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Multi-Regional Input-Output Analysis (MRIO): Exploring Trends and Gaining Key Insights Through Bibliometric Analysis

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Abstract: Understanding the interaction of economies with the environment is very important in today's globalized world. Traditional economic models, which focus on single regions, are often inadequate for capturing the complexity of these global interactions. To overcome this, Multi-Regional Input-Output (MRIO) matrices expand conventional Input Output (IO) models by incorporating multiple regions, providing a comprehensive view of economic relationships within the global economy. The purpose of this study is to present a comprehensive bibliometric review of scientific articles published on the topic of "Multi-Regional Input-Output" analysis in an attempt to understand the research trends, key themes, and future research directions in this field. The methodology undertaken in this paper is a bibliometric analysis of 1,247 research publications from 2003 to 2024. This has been performed by extracting bibliometric data with the Biblioshiny function of the Bibliometrix package in R-studio and mapping it to identify crucial trends and contributors to MRIO research. The findings of these analyses can be summarised into five key points. First, research in the MRIO field is significantly increasing, especially since 2014 and peaking in 2022. Second, the Journal of Cleaner Production is by far the most prolific source for MRIO research. The thematic analysis finds that "carbon pricing," "environmental policy," and "embodied energy" are among the dominant and popular themes within MRIO research. The study highlights the importance of collaboration networks and key contributors within the field, identifying influential authors, sources, and trending keywords. Furthermore, the study underlines that important authors, sources and trending keywords in MRIO research agree with the pattern of collaboration extrapolated considering works cited. Finally, great value is put into future research to investigate new themes and work further on integrating and consolidating them into a wider MRIO framework. This is one of the first attempts at a bibliometric analysis of MRIO research. Hence, this bibliometric review provides valuable insights for future research by pinpointing areas for further investigation, such as integrating MRIO methodologies into broader sustainability assessment frameworks and improving their applicability for policy decision-making.

Keywords: Multi-Regional Input-Output matrices; MRIO; bibliometric analysis; embodied energy; carbon pricing.

Introduction

Understanding the interactions between economies and their consequences on the environment is essential in a world where globalization has made everything increasingly interconnected (Lorente, Murshed, & Nuta, 2023). Global trade and the integration of global supply chains have created complex economic linkages that surpass national and regional boundaries (Gereffi, Lim, & Lee, 2021). Economic research has consistently emphasized the analysis of economic relationships, with the input-output (IO) model serving as a key tool (Batey, 1985). The Input-Output model, developed in the 1930s by Wassily Leontief, is a numerical economic technique that shows the relationships between different economic sectors in a nation (Haimes et al., 2005). In order to fully understand industrial relationships and the impact of changes in one sector on other sectors, the basic

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IO model depends on creating IO tables, which display the relationships between producers and consumers in an economy (Xu & Liang, 2019).

The IO model fundamentally uses a matrix format to depict these economic connections. The fundamental IO table has the following structure:

$$X = AX + Y$$

Where:

- X is the vector of total output for each industry.
- A is the matrix of technical coefficients, representing the input requirements per output unit.
- Y is the vector of final demands for the outputs of each industry.

Matrix A is obtained from the direct requirements table. It displays the needed inputs for each industry to manufacture one unit of output. The basic connection in the IO model can be reorganised to calculate the total output.

$$X = (I - A)^{-1}Y$$

$(I–A)^{-1}$ is referred to as the Leontief inverse matrix, representing the overall input (including both direct and indirect) necessary to meet a specific amount of final demand.

Traditional economic models, which usually focus on just one region at a time, fail to capture the broad spectrum of these interactions, where they typically disregard the complexities of today's global economic interactions (Huo et al., 2022). As a result, there has recently been a greater need for sophisticated analytical tools that provide an exhaustive overview of global economic activities and their impacts (Chen, 2019). Multi-Regional Input-Output (MRIO) matrices have emerged as a valuable tool to address these challenges. MRIO matrices extend conventional Input-Output (IO) models by including many regions, offering a comprehensive view of the economic relationships between regions and the global economy (Huo et al., 2022). This approach provides vital details on international supply chains, trade patterns, and environmental sustainability by allowing the examination of the distribution of commodities, services, and economic consequences among different regions (Koberg & Longoni, 2019).

Wassily Leontief (1906-1999) developed a way to detect the interconnectivity of the economy by analysing which industries purchase products and services from each other and which provide them. Furthermore, the MRIO framework has also been used in collaboration with inter-regional trade coefficients to study product flows between regions (Mi et al., 2018). The I-O model is built on actual economic data (Wiedmann, Wilting, Lenzen, Lutter, & Palm, 2011). As globalisation progresses, there is an increasing need for more complex technologies that provide a full view of these interactions (Malik, McBain, Wiedmann, Lenzen, & Murray, 2018). Input-output models are characterised as "general equilibrium models" because they imply that total inputs equal total outputs in an economy (Davar, 2006). As globalisation continues, there is an increasing desire for more complex tools that provide a full understanding of how these interact (Huo et al., 2022). Based on Leontief's work, academics started broadening these models to include numerous domains, effectively showing the trade of commodities and services inside and between regional and national borders (Haimes & Jiang, 2001). The ground-breaking work of Wassily Leontief, involving the interconnectedness between industries, was the very foundation upon which MRIO models were set. Improved data-gathering techniques, computational tools, and analytical methods have revolutionized MRIO models, enabling an in-depth examination of economic relationships and environmental implications (Malik, McBain, Wiedmann, Lenzen, & Murray, 2018). As a result of these improvements, MRIO matrices are currently employed in environmental impact assessments, sustainability evaluations, and worldwide economic interactions (Cabernard & Pfister, 2021).

One key distinction of the MRIO is that it considers flows of goods between sectors of various regions as internal to the model, incorporating sectoral exchanges at a regional level in the I-O framework (Su, Ang, & Liu, 2021). Integration of inter-regional trade flows

Vol.12 (2024) no.4, pp.321-341; DOI 10.2478/mdke-2024-0019

within MRIO models allows the representation of economic systems to be far completer and more realistic than in traditional models, for which such inter-regional exchanges often may have to be assumed as exogenous imports or exports (Sargento, Ramos, & Hewings, 2012). Therefore, the MRIO models go deeper into showing the interconnectedness between regional economies and sectors, further increasing the accuracy of the estimates of economic impacts (Olsen et al., 2016). The important thing about MRIO is that it improves regional I-O representation by internally managing sectoral interactions across regions that were previously viewed as imports (Mi et al., 2018). These models often contain hundreds of thousands or even millions of collected data points. This depth of data enables researchers to track not just sectoral outputs but also the environmental and social consequences of production and consumption at both regional and global levels (Wang et al., 2024). Koop (2017) claims that there is no other way to analyse such a huge volume of data from a macroeconomic viewpoint. As supply chains grew in complexity around the globe, MRIO models have become necessary in macroeconomic analysis, allowing for data management and interpretation much larger than previously available. This model helps policy planners identify key nodes within supply chains, test economic vulnerabilities and design more robust systems against disruptions at a global level, either caused by trade wars or pandemics (Lorente, Murshed, & Nuta, 2023). While the demand for sustainability assessments keeps increasing, MRIO models have been used to capture the environmental footprints of regional and international trade, addressing a suite of crucial insights toward parlaying the achievement of sustainable development goals (Cabernard & Pfister, 2021).

According to Aylmer, Aylmer, Aylmer, and Dias (2024), the matrix below illustrates MRIO for regions L and M, with identified trade connections for intermediate inputs. The L and M regions can act as both providers and consumers of inputs, and there may also be a final demand from these regions for the finished products of both regions' sectors. The overall production of each industry in the sectors. The two areas are handled individually, and the inflows from other areas into the system are viewed as imports from the global community.

$$\begin{bmatrix} Y_L \\ Y_M \end{bmatrix} = \begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix} - \begin{bmatrix} A_{LL} & A_{LM} \\ A_{ML} & A_{MM} \end{bmatrix} \begin{bmatrix} X_L \\ X_M \end{bmatrix}$$

Where:

- X_L and X_M are the output vectors for regions L and M, respectively.
- A_{LL} and A_{MM} are the intra-regional technical coefficient matrices for regions L and M.
- A_{LM} and A_{ML} are the inter-regional technical coefficient matrices representing the trade between regions L and M.
- Y_L and Y_M are the final demand vectors for regions L and M.

Rearranging the above equation:

$$\begin{bmatrix} X_L \\ X_M \end{bmatrix} = \left(\begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix} - \begin{bmatrix} A_{LL} & A_{LM} \\ A_{ML} & A_{MM} \end{bmatrix} \right)^{-1} \begin{bmatrix} Y_L \\ Y_M \end{bmatrix}$$

As a result, the multi-regional input-output model builds upon the core input-output model by incorporating multiple regions into the study (Zhang et al., 2015). While the above focuses on a two-region model, it may be expanded to n areas without changing the design. International I-O databases, such as the EE-MRIO, provide trustworthy information on cross-country sectoral relationships, address environmental concerns, and increase the MRIO's scope for economic and environmental study (Stadler, 2021).

Applications of MRIO and EE-MRIO

MRIO and EE-MRIO models are currently essential instruments in economic and environmental research. They are commonly used to investigate the consequences of trade policies, evaluate the endurance of supply chains, and assess the allocation of environmental and economic advantages across regions (Stadler, 2021). These models provide critical information to decision-makers, allowing them to make rational decisions that support sustainable development and address global concerns such as climate change and resource depletion (Chen, 2019). For example, MRIO models have been used to examine global supply networks' economic and environmental consequences, revealing how sectors and regions interact to cause environmental impact (Huo et al., 2022). EE-MRIO models have been significant in carbon footprint studies, allowing researchers to trace carbon emissions across complex supply chains (Lorente, Murshed, & Nuta, 2023).

Objectives of the study

Despite the significant advancements in MRIO and EE-MRIO modelling, there is an increasing requirement for a comprehensive bibliometric study to systematically monitor advances and trends in this field. Bibliometric analysis evaluates research findings and identifies significant works, trends, and patterns in the MRIO literature (Amarathunga, 2024). This study employs bibliometric analysis in the field of MRIO; what could add more significance to the choice of this method is a more explicit comparison with other methods common in previous MRIO literature reviews, such as content analysis or systematic reviews. Content analysis and systematic reviews have been important in highlighting qualitative trends within MRIO research. Yet, this field is increasingly complex and interdisciplinary, so bibliometric analysis is especially suitable for tracing the large volume of literature across domains (Mukherjee, Lim, Kumar, & Donthu, 2022). While various works are done on the MRIO models from the application perspective in environmental impact assessments and trade flow analysis, there is a significant gap in mapping the research landscape systematically using bibliometric analysis. Previous studies related to fields like environmental science and sustainable development have also used bibliometric approaches to identify the keystone research trends and influential works (Ellili, 2024). However, this approach has never been holistically applied in the research of the MRIO; thus, this study is one of the major contributors to this topic. As such, the main objective of this study is to explore the trend of research conducted in MRIO through bibliometric analysis by employing a large volume of articles published between 2003 and 2024.

Research methodology

Bibliometric analysis is a method that quantitatively analyses techniques for describing published articles to be used for scientific evaluation. This is the mining of past publications aiming to identify phrases' correlation and connection. The method allows for temporal and geographical analysis of publications across disciplines. This systematic review technique provides detailed, reliable, and replicable processes, reducing possible errors resulting from manual and qualitative analysis in the case of large datasets. It aids in laying down research objectives, determining research coverage, and picking out abnormal results for further investigation. Graphical analysis represents the research trends, covering author information, publication locations, article titles, and keywords. Guided by the preceding advantages, we use, in this paper, a bibliometric methodological approach in doing a comprehensive description of the publication trends, influential authors and journals, as well as papers a. We will also conduct citation analysis, collaboration analysis, and keyword analysis using the biblioshiny function of the bibliometrix package in R-studio software for text mining analysis. Moreover, we have used the subject category of co-occurrence conceptual structure and the keyword selection made by authors to study MRIO publications coming under diverse scientific fields, thus identifying main topics and emerging research frontiers using biblioshiny. Hence, the bibliometric analysis provides a systemic and in-depth view of the research landscape of MRIO. It aids in visualizing and making sense of complex bibliometric data with Biblioshiny tools to make more informed and strategic research decisions.

Vol.12 (2024) no.4, pp.321-341; DOI 10.2478/mdke-2024-0019

Search results and data description

In our search for relevant academic papers on "Multi-Regional Input-Output Matrices," we conducted a comprehensive search on the OpenAlex database, which encompasses a large volume of online scientific literature which is free open access compared to Scopus and Web of Science (Simard, Basson, Hare, Lariviere, & Mongeon, 2024). We selected OpenAlex because it contains a large, heterogeneous collection of high-quality research articles. To ensure uniformity of data and prevent duplication, our research exclusively used OpenAlex articles for analysis. However, the dataset utilized in this study had been adjusted based on specified inclusion and exclusion criteria. Only English-published publications were included to guarantee uniformity across the dataset, with non-article document types such as conference proceedings or editorials discarded. It is important to note that, while OpenAlex provides access to a wide range of high-quality articles, the exclusive use of this database may have resulted in the exclusion of studies indexed only on other platforms such as Scopus or Web of Science, potentially affecting the comprehensiveness of our analysis because these platforms only provide limited access.

A search using the OpenAlex database for research items containing "Multi-Regional Input-Output Matrices" OR "MRIO" OR "EE-MRIO" OR "extended MRIO" OR "multi-regional input-output analysis" OR "multi-regional input-output model" OR "MRIO matrices" OR "MRIO analysis" OR "MRIO framework" OR "multi-regional economic modelling" OR "extended input-output matrices" OR "EE-MRIO model" OR "EE-MRIO analysis" OR "environmental extended MRIO" OR "MRIO and environmental impact" OR "MRIO and sustainability" OR "global MRIO" OR "international MRIO" OR "interregional input-output matrices" OR "interregional MRIO" from 2003 to 2024 yielded a list of 1247 published documents in more than 559 sources. This exhaustive search has enabled us to describe the MRIO publications temporally and geographically, specify top contributing institutions and countries, and identify key contributing authors and influential journals within this area. Such an approach provides a comprehensive perspective of the research landscape, outlining the most important trends and contributions to the study of Multi-Regional Input-Output Matrices.

Data analysis

Descriptive features of the extracted data

Figure 1 represents a time series plot of the data, showing the trend to be relatively upward over the years, with a peak number of 164 articles published in 2022. Productivity was low between 2003 and 2009 and added up to 51 articles. However, from 2009, it increased exponentially, with more than 85 articles per year. These findings suggest a growing interest in MRIO research in recent years. In this respect, the issue of Multi-Regional Input-Output Matrices has risen tremendously from 2003 to 2024 at an annual growth rate of 19.34%. This clearly shows that more interest is paid to, and research is done on the topic. This also means it is a field maturing based on a solid accumulated research foundation, as expressed by the average age of 5.35 years for the documents.

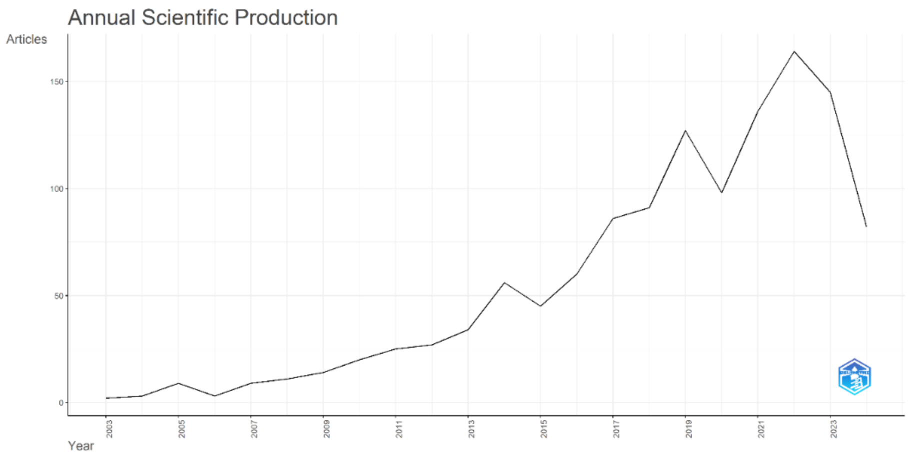

Figure 1. Time series of annual scientific production
Source: output of Biblioshiny software

One of the salient features of MRIO research is its collaborativeness, with 4.03 co-authors on average per document. On the other hand, international co-authorship has not yet assumed significance, which probably reflects a regional or national focus of studies. The average number of citations per document is 28.5, indicating a reasonable impact within the research community. An in-depth analysis of 327 keywords would have revealed more about the main themes and trends in research. However, the lack of information on documents other than articles is a weakness in understanding the research scenario. Table 1 shows the results from the descriptive analysis.

Table 1. Description of extracted documents

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	2003:2024
Sources (Journals, Books, etc.)	559
Documents	1247
Annual Growth Rate %	19.34
Document Average Age	5.35
Average citations per doc	28.5
References	20009
DOCUMENT CONTENTS	
Keywords Plus (ID)	327
Author's Keywords (DE)	327
AUTHORS	
Authors	2794
Authors of single-authored docs	102
AUTHORS COLLABORATION	
Single-authored docs	110
Co-Authors per Doc	4.03
International co-authorships %	0
DOCUMENT TYPES	
article	1247

Source: output of Biblioshiny software

Top authors and journals

The current research covered 559 forms of credible sources. Figure 2 illustrates the top ten sources of the largest number of scientific publications for MRIO study. Journal of Cleaner Production ranked first with the highest number of documents, 94. It was followed by Economic Systems Research with 41 documents. The next highest number of documents is contributed by Science of the Total Environment, with 28. Applied Energy and the Journal of Environmental Management contributed 25 documents each to the corpus. Ecological Economics and Resources Conservation and Recycling have 21 documents each. Then, there are 20 Energy Policy and Environmental Science & Technology documents.

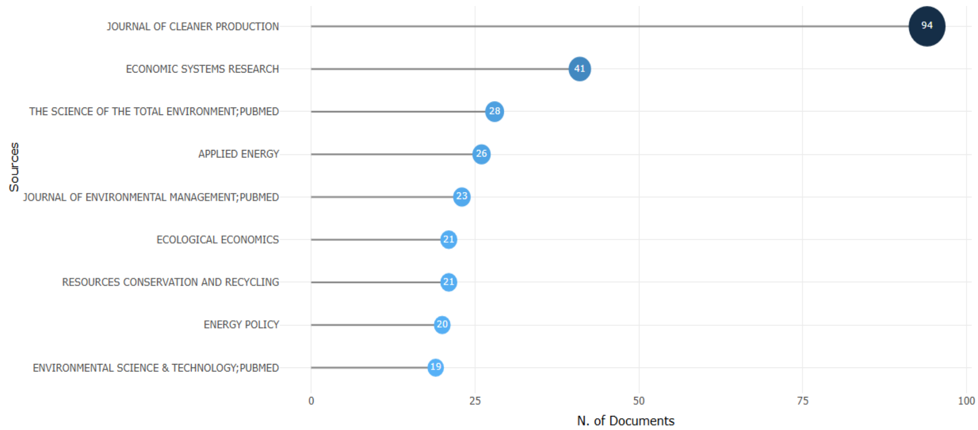

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Figure 2. Top 10 journals
Source: output of Biblioshiny software

The high-impact sources of the MRIO analysis field are ranked in Table 2 by bibliometric indicators: h-index, g-index, m-index, total citations (TC), number of papers (NP), and publication start year (PY_start) for the appraisal of the influence and the productivity records. Journal of Cleaner Production is found to be the most impacting journal in the MRIO domain, governing all evaluated metrics with the highest score in h-index 34 and g_index 48, m-index 3.4, total cites 2694 and a good number of papers 94, since it took interest in this field since 2015.

Table 2. Top ten journals

Source	h_index	g_index	m_index	TC	NP	PY_start
Journal of Cleaner Production	34	48	3.4	2694	94	2015
Economic Systems Research	28	41	1.75	5060	41	2009
Applied Energy	16	26	1.6	1155	26	2015
Ecological Economics	15	21	0.938	2181	21	2009
Resources Conservation and Recycling	15	21	2.143	626	21	2018
The Science of the Total Environment	15	28	1.364	954	28	2014
Energy Policy	14	20	0.778	1104	20	2007
Environmental Science & Technology	12	19	0.8	1672	19	2010
Journal of Environmental Management	11	21	1.833	483	23	2019
Journal of Industrial Ecology	11	14	0.688	469	14	2009

Note: TC = Total Citations, NP = Number of publications, PY_Start = Publication start year
Source: output of Biblioshiny software

Economic Systems Research is found to be a journal having all the time a strong h-index of 28 and a g-index of 41, showing its significant impact and all the time a good number of publications since 2009. Applied Energy, Ecological Economics, Resources Conservation and Recycling and The Science of the Total Environment appear among good journals since they score a respectable h-index and g-index, and citation counts in MRIO. These indicators provide insight into the impact of research within the field, with the h-index measuring the number of citations an author has received across a certain number of publications and the m-index adjusting the h-index by taking into account the number of years since the first publication, providing a better picture of an author's citation impact over time. This variability in the publication landscape indicates the wide range of journals that contribute to MRIO research in an interdisciplinary arena comprising energy, economics, environment, and ecology.

As presented in Table 1"Building Eora: A Global Multi-Region Input-Output Database At High Country And Sector Resolution" is an important contribution toward the global multi-region input-output database by Manfred Lenzen, Daniel Moran, Keiichiro Kanemoto, and Arne Geschke, published in the Economic Systems Research Journal. The same has not turned obsolete even today after its publication in the year 2013 by Taylor and Francis publishers. The paper describes the construction of the Eora MRIO database, which differs from its predecessors by including all countries at a detailed sectoral level, with capabilities for continuous updating and including information about data reliability, margins and taxation. Additionally, a historical time series component sets it apart from other MRIO frameworks, many of which have much shallower and narrower depths. The paper focuses on the problems and solutions when constructing large-scale MRIO databases, underscoring procedural standardization, automation, and efficient data organisation. The Eora project comprises all the shortcomings of the earlier initiatives to provide a more elaborate and trustworthy MRIO framework that becomes a very useful tool for researchers and policymakers alike. Moreover, the second highly cited article among the top 10 highly cited articles on MRIO has been authored by Manfred Lenzen, wherein the total citation for that article is 816.

Table 1. Top ten globally cited articles

Author	Year	DOI	Source	TC
Manfred Lenzen	2013	10.1080/09535314.2013.769938	Economic Systems Research	1099
Manfred Lenzen	2012	10.1021/es300171x	Environmental Science & Technology	816
Zhifu Mi	2017	10.1038/s41467-017-01820-w	Nature Communications	710
Konstantin Stadler	2018	10.1111/jiec.12715	Journal of Industrial Ecology	605
Angela Druckman	2009	10.1016/j.ecolecon.2009.01.013	Ecological Economics	526
Jan C. Minx	2009	10.1080/09535310903541298	Contribution to journal	477
Arnold Tukker	2013	10.1080/09535314.2012.761179	Economic Systems Research	426
Chao Zhang	2014	10.1016/j.ecolecon.2014.02.006	Ecological Economics	370
Thomas Wiedmann	2011	10.1016/j.ecolecon.2011.06.014	Ecological Economics	342
Glen P. Peters	2011	10.1080/09535314.2011.563234	Economic Systems Research	320

Note: TC=Total Citations
Source: output of Biblioshiny software

Out of these 1,247 papers, which consist of 2,794 authors, Table 4 shows the most relevant and high-impact authors concerning the h-index, g-index, m-index, number of publications, and total number of citations in global multi-region input-output MRIO databases. As shown in Table 5, based on indicators like the number of publications, the h-index, g-index, and m-index, Lenzen M, Moran D, and Kanemoto K are the top three high-impact authors in MRIO. Besides, Lenzen M, Geschke A, and Moran D are the top three

Vol.12 (2024) no.4, pp.321-341; DOI 10.2478/mdke-2024-0019

authors whose publications regarding MRIO have been most highly cited. However, of the total citations awarded to the top ten authors, Lenzen M received 20% from 2013 to date because he published relatively more publications in the MRIO field.

Table 4. Top ten articles fractionalized

Authors	Articles	Articles fractionalized
Manfred Lenzen	45	9.78
Kuishuang Feng	41	7.91
Richard Wood	41	8.80
Bin Chen	36	9.05
Klaus Hubacek	31	5.77
Thomas Wiedmann	30	7.29
Dabo Guan	28	4.46
Sai Liang	24	3.91
Jing Meng	23	4.39
Daniel Moran	22	4.94

Source: output of Biblioshiny software

Authors collaboration

Figure 3 displays the collaboration network among researchers in the field of MRIO: A few distinct clusters are visible, which are relatively small in size. The network structure shows a comparatively diverse collaboration pattern where most clusters have only a small number of authors. Though a big cluster is observed, the dominant nodes in the same cluster are only a few, showing the presence of dominant authors like Manfred Lenzen and Richard Wood, reflecting their huge influence and collaboration in this field. Other important contributors, such as Dabo Guan and Klaus Hubacek, play central roles in their respective clusters. The clusters' size differs, indicating that some scholars collaborate and build large, strong networks, while others work within small, relatively isolated groups. This distribution mirrors the importance of increasing the scope of collaborations to improve research output and connectivity among the MRIO research community.

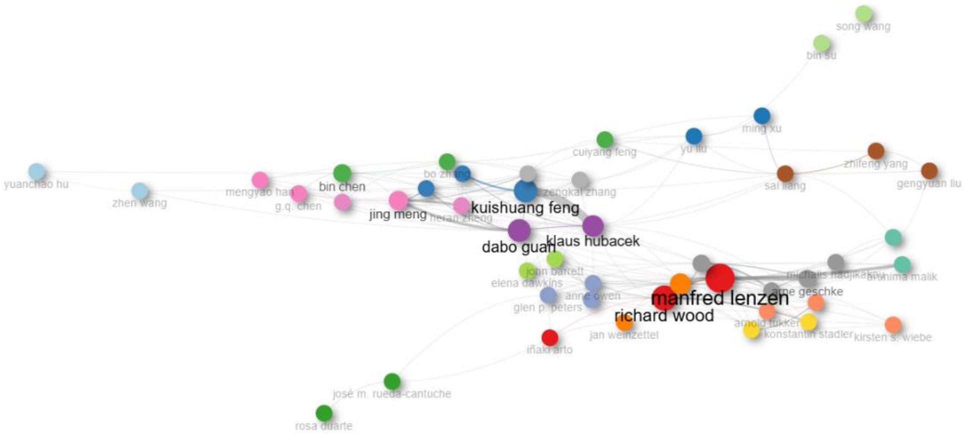

Figure 3. Authors' collaboration network diagram
Source: output of Biblioshiny software

The outcomes of Bradford's law of scattering and Lotka's law of scientific productivity

Introduced by Samuel C. Bradford in 1934, Bradford's law of scattering describes the dispersion of literature on a particular topic across journals. Basically, this is categorized according to core, intermediate, and outlying zones according to the number of articles a journal publishes (Desai, Veras, & Gosain, 2018). The scatterplot of the articles is proportional in distribution 1: n: n^2, whereby the core zone contains source journals that most often publish on the topic and will generally give researchers the most relevant material (Thelwall & Wilson, 2014). This principle helped researchers to identify the core journals in their subject of interest and was applied to subjects such as literature analyses on Diabetes Mellitus type 1, cancer research in India, Information Science, and Epidemiology publications from India and Japan (Arya, Jaiswal, & Bisaria, 2024). If a researcher is aware of Bradford's law, then the author does not need to spend much time going through the journals to access the required articles on the subject of interest.

Table 2 illustrates the distribution of the first one-third of articles among the relevant sources. The ten most relevant journals among the 559 sources are identified as the core sources in the discipline of MRIO, as depicted in Figure 4. These core journals are the primary outlets for articles on MRIO, underscoring their significance in the field.

Table 2. Outcomes of Bradford's law of scattering

Zones	Number of cumulative articles	Number of sources
Core zone (Zone 1)	388	15
Intermediate zone (Zone 2)	767	179
Outlying zone (Zone 3)	1144	556
Total	2299	750

Source: output of Biblioshiny software

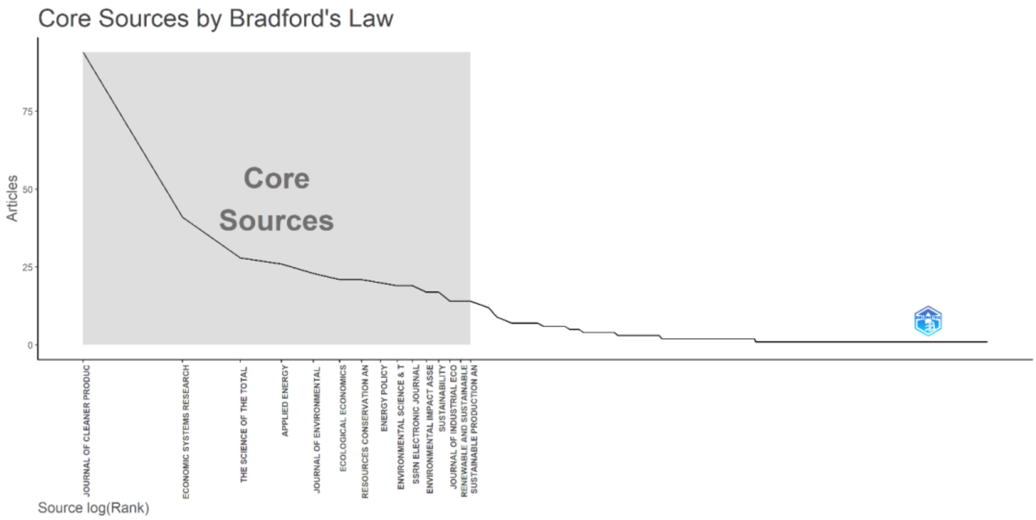

Figure 4. Bradford's law of scattering
Source: output of Biblioshiny software

Lotka's Law, proposed by Alfred J. Lotka in 1926, is a bibliometric principle applied to estimate the productivity of authors according to the distribution of published papers. In this respect, it has formed the basis for a number of studies that try to relate productivity patterns in different areas (Kawamura, Thomas, Tsurumoto, Sasahara, & Kawaguchi, 2000).

Table 3 expresses the scatter of authors against the number of documents they have written, based on Lotka's Law of Scientific Productivity. Of these, 1,974 authors (71%) have written a single article each. A smaller proportion was contributed by 443 authors who have written two articles each. The productivity further drops off, with 146 authors having written three articles and 82 authors having written four articles. Only 39 authors have written five articles (1%), while 36 have written six articles (1%). Moreover, 14 authors have written seven articles (1%), 13 eight articles (1%), five authors have written nine articles (0%), and eight have written ten articles (0%). These results, based on

Vol.12 (2024) no.4, pp.321-341; DOI 10.2478/mdke-2024-0019

Biblioshiny's output, reflect the typical pattern of Lotka's Law: a bulk of authors publish a single article, while just a small proportion are multiple contributors.

Table 3. Outcomes of Lotka's law of scientific productivity

Documents written	Number of authors	Percentage of authors (%)
1	1974	71
2	443	16
3	146	5
4	82	3
5	39	1
6	36	1
7	14	1
8	13	1
9	5	0
10	8	0

Source: output of Biblioshiny software

Future studies in MRIO: trending research avenues

Keywords are the smallest unit to represent a research article's central ideas and landscape, acting as essential indicators of research hotspots, themes, trends, and directions. This might turn out particularly to be the case for keyword analysis using techniques like keyword clustering and keyword density visualisation with tools such as Biblioshiny, which would bring out the underlying patterns within a field of study. The goal of keyword co-occurrence analysis is mainly to consider the co-relationship between keywords in a set of papers to identify prevalent topics and further enhance scholars' understanding of current scientific issues in the MRIO field.

Keyword analysis

Keywords are of utmost importance for further increasing the visibility of a research paper to readers and, therefore, to potential citers. A good set of keywords should be relevant to the topic and should form a good number in related literature. A keyword tool has been used to choose efficient keywords, considering their relevance to the theme under study and their prevalence in related literature. Figure 5 displays the tree map of the most frequently used keywords regarding MRIO in the literature. It shows that only a few keywords, such as "input-output analysis," "carbon footprint," "water footprint," and "carbon pricing," have dominated the field, with "input-output analysis" taking a proportion of 20%. Other high-frequency core words are "sustainability assessment," "CO2 emissions," "energy use," "embodied energy," and "consumption," all of which also ranked highly. Other terms, like "decomposition analysis," "exporting," "trade openness," "hydro-economic models," and "life cycle assessment" also only appear with a very high frequency and thus are very important in MRIO research. While these keywords represent the very basic themes in the field, other individual keywords, like "energy transitions," "industrial ecology," "environmental impacts," and "material flow," are infrequently used but contribute to the general discourse in MRIO studies.

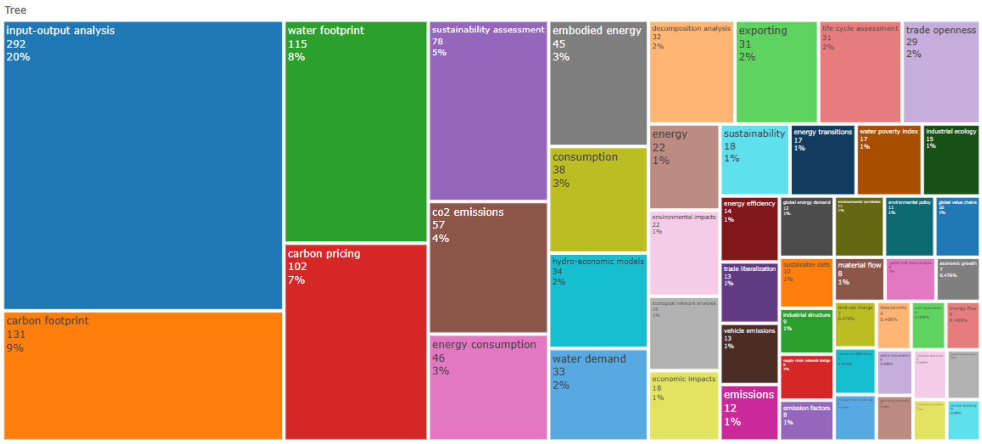

Figure 5. Tree mapping of the most relevant words used
Source: output of Biblioshiny software

Keyword co-occurrence analysis

The present investigation generated the keyword co-occurrence analysis with Biblioshiny, which shows a complex network of keywords around MRIO research. Figure 6 displays a keyword co-occurrence network with different colors, which refer to different keyword clusters. Node sizes reflect the frequency of the keyword, and line thickness refers to the strength of the relationship between keywords.

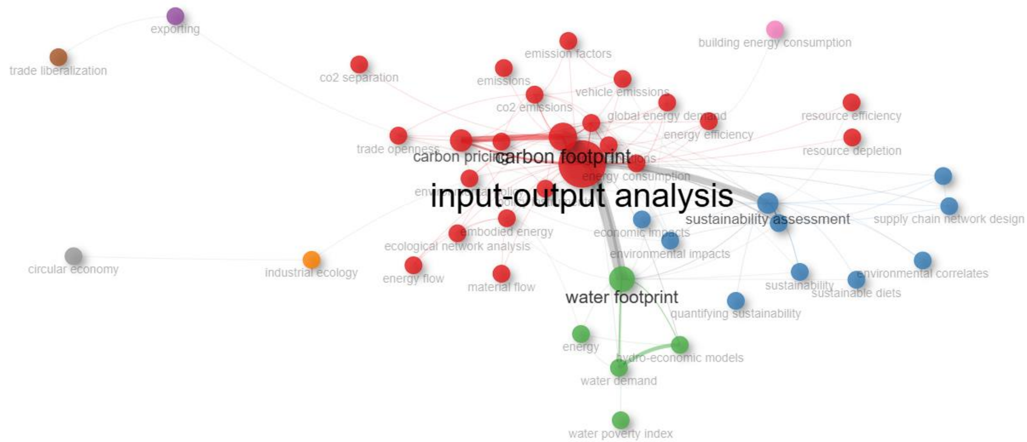

Figure 6. Keyword clusters map
Source: output of Biblioshiny software

The result of the analysis showed several prominent clusters. Cluster 1, in red colour, focuses on keywords such as "input-output analysis," "carbon footprint," and "carbon pricing," thus indicating a strong link to environmental impacts and carbon accounting. Cluster 2, coloured in green, includes keywords like "water footprint," "water demand," and "hydro-economic models," emphasizing water resource management and its economic significance in MRIO studies. Cluster 3, in blue, contains keywords such as "sustainability assessment," "environmental impacts," and "supply chain network design," thereby emphasizing the metrics of sustainability and environmental impact assessment in supply chains. Cluster 4 includes keywords like "industrial ecology" and "circular economy," with an increased focus on the systemic approaches in handling resources and mitigating the impact of industries and economic systems on the environment. The keywords that appeared most frequently were "input-output analysis," "carbon footprint," and "water footprint," as represented by larger nodes in the network. This analysis gives an interesting insight into the main focus directions and the interconnectedness of different topics within MRIO research.

Table 4 This paper presents an in-depth summary of the keyword analysis conducted on MRIO studies. It highlights the major themes generated from the keyword analysis and further relates them to relevant research in the area. This table provides an overview of the key research areas, emerging trends, and central topics within MRIO studies by explaining the various keywords connected to relevant themes to increase knowledge about the research area under study.

Table 4. Key themes in MRIO studies and related research

Cluster	Keyword	Description	Related research
Cluster 1 (Red-colored)	Input-Output Analysis	The central keyword reflects the core methodological framework used in MRIO studies.	Minx et al., 2009
	Carbon Footprint	MRIO research frequently examines the environmental impact of different economic activities.	Hasegawa, Kagawa, & Tsukui, 2015
	Carbon Pricing	The central keyword that most characterises the core methodology applied to MRIO studies.	Choi, Bakshi, & Haab, 2010
	CO2 Emissions	It is most often explored from MRIO research on the environmental impact of economic activities.	Wang et al., 2021
	Emissions Factors	The major policy-related keyword indicates studies on economic policies to reduce carbon emissions.	Andrew, Peters, & Lennox, 2010
	Energy Efficiency	An important facet of environmental impact studies is often analysed in conjunction with input-output analysis.	Munksgaard, Wier, Lenzen, & Dey, 2005
	Resource Efficiency	Used to quantify emissions from various sources within MRIO frameworks.	Ewing et al., 2012
Cluster 2 (Green-colored)	Water Footprint	Reflects the focus on optimising energy use to reduce environmental impact.	Okadera et al., 2015
	Water Demand	It measures the resource use efficiency of natural resources in economies.	Zhang & Anadon, 2014
	Hydro-Economic Models	Central to research on water use and associated environmental impacts at regional levels.	Wang et al., 2024
Cluster 3 (Blue-colored)	Sustainability Assessment	Study the demands of water resources by different economic sectors.	Zhang et al., 2022
	Supply Chain Network Design	The impact of the supply chain on sustainability is transnational and multidimensional, and MRIO can be used as a supply chain green-degree assessment method.	Wang, Jiang, & Li, 2022
	Environmental Impacts	Key to the assessment of the overall sustainability of economic activities and policy.	Asada et al., 2020
Cluster 4 (Orange-colored)	Industrial Ecology	Emphasises the need to optimise supply chains for sustainability.	Wang, Pan, Wang, & Zhou, 2020
	Circular Economy	A general keyword representing a broad range of studies on the ecological impact of economic activities.	Donati et al., 2020
Other Notable Keywords	Trade Openness	Examines the interaction between industrial systems and the natural environment.	Wang & Han, 2021
	Energy Consumption	Represents the growing interest in sustainable economic systems that reduce waste and maximise resources.	Siala, Rúa , Lechón, &

Cluster	Keyword	Description	Related research
			Hamacher, 2019
	Embodied Energy	Examines how trade policy influences environmental and economic outcomes.	Zhang, Zhu, & Hewings, 2017
	Decomposition Analysis	Examines patterns and impacts of energy use in different regions and sectors.	Hong, Shen, Guo, Xue, & Zheng, 2016
	Life Cycle Assessment	Study the total amount of energy used to produce goods and services, including indirect energy use. Break down changes in environmental impacts into contributing factors. Evaluate the environmental impacts associated with all stages of a product's life. It focuses on worldwide energy requirements and the implications of MRIO studies.	Piñero et al., 2018
Additional Keywords	Global Energy Demand	The central keyword that most characterises the core methodology applied to MRIO studies.	Cui, Peng, & Zhu, 2015
	Resource Depletion	It is most often explored from MRIO research on the environmental impact of economic activities.	Duchin, Levine, & Strømman, 2015
	Environmental Policy	It reflects the examination of government policies towards mitigating the environment.	Wiedmann & Barrett, 2013
	Sustainable Diets	A growing field that examines diets and food production systems for their environmental consequences.	Boylan et al., 2020

Source: own processing

Trend topics

As depicted in Figure 7, the trend topics plot from the biblioshiny software on MRIO outlines key themes and their development across time. "Input-output analysis" has increased centrality in the recent past, with a frequency of 292 occurrences, underlining the growing relevance of the topic to MRIO research. "Carbon pricing" has appeared 102 times, further underlining its rise to prominence in contemporary environmental and economic policy debate. Such an increase in interest is naturally connected to the growing worldwide awareness of climate change and the necessity of efficient policy tools that combine environmental impact assessments with economic operations (Agrawala, Kramer, Richard, Sainsbury, & Schreitter, 2012). Furthermore, Carbon pricing is a very trendy topic due to its potential to provide market-based incentives in an effort to cut down on greenhouse gas emissions (Baranzini, Bergh, Carattini, Howarth, & Padilla, 2017). Many countries have opened their doors to mechanisms concerning carbon pricing, which include carbon taxes and emission trading systems, due to the increase in the impacts of climate change experienced across the world's economy (Okoli, Otonnah, Nwankwo, & Nwankwo, 2024). These mechanisms are considered fundamental tools for achieving the set targets outlined under various international agreements such as the Paris Agreement (Zapf, Pengg, & Weindl, 2019). Due to this, MRIO models are increasingly applied to study the economic effects of carbon pricing in various sectors and regions. Because of this fact, carbon pricing certainly forms a critical area of focus when considering areas of MRIO research (Wang et al., 2021).

In addition, "environmental policy" comes to the fore with a peak from 2011 to 2020, reflecting a growing interest in incorporating the environment into MRIO frameworks. This trend is most likely driven by the worldwide push for sustainable development and the growing demand for thorough policy studies considering environmental consequences (Basheer et al., 2022). Given the findings, future collaboration might focus on developing more integrated MRIO models across regions, accounting for the

Vol.12 (2024) no.4, pp.321-341; DOI 10.2478/mdke-2024-0019

heterogeneity generated by environmental policy and variations in economic conditions (Cabernard & Pfister, 2021).

Other terms, like "spatial shift-share analysis" and "industrial structure," show slow growth, indicating that their topics are likely of growing significance within the MRIO research arena. Spatial shift-share analysis is a methodological extension of the classical shift-share analysis, adding spatial dimensions to regional assessments of economic dynamics. Using this approach, employment changes and industrial competitiveness may be compared within various geographical contexts (Gennadievna, 2022). Spatial shift-share analysis includes spatially lagged variables, thus combining the classical model with regional spillovers. It also captured regional dynamics, which the classical shift-share analysis will most likely omit. This analytical approach helps decompose changes in regional economies into national growth, industrial mix, and regional competitiveness components; hence, it is useful for understanding the wider implications of economic transitions. (Antczak & Gwarda, 2015).

Other topics, such as "transportation," "transportation modelling," and "water," are much less frequent and might, therefore, represent more specialised or niche themes in MRIO research. Although environmental policy and carbon pricing are the most prominent themes, "transportation" and "transportation modelling" are less discussed but still significant in some situations, such as supply chain assessment, trade logistics, and infrastructure development evaluation (Göhlich et al., 2021). These topics have become vital following the progressive initiatives by industry and policymakers to decarbonise the transportation sector.

The overall plot indicates a visible trend incorporating the environment and policy dimensions in MRIO research, and this monetisation or carbon pricing and input-output analysis has gone on a high in the last couple of years. This growth is partly driven by the fact that MRIO research nowadays better aligns with broader global initiatives, such as the United Nations' SDGs, which emphasise the need for economic, social, and environmental considerations to be integrated into policy and practice. Carbon pricing, for example, directly informs SDG 13 (Climate Action), hence falling under the practical lens of both research and policy discussions (Wiebe, Bjelle, Többen, & Wood, 2018). Moreover, with more ambitious commitments to climate targets and green recovery in light of the pandemic, there is a more pronounced requirement for stronger economic and environmental models like MRIO that will help verify the probable impacts of such policies (Lahcen et al., 2020). In addition, this plot is indicative of wider priorities at a global scale, such as shifting to greener economies, which require complete modelling to represent the economic and environmental outcomes. International agreements and national strategies on resource efficiency and sustainable economic growth have triggered research into the application of MRIO models in analysing various environmental policy implications and interventions within multiple sectors. For instance, efforts to achieve effective decarbonisation in industries and across regions call for complete MRIO assessments of the interactive impacts on value chains within the global system and regional economies (Cabernard & Pfister, 2021).

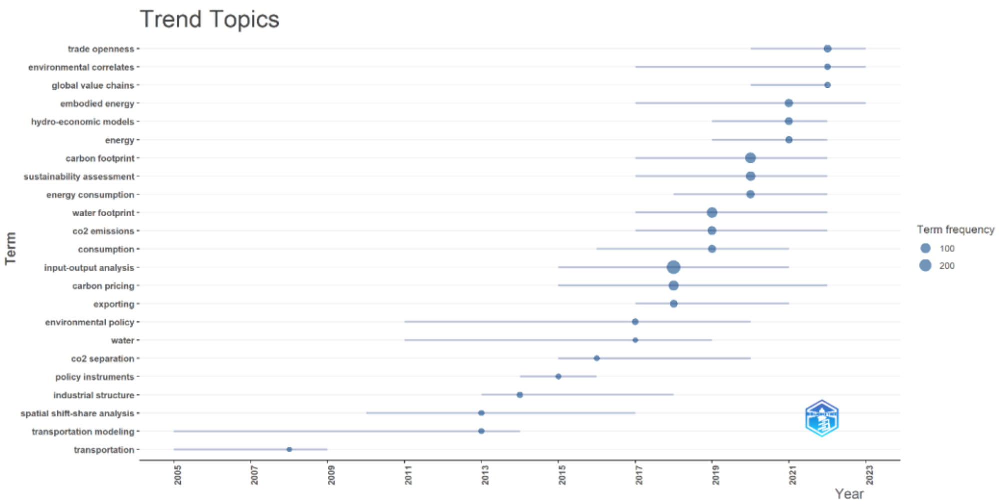

Figure 7. Trending topics
Source: output of Biblioshiny software

Conclusions

The present study utilised the OpenAlex database, covering the period from 2003 to 2024, to analyse relevant MRIO articles using the Biblioshiny software. Some key conclusions have been drawn from this analysis. MRIO research is very broad, covering a wide array of subject areas. A detailed bibliometric evaluation is necessary to understand its evolution, current situation, and perspectives of development. This study further integrated data obtained from the OpenAlex database for the period ranging from 2003 through 2023, finding a total of 1,247 articles written by 2,794 researchers from 559 reputable sources. The research on MRIO has shown consistent growth, with a notable increase in activity since 2014, peaking in 2022 with 164 publications. The Journal of Cleaner Production, active since 1993, emerged as the leading journal in MRIO research. The thematic map underlined several future research directions in the keyword analysis: carbon pricing, environmental policy, trade openness, hydro-economic models, and embodied energy.

While this study has contributed in many ways, several limitations that naturally characterise most bibliometric investigations must be considered. First, the dimension and span of the article database were consequently limited by the process of keyword choice since the keywords were used only for titles, abstracts, and keywords. A larger database would have resulted if the full article content had been incorporated into the keyword searches. Moreover, the research only used the OpenAlex database, a reliable database that might be limiting for searching for other pertinent works. Future studies could use other databases like Web of Science, Google Scholar, IEEE, ProQuest, Scopus, and Dimensions to become more inclusive. Incorporating multiple databases in future research would likely capture a broader spectrum of the MRIO literature. Second, the focus of this study was restricted to MRIO, excluding relevant insights from adjacent fields, such as environmental management, the circular economy, and sustainability science. Future studies could adopt an interdisciplinary approach, broadening the scope to examine how MRIO research intersects with these mutually inclusive fields.

Despite these limitations, the present study's findings have theoretical and practical implications. The bibliometric analysis in this research provided an enhanced empirical understanding of MRIO through the evolution of the discipline, key themes, and trends. The analysis highlighted significant authors, articles, and sources within the MRIO field, revealing critical research areas such as carbon pricing, environmental policy, and embodied energy. These findings map not only the present state of research in MRIO; they also point to promising avenues for future investigations. This study provides the next generation of scholars with a starting point from which to study and contribute further to the major themes of the MRIO research.

Furthermore, the findings of this research have direct implications for related fields, such as environmental management and economic development. Because MRIO models integrate economic and environmental impact assessments, they form a robust tool in studying the environmental consequences of various economic activities; therefore, they are very valued in sustainability science. For example, MRIO can also be used to track carbon footprints from international supply chains or to quantify various environmental costs of industrial activities to devise sustainable resource management strategies. Regarding economic development, the MRIO frameworks could also be leveraged to test policymakers on potential economic consequences accompanying environmental regulations regarding financial impact, such as with the application of carbon pricing. In turn, this should unlock a more rounded economic growth through increased compatibility of economic growth with environmental sustainability. These interdisciplinary linkages represent the wider relevance of MRIO research and play a key role in addressing global problems related to sustainable development, resource management, and climate change mitigation.

These key areas emerging from the bibliometric analysis of MRIO provide some practical implications: knowing prominent themes and influential works in MRIO, researchers and students will align their research and academic pursuits to better fit contemporary trends and increase their competitive edge in the field. Such an alignment will be capable of bridging the gap between theoretical knowledge and practical applications, which would provide a further understanding of key concepts of MRIO and research relevance. In that regard, findings from this study can go a long way to help practitioners and policymakers take key areas in decision-making and policy formulation, such as carbon pricing and environmental policy. Consequently, the study enriches the MRIO research field with valuable insights for scholars, practitioners, policymakers, and educators, guiding further research and practical applications. For instance, it will underline the carbon pricing and environmental policy under MRIO that can be used directly in environmental impact assessment and long-term economic planning (Wang et al., 2024). The results provide a sound basis for embedding MRIO models in decision-making frameworks confronting sustainability and climate change problems.

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