoption of renewable energy, thereby improving environmental quality (AL-Barakani et al., 2022; Sheraz et al., 2022). Moreover, the moderating effect of institutional quality exhibits heterogeneity among countries with different income levels (Wang et al., 2023). Therefore, BRI countries should formulate policies to improve institutional quality based on their specific circumstances. Strong institutional quality can create a stable and supportive environment for green investment, facilitating funding and policy support for renewable energy projects. This helps achieve sustainable development goals and reduces reliance on traditional fossil fuels.

The BRI has seen its reach extend, with around 151 international partners now involved (Plackett, 2024). A core aspect of the green BRI is to preemptively address environmental impacts rather than retroactively fixing them (Ascensão et al., 2018). In this regard, our study found that the digital economy and information and communication technology have appeared in related research since 2022 (The normalized annual frequency of author keyword (frequencies $\geq$ 3) is shown in Supporting Information S2). As technological innovation advances, digitization may increasingly facilitate the construction of green BRI infrastructure (Lee and Roh, 2023). Here, the prevailing assumption is that digital technologies — such as computer devices, telecom networks, cloud computing, big data analytics, and artificial intelligence — are key to advancing green BRI projects by predicting, tracking and optimizing solutions to minimize environmental impacts in advance. Nonetheless, more empirical evidence is required to substantiate the role of these technologies in fostering green economic development (Chang et al., 2023; Feng et al., 2024; Zhao et al., 2022). The future of the BRI ought to be shaped by practical, responsive, and flexible mechanisms that continuously address social development needs (Liu et al., 2022). Policies should therefore consider the potential of digital technologies in mitigating environmental impact and developing green BRI construction. Furthermore, scholars have raised concerns regarding the resource consumption and environmental challenges associated with the spread of digital technologies such as artificial intelligence (Donati et al., 2022; George et al., 2023). Policymakers should take this into consideration.

4.3. Research limitations

While this study aims to narrow gaps in the literature and identify research hotspots, trends, and patterns in BRI related eco-environmental research, several limitations should be acknowledged.

First, our study focuses on English articles and reviews sourced exclusively from the Web of Science. This should reflect the state of the art of the international scientific community. However, future research should also integrate data from Scopus to ensure a more comprehensive dataset. Given that China proposed the BRI, it is essential to investigate the evolution trends of the BRI's ecological and environmental research within Chinese literature databases. Using the China National Knowledge Infrastructure (CNKI) database, we retrieved 660 relevant articles. Detailed search methodologies are provided in the Supporting Information S1. Results of the normalized annual frequency and trend factors reveal differing topic trends between Chinese and English literature. For example, while CO_2 emissions and renewable energy are trending topics in English literature, they are nearly absent in Chinese literature. In contrast, green development and green finance/economy emerged as trending topics in Chinese literature as early as 2015 but only appeared in English literature in 2022. This is primarily because Chinese literature is dominated by articles on policy analysis in the humanities or social sciences, with relatively few scientific research articles on ecological and environmental issues.

Second, from a methodological perspective, while Word2vec and Top2vec are highly effective for extracting topics from large text datasets, they have inherent limitations in capturing deeper semantic structures and complex topic hierarchies. Specifically, Word2vec identifies word similarity by recognizing co-occurrence patterns within sentences or phrases but cannot fully capture complex contextual relationships. Similarly, Top2vec generates topics by clustering similar text embeddings but struggles to identify fine-grained semantic distinctions and lacks the capability to model multi-layer topic structures.

Replacing Word2vec and Top2vec with context-aware embedding models could be a promising direction. For example, BERT's bidirectional transformer architecture enables it to capture the subtle contextual information of words within a single text fragment, providing a richer semantic understanding (Callaghan et al., 2021). This approach can substantially increase the granularity of topic extraction, enabling a more nuanced understanding of the underlying text. Furthermore, integrating these models with hierarchical clustering techniques may uncover multi-level topic structures, thus addressing the limitations of current methods.

5. Conclusions

We focused on exploring trends, hotspot topics, and their interconnections. We identified 31 trending keywords, 28 of which (e.g., renewable energy and institutional quality) emerged recently (2019–2023), except for CO_2 emission, urbanization, and economic growth. The top co-occurring keyword pairs are CO_2 emissions, economy (e.g., economic growth), and energy (i.e., renewable energy).

Word2vec and Top2vec are text analysis methods in the natural language processing field. They convert unstructured information into structured data, revealing intrinsic relationships between textual data and scientific discoveries. To the best of our knowledge, this is the first instance where Word2vec and Top2vec have been used to investigate research changes within the BRI eco-environmental impacts domain. Word2vec modeling revealed that the eco-environmental has bidirectional causal relationships with other systems. The study of BRI related eco-environmental implications involves analyzing the coupling coordination between the eco-environment and factors such as economic activities, energy and resources, and institutional governance. Additionally, we performed a trend factor analysis on 15 document-based topics, identifying two trending topics and one emerging topic. These hotspots focus on the interaction between human (socioeconomic system) and natural (eco-environment system) systems, using systems thinking to solve problems. For example, greening the BRI requires balancing economic growth, institutional quality, renewable energy, and technologies.

Finally, we reviewed the green development trajectory of the BRI based on the evolution of author keywords. Green development, green finance, green total factor productivity, and renewable energy have gradually become the core of the BRI-related environmental studies. As technological innovation advances, the expansion of the digital economy and information and communication technology could facilitate the development of a greener BRI. Furthermore, the moderating influence of institutional quality plays a crucial role in enhancing the sustainability of the green BRI. Policymakers must also consider the potential environmental downsides of emerging technologies, such as artificial intelligence.

CRediT authorship contribution statement

Yongyue Gong: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Heming Wang:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Asaf Tzachor:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Tomer Fishman:** Writing – review & editing, Funding acquisition. **Fengmei Ma:** Writing – review & editing, Methodology. **Lingli Hou:** Writing – review & editing, Funding acquisition. **Yao Wang:** Writing – review & editing. **Wenju Sun:** Writing – review & editing, Methodology. **Yihan Song:** Writing – review & editing, Methodology. **Kai Fang:** Writing – review & editing, Funding acquisition. **Wei-Qiang Chen:** Writing – review & editing. **Yuri Mazei:** Writing – review & editing. **Alexei Tiunov:** Writing – review & editing.

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.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (52070034, 52470207, and 72074193). Heming Wang acknowledged financial support from the China Scholarship Council (Grant No. 202306080047). Lingli Hou would like to thank the support of the China Scholarship Council (Grant No. 202208310075). Tomer Fishman was funded by the European Union (ERC- 2023-STG, Materials-GRoWL, project 101116116). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them. We appreciate the helpful feedback from the editor and anonymous reviewers.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108217.

Data availability

Data will be made available on request.

References

Adekoya, O.B., Oliyide, J.A., Kenku, O.T., Ajayi, O.F., 2023. China's technological spillover effect on the energy efficiency of the BRI countries. Energy Policy 182, 113740. https://doi.org/10.1016/j.enpol.2023.113740.

Bin, L., Zhang, X., Saeed, M., Qahtan, A.S.A., Hamood Ghallab, H.M., 2022. Spatial analysis of financial development's effect on the ecological footprint of belt and road initiative countries: mitigation options through renewable energy consumption and institutional quality. J. Clean. Prod. 366, 132696. https://doi.org/10.1016/j.jclepro.2022.132696.

An, Y., Tan, X., Gu, B., Zhu, K., 2020. Flood risk assessment using the CV-TOPSIS method for the Belt and Road Initiative: an empirical study of Southeast Asia. Ecosyst Health Sustain 6, 1765703. https://doi.org/10.1080/20964129.2020.1765703.

Angelov, D., 2020. Top2Vec: Distributed Representations of Topics.

Ariken, M., Zhang, F., Chan, N.W., Kung, H., 2021. Coupling coordination analysis and spatio-temporal heterogeneity between urbanization and eco-environment along the Silk Road Economic Belt in China. Ecol. Indic. 121, 107014. https://doi.org/10.1016/j.ecolind.2020.107014.

Ascensão, F., Fahrig, L., Clevenger, A.P., Corlett, R.T., Jaeger, J.A.G., Laurance, W.F., Pereira, H.M., 2018. Environmental challenges for the Belt and Road Initiative. Nat. Sustain. 1, 206–209. https://doi.org/10.1038/s41893-018-0059-3.

Bahtebay, J., Zhang, F., Ariken, M., Chan, N.W., Tan, M.L., 2021. Evaluation of the coordinated development of urbanization-resources-environment from the incremental perspective of Xinjiang. China. J. Cleaner Product. 325, 129309. https://doi.org/10.1016/j.jclepro.2021.129309.

Bashir, M.F., Ma, B., Qin, Y., Bashir, M.A., 2021. Evaluation of One Belt One Road publications: a bibliometric and literature review analysis. Environ Sci Pollut Res 28, 37016–37030. https://doi.org/10.1007/s11356-021-14621-y.

Battamo, A.Y., Varis, O., Sun, P., Yang, Y., Oba, B.T., Zhao, L., 2021. Mapping socio-ecological resilience along the seven economic corridors of the Belt and Road Initiative. J. Clean. Prod. 309, 127341. https://doi.org/10.1016/j.jclepro.2021.127341.

Budiarto, A., Rahutomo, R., Putra, H.N., Cenggoro, T.W., Kacamarga, M.F., Pardamean, B., 2021. Unsupervised News Topic Modelling with Doc2Vec and Spherical Clustering. Procedia Comput. Sci. 5th Int. Confer. Comput. Sci. Computat. Intellig. 2020 179, 40–46. https://doi.org/10.1016/j.procs.2020.12.007.

Cai, B., Wang, J., He, J., Geng, Y., 2016. Evaluating CO2 emission performance in China's cement industry: an enterprise perspective. Appl. Energy 166, 191–200. https://doi.org/10.1016/j.apenergy.2015.11.006.

Callaghan, M., Schleussner, C.-F., Nath, S., Lejeune, Q., Knutson, T.R., Reichstein, M., Hansen, G., Theokritoff, E., Andrijevic, M., Brecha, R.J., Hegarty, M., Jones, C., Lee, K., Lucas, A., Van Maanen, N., Menke, I., Pfleiderer, P., Yesil, B., Minx, J.C., 2021. Machine-learning-based evidence and attribution mapping of 100,000 climate impact studies. Nat. Clim. Chang. 11, 966–972. https://doi.org/10.1038/s41558-021-01168-6.

Cao, M., Alon, I., 2020. Intellectual Structure of the Belt and Road Initiative Research: a Scientometric Analysis and Suggestions for a Future Research Agenda. Sustainability 12, 6901. https://doi.org/10.3390/su12176901.

Chang, L., Taghizadeh-Hesary, F., Mohsin, M., 2023. Role of artificial intelligence on green economic development: joint determinates of natural resources and green total factor productivity. Resour. Policy. 82, 103508. https://doi.org/10.1016/j.resourpol.2023.103508.

Chen, L., Jeong, J., Simpkins, B., Ferrara, E., 2023a. Exploring the Behavior of Users With Attention-Deficit/Hyperactivity Disorder on Twitter: comparative Analysis of Tweet Content and User Interactions. J. Med. Internet. Res. 25, e43439. https://doi.org/10.2196/43439.

Chen, Y., Liu, C., Li, H., Xue, X., 2023b. How do countries along the Maritime Silk Road perform in sustainable use of natural resources? Progress of natural resources-related SDGs. Ecol. Indic. 149, 110194. https://doi.org/10.1016/j.ecolind.2023.110194.

Cheng, Z., Zhao, L., Wang, G., Li, H., Hu, Q., 2021. Selection of consolidation center locations for China railway express to reduce greenhouse gas emission. J. Clean. Prod. 305, 126872. https://doi.org/10.1016/j.jclepro.2021.126872.

China's Ministry of Ecology and Environment, 2017a. The Belt and Road Ecological and Environmental Cooperation Plan [WWW Document]. URL. https://english.mee.gov.cn/Resources/Policies/policies/Frameworkp1/201706/t20170628_416869.shtml (accessed 6.27.24).

China's Ministry of Ecology and Environment, 2017b. Guidance on Promoting Green Belt and Road [WWW Document]. URL. https://english.mee.gov.cn/Resources/Policies/policies/Frameworkp1/201706/t20170628_416864.shtml (accessed 6.27.24).

Chiyemura, F., Shen, W., Burgess, M., Mulugetta, Y., Wang, Y., 2023. A dynamic institutional analysis of China's engagement with Africa's renewable energy market. Env. Polit. 32, 1140–1162. https://doi.org/10.1080/09644016.2023.2194773.

Donati, F., Dente, S.M.R., Li, C., Vilaysouk, X., Froemelt, A., Nishant, R., Liu, G., Tukker, A., Hashimoto, S., 2022. The future of artificial intelligence in the context of industrial ecology. J. Indus. Ecol. 26, 1175–1181. https://doi.org/10.1111/jiec.13313.

Duan, F., Ji, Q., Liu, B.-Y., Fan, Y., 2018. Energy investment risk assessment for nations along China's Belt & Road Initiative. J. Clean. Prod. 170, 535–547. https://doi.org/10.1016/j.jclepro.2017.09.152.

Duan, Y., Xiong, J., Cheng, W., Wang, N., Li, Y., He, Y., Liu, J., He, W., Yang, G., 2022. Flood vulnerability assessment using the triangular fuzzy number-based analytic hierarchy process and support vector machine model for the Belt and Road region. Nat Hazards 110, 269–294. https://doi.org/10.1007/s11069-021-04946-9.

Elnagar, A., Al-Debsi, R., Einea, O., 2020. Arabic text classification using deep learning models. Inf. Process. Manage 57, 102121. https://doi.org/10.1016/j.ipm.2019.102121.

Fan, G., Xia, J., Song, J., Sun, H., Liang, D., 2022. Research on application of ecohydrology to disaster prevention and mitigation in China: a review. Water Supply 22, 2946–2958. https://doi.org/10.2166/ws.2021.426.

Fan, J.-L., Da, Y.-B., Wan, S.-L., Zhang, M., Cao, Z., Wang, Y., Zhang, X., 2019. Determinants of carbon emissions in 'Belt and Road initiative' countries: a production technology perspective. Appl. Energy 239, 268–279. https://doi.org/10.1016/j.apenergy.2019.01.201.

Fang, K., Wang, S., He, J., Song, J., Fang, C., Jia, X., 2021. Mapping the environmental footprints of nations partnering the Belt and Road Initiative. Resources. Conservation and Recycling 164, 105068. https://doi.org/10.1016/j.resconrec.2020.105068.

Fang, K., Wang, Tingting, He, J., Wang, Tijian, Xie, X., Tang, Y., Shen, Y., Xu, A., 2020. The distribution and drivers of PM2.5 in a rapidly urbanizing region: the Belt and Road Initiative in focus. Sci. Total Environ. 716, 137010. https://doi.org/10.1016/j.scitotenv.2020.137010.

Fang, K., Xu, A., Wang, S., Jia, X., Liao, Z., Tan, R.R., Sun, H., Su, F., 2023. Progress towards Sustainable Development Goals in the Belt and Road Initiative countries. J. Clean. Prod. 424, 138808. https://doi.org/10.1016/j.jclepro.2023.138808.

Feng, C., Ye, X., Li, J., Yang, J., 2024. How does artificial intelligence affect the transformation of China's green economic growth? An analysis from internal-structure perspective. J. Environ. Manage. 351, 119923. https://doi.org/10.1016/j.jenvman.2023.119923.

Garg, N., Schiebinger, L., Jurafsky, D., Zou, J., 2018. Word embeddings quantify 100 years of gender and ethnic stereotypes. Proceed. National Academy of Sciences 115, E3635–E3644. https://doi.org/10.1073/pnas.1720347115.

George, A.S., George, A.S.H., Martin, A.S.G., 2023. The Environmental Impact of AI: a Case Study of Water Consumption by Chat GPT. Partners Universal Int.Innovation J.l 1, 97–104. https://doi.org/10.5281/zenodo.7855594.

Ghasiya, P., Okamura, K., 2021. A Comparative Analysis of Japan and India COVID-19 News Using Topic Modeling Approach. In: Sharma, H., Gupta, M.K., Tomar, G.S., Lipo, W. (Eds.), Communication and Intelligent Systems. Springer, Singapore, pp. 447–460. https://doi.org/10.1007/978-981-16-1089-9_36.

Grand, G., Blank, I.A., Pereira, F., Fedorenko, E., 2022. Semantic projection recovers rich human knowledge of multiple object features from word embeddings. Nat. Hum. Behav. 6, 975–987. https://doi.org/10.1038/s41562-022-01316-8.

Gu, A., Zhou, X., 2020. Emission Reduction Effects of the Green Energy Investment Projects of China in Belt and Road Initiative Countries. Ecosystem Health and Sustainability.

Guan, Q., Cai, A., Wang, F., Yang, L., Xu, C., Liu, Z., 2017. Spatio-temporal variability of particulate matter in the key part of Gansu Province, Western China. Environ Pollution 230, 189–198. https://doi.org/10.1016/j.envpol.2017.06.045.

Howard, K.W.F., Howard, K.K., 2016. The new "Silk Road Economic Belt" as a threat to the sustainable management of Central Asia's transboundary water resources. Environ. Earth. Sci. 75, 976. https://doi.org/10.1007/s12665-016-5752-9.

Hu, M., Li, R., You, W., Liu, Y., Lee, C.-C., 2020. Spatiotemporal evolution of decoupling and driving forces of CO2 emissions on economic growth along the Belt and Road. J. Clean. Prod. 277, 123272. https://doi.org/10.1016/j.jclepro.2020.123272.

Huang, C., Qin, Y., Du, X., He, J., Fan, X., 2022. Ecosystem Health and Environmental Geography in the Belt and Road Regions. IJERPH 19, 5843. https://doi.org/10.3390/ijerph19105843.

Huang, Z., Zhang, H., Duan, H., 2019. Nonlinear globalization threshold effect of energy intensity convergence in Belt and Road countries. J. Clean. Prod. 237, 117750. https://doi.org/10.1016/j.jclepro.2019.117750.

Hussain, J., Khan, A., Zhou, K., 2020a. The impact of natural resource depletion on energy use and CO2 emission in Belt & Road Initiative countries: a cross-country analysis. Energy 199, 117409. https://doi.org/10.1016/j.energy.2020.117409.

Hussain, J., Zhou, K., Guo, S., Khan, A., 2020b. Investment risk and natural resource potential in "Belt & Road Initiative" countries: a multi-criteria decision-making approach. Sci. Total Environ. 723, 137981. https://doi.org/10.1016/j.scitotenv.2020.137981.

Jiang, Q., Rahman, Z.U., Zhang, X., Guo, Z., Xie, Q., 2022. An assessment of the impact of natural resources, energy, institutional quality, and financial development on CO2 emissions: evidence from the B&R nations. Resour. Policy. 76, 102716. https://doi.org/10.1016/j.resourpol.2022.102716.

Jin, G., Huang, Z., 2023. Asymmetric influence of China's outward FDI and exports on trade-adjusted resources footprint in belt and road node countries: moderating role of governance. Resour. Policy. 82, 103558. https://doi.org/10.1016/j.resourpol.2023.103558.

Jin, Y., Li, A., Bian, J., Nan, X., Lei, G., Muhammad, K., 2021. Spatiotemporal analysis of ecological vulnerability along Bangladesh-China-India-Myanmar economic corridor through a grid level prototype model. Ecol. Indic. 120, 106933. https://doi.org/10.1016/j.ecolind.2020.106933.

Jing, S., Zhihui, L., Jinhua, C., Zhiyao, S., 2020. China's renewable energy trade potential in the "Belt-and-Road" countries: a gravity model analysis. Renew. Energy 161, 1025–1035. https://doi.org/10.1016/j.renene.2020.06.134.

Kalyagin, V.A., Koldanov, A.P., Koldanov, P.A., 2022. Reliability of maximum spanning tree identification in correlation-based market networks. Physica A: Statistical Mechanics and its Applications 599, 127482. https://doi.org/10.1016/j.physa.2022.127482.

Khan, A., Chenggang, Y., Hussain, J., Kui, Z., 2021. Impact of technological innovation, financial development and foreign direct investment on renewable energy, non-renewable energy and the environment in belt & Road Initiative countries. Renew. Energy 171, 479–491. https://doi.org/10.1016/j.renene.2021.02.075.

Khan, I., Zhong, R., Khan, H., Dong, Y., Nuţă, F.M., 2023. Examining the relationship between technological innovation, economic growth and carbon dioxide emission: dynamic panel data evidence. Environ. Dev. Sustain. https://doi.org/10.1007/s10668-023-03384-w.

Lechner, A.M., Chan, F.K.S., Campos-Arceiz, A., 2018. Biodiversity conservation should be a core value of China's Belt and Road Initiative. Nat. Ecol. Evol. 2, 408–409. https://doi.org/10.1038/s41559-017-0452-8.

Lee, C., Jeon, D., Ahn, J.M., Kwon, O., 2020. Navigating a product landscape for technology opportunity analysis: a word2vec approach using an integrated patent-product database. Technovation 96–97, 102140. https://doi.org/10.1016/j.technovation.2020.102140.

Lee, M.-J., Roh, T., 2023. Unpacking the sustainable performance in the business ecosystem: coopetition strategy, open innovation, and digitalization capability. J. Clean. Prod. 412, 137433. https://doi.org/10.1016/j.jclepro.2023.137433.

Li, J., Zhou, K., Cheng, Z., 2022. Does China's "Belt and Road" Initiative promote green total factor productivity growth in countries along the route? J. Clean. Prod. 367, 133004. https://doi.org/10.1016/j.jclepro.2022.133004.

Li, P., Qian, H., Howard, K.W.F., Wu, J., 2015. Building a new and sustainable "Silk Road economic belt. Environ. Earth. Sci. 74, 7267–7270. https://doi.org/10.1007/s12665-015-4739-2.

Liu, X., Blackburn, T.M., Song, T., Li, X., Huang, C., Li, Y., 2019. Risks of Biological Invasion on the Belt and Road. Current Biology 29, 499–505. https://doi.org/10.1016/j.cub.2018.12.036. .e4.

Liu, X., Lin, C., Bennett, M., Gong, P., 2022. China's Belt and Road: time to make it greener. Nature 610, 630. https://doi.org/10.1038/d41586-022-03319-x. –630.

Liu, Y., Hao, Y., 2018. The dynamic links between CO2 emissions, energy consumption and economic development in the countries along "the Belt and Road. Science of The Total Environment 645, 674–683. https://doi.org/10.1016/j.scitotenv.2018.07.062.

Lu, Q., Fang, K., Heijungs, R., Feng, K., Li, J., Wen, Q., Li, Y., Huang, X., 2020. Imbalance and drivers of carbon emissions embodied in trade along the Belt and Road Initiative. Appl. Energy 280, 115934. https://doi.org/10.1016/j.apenergy.2020.115934.

Luo, S., Zhang, S., 2022. How R&D expenditure intermediate as a new determinants for low carbon energy transition in Belt and Road Initiative economies. Renew. Energy 197, 101–109. https://doi.org/10.1016/j.renene.2022.06.152.

Mahadevan, R., Sun, Y., 2020. Effects of foreign direct investment on carbon emissions: evidence from China and its Belt and Road countries. J. Environ. Manage. 276, 111321. https://doi.org/10.1016/j.jenvman.2020.111321.

Muhammad, S., Long, X., 2021. Rule of law and CO2 emissions: a comparative analysis across 65 belt and road initiative(BRI) countries. J. Clean. Prod. 279, 123539. https://doi.org/10.1016/j.jclepro.2020.123539.

Muhammad, S., Long, X., Salman, M., Dauda, L., 2020. Effect of urbanization and international trade on CO2 emissions across 65 belt and road initiative countries. Energy 196, 117102. https://doi.org/10.1016/j.energy.2020.117102.

Narain, D., Maron, M., Teo, H.C., Hussey, K., Lechner, A.M., 2020. Best-practice biodiversity safeguards for Belt and Road Initiative's financiers. Nat. Sustain. 3, 650–657. https://doi.org/10.1038/s41893-020-0528-3.

Nature Editorial, 2023. China's Belt and Road Initiative is boosting science — The West must engage, not withdraw. Nature 622, 669–670.

Panibratov, A., Kalinin, A., Zhang, Y., Ermolaeva, L., Korovkin, V., Nefedov, K., Selivanovskikh, L., 2022. The belt and road initiative: a systematic literature review and future research agenda. EurAsian Geogr. Econ. 63, 82–115. https://doi.org/10.1080/15387216.2020.1857288.

Peng, H.-R., Qi, S.-Z., Zhang, Y.-J., 2021. Does trade promote energy efficiency convergence in the Belt and Road Initiative countries? J. Clean. Prod. 322, 129063. https://doi.org/10.1016/j.jclepro.2021.129063.

Peng, H.-R., Tan, X., Managi, S., Taghizadeh-Hesary, F., 2022. Club convergence in energy efficiency of Belt and Road Initiative countries: the role of China's outward foreign direct investment. Energy Policy 168, 113139. https://doi.org/10.1016/j.enpol.2022.113139.

Plackett, B., 2024. Chinese research collaborations shift to the Belt and Road. Nature 630, S10–S11. https://doi.org/10.1038/d41586-024-01598-0.

Qi, S.-Z., Peng, H.-R., Zhang, Y.-J., 2019. Energy intensity convergence in Belt and Road Initiative (BRI) countries: what role does China-BRI trade play? J. Clean. Prod. 239, 118022. https://doi.org/10.1016/j.jclepro.2019.118022.

Řehůřek, R., Sojka, P., 2010. Software Framework for Topic Modelling with Large Corpora. In: Proceedings of the LREC 2010 Workshop on New Challenges for NLP Frameworks. ELRA, Valletta, Malta, pp. 45–50.

Rosenthal, G., Váša, F., Griffa, A., Hagmann, P., Amico, E., Goñi, J., Avidan, G., Sporns, O., 2018. Mapping higher-order relations between brain structure and function with embedded vector representations of connectomes. Nat. Commun. 9, 2178. https://doi.org/10.1038/s41467-018-04614-w.

Sheraz, M., Deyi, X., Sinha, A., Mumtaz, M.Z., Fatima, N., 2022. The dynamic nexus among financial development, renewable energy and carbon emissions: moderating roles of globalization and institutional quality across BRI countries. J. Clean. Prod. 343, 130995. https://doi.org/10.1016/j.jclepro.2022.130995.

Smith, T.B., Vacca, R., Mantegazza, L., Capua, I., 2023. Discovering new pathways toward integration between health and sustainable development goals with natural language processing and network science. Global. Health 19, 44. https://doi.org/10.1186/s12992-023-00943-8.

Sun, C., Luo, Y., Huang, Y., Ouyang, X., 2017. A comparative study on the production efficiencies of China's oil companies: a true fixed effect model considering the unobserved heterogeneity. J. Clean. Prod. 154, 341–352. https://doi.org/10.1016/j.jclepro.2017.03.222.

Sun, H., Samuel, C.A., Kofi Amissah, J.C., Taghizadeh-Hesary, F., Mensah, I.A., 2020. Non-linear nexus between CO2 emissions and economic growth: a comparison of OECD and B&R countries. Energy 212, 118637. https://doi.org/10.1016/j.energy.2020.118637.

Tan, Q., Yasmeen, H., Ali, S., Ismail, H., Zameer, H., 2023. Fintech development, renewable energy consumption, government effectiveness and management of natural resources along the belt and road countries. Resour. Policy. 80, 103251. https://doi.org/10.1016/j.resourpol.2022.103251.

Teo, H.C., Campos-Arceiz, A., Li, B.V., Wu, M., Lechner, A.M., 2020. Building a green Belt and Road: a systematic review and comparative assessment of the Chinese and English-language literature. PLoS. One 15, e0239009. https://doi.org/10.1371/journal.pone.0239009.

Tshitoyan, V., Dagdelen, J., Weston, L., Dunn, A., Rong, Z., Kononova, O., Persson, K.A., Ceder, G., Jain, A., 2019. Unsupervised word embeddings capture latent knowledge from materials science literature. Nature 571, 95–98. https://doi.org/10.1038/s41586-019-1335-8.

Tzachor, A., Wang, H., Richards, C.E., 2024. Addressing the excessive water consumption of materials manufacturing. Nature Water 2, 4–7. https://doi.org/10.1038/s44221-023-00179-1.

Wang, H., Wang, P., Zhang, X., Chen, W.-Q., Tzachor, A., Fishman, T., Schandl, H., Acuto, M., Yang, Y., Lu, Y., Böcher, C., Ma, F., Zhang, C., Yue, Q., Du, T., Liu, J., Zhu, Y.-G., 2024a. Substantial increase in China's manufactured sand supply since 2010. Nat. Geosci 1–4. https://doi.org/10.1038/s41561-024-01501-6.

Wang, H., Wang, X., Zhang, X., Liu, G., Chen, W.Q., Chen, S., Du, T., Shi, L., 2022. The coupling between material footprint and economic growth in the " Belt and Road " countries. J. Clean. Prod. 359, 132110. https://doi.org/10.1016/j.jclepro.2022.132110.

Wang, X., Wang, Y., Wei, C., 2023. The impact of natural resource abundance on green economic growth in the belt and road countries: the role of institutional quality. Environ. Impact. Assess. Rev. 98, 106977. https://doi.org/10.1016/j.eiar.2022.106977.

Wang, Z., Cao, X., Ren, X., 2024b. Green development and economic resilience: evidence from Chinese resource-based cities. Front. Eng. Manag. 11, 194–206. https://doi.org/10.1007/s42524-024-0307-3.

Web of Science Core Collection Help. https://images.webofknowledge.com/images/help/WOS/hp_research_areas_easca.html [WWW Document], n.d. URL (accessed 7.15.24).

Wei, G., Zhang, Z., Ouyang, X., Shen, Y., Jiang, S., Liu, B., He, B.-J., 2021. Delineating the spatial-temporal variation of air pollution with urbanization in the Belt and Road Initiative area. Environ. Impact. Assess. Rev. 91, 106646. https://doi.org/10.1016/j.eiar.2021.106646.

Wu, H., Ren, S., Yan, G., Hao, Y., 2020a. Does China's outward direct investment improve green total factor productivity in the "Belt and Road" countries? Evidence from dynamic threshold panel model analysis. J. Environ. Manage. 275, 111295. https://doi.org/10.1016/j.jenvman.2020.111295.

Wu, Y., Wang, J., Ji, S., Song, Z., 2020b. Renewable energy investment risk assessment for nations along China's Belt & Road Initiative: an ANP-cloud model method. Energy 190, 116381. https://doi.org/10.1016/j.energy.2019.116381.

Xu, X., Liu, H., Jiao, F., Gong, H., Lin, Z., 2021. Nonlinear relationship of greening and shifts from greening to browning in vegetation with nature and human factors along the Silk Road Economic Belt. Science of The Total Environment 766, 142553. https://doi.org/10.1016/j.scitotenv.2020.142553.

Yang, Y., Hu, N., 2019. The spatial and temporal evolution of coordinated ecological and socioeconomic development in the provinces along the Silk Road Economic Belt in China. Sustain. Cities. Soc. 47, 101466. https://doi.org/10.1016/j.scs.2019.101466.

Yasmeen, R., Hao, G., Ye, Y., Hassan Shah, W.U., Kamal, M.A., 2023. The role of governance quality on mobilizing environmental technology and environmental taxations for renewable energy and ecological sustainability in belt and road economies: a methods of Moment's quantile regression. Energy Strategy Reviews 50, 101258. https://doi.org/10.1016/j.esr.2023.101258.

Yasmeen, R., Zhaohui, C., Hassan Shah, W.U., Kamal, M.A., Khan, A., 2022. Exploring the role of biomass energy consumption, ecological footprint through FDI and technological innovation in B&R economies: a simultaneous equation approach. Energy 244, 122703. https://doi.org/10.1016/j.energy.2021.122703.

Yu, S., Lu, H., 2018. Relationship between urbanisation and pollutant emissions in transboundary river basins under the strategy of the Belt and Road Initiative. Chemosphere 203, 11–20. https://doi.org/10.1016/j.chemosphere.2018.03.172.

Yuan, J., Li, X., Xu, C., Zhao, C., Liu, Y., 2019. Investment risk assessment of coal-fired power plants in countries along the Belt and Road initiative based on ANP-Entropy-TODIM method. Energy 176, 623–640. https://doi.org/10.1016/j.energy.2019.04.038.

Zhang, D., Guo, Z., Niu, X., Gao, Y., Wang, C., Xu, H., 2022a. Comprehensive evaluation on sustainable development based on planetary pressures and ecological well-being performance: a case study on the belt and road regions. J. Clean. Prod. 376, 134211. https://doi.org/10.1016/j.jclepro.2022.134211.

Zhang, D., Mohsin, M., Rasheed, A.K., Chang, Y., Taghizadeh-Hesary, F., 2021a. Public spending and green economic growth in BRI region: mediating role of green finance. Energy Policy 153, 112256. https://doi.org/10.1016/j.enpol.2021.112256.

Zhang, D., Wu, L., Huang, S., Zhang, Z., Ahmad, F., Zhang, G., Shi, N., Xu, H., 2021b. Ecology and environment of the Belt and Road under global climate change: a systematic review of spatial patterns, cost efficiency, and ecological footprints. Ecol. Indic. 131, 108237. https://doi.org/10.1016/j.ecolind.2021.108237.

Zhang, R., Jia, C., Wang, J., 2022b. Text emotion classification system based on multifractal methods. Chaos, Solitons & Fractals 156, 111867. https://doi.org/10.1016/j.chaos.2022.111867.

Zhang, Z., Chen, W., 2022. Embodied carbon transfer between China and the Belt and Road Initiative countries. J. Clean. Prod. 378, 134569. https://doi.org/10.1016/j.jclepro.2022.134569.

Zhao, L., Li, D., Guo, X., Xue, J., Wang, C., Sun, W., 2021. Cooperation risk of oil and gas resources between China and the countries along the Belt and Road. Energy 227, 120445. https://doi.org/10.1016/j.energy.2021.120445.

Zhao, P., Gao, Y., Sun, X., 2022. How does artificial intelligence affect green economic growth?—Evidence from China. Science of The Total Environment 834, 155306. https://doi.org/10.1016/j.scitotenv.2022.155306.

Zhou, C., Zhao, C.X., Yang, Z.P., 2017. Strategies for environmentally friendly development in the Northern Tianshan Mountain Economic Zone based on scenario analysis. J. Clean. Prod. 156, 74–82. https://doi.org/10.1016/j.jclepro.2017.03.109.

Zhu, J.-J., Dressel, W., Pacion, K., Ren, Z.J., 2021. *ES&T* in the 21st Century: a Data-Driven Analysis of Research Topics, Interconnections, And Trends in the Past 20 Years. Environ. Sci. Technol. 55, 3453–3464. https://doi.org/10.1021/acs.est.0c07551.

Zhu, J.-J., Ren, Z.J., 2023. The evolution of research in resources, conservation & recycling revealed by Word2vec-enhanced data mining. Resources, Conservation and Recycling 190, 106876. https://doi.org/10.1016/j.resconrec.2023.106876.