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Carbon Footprints

Review

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Review of material flow analysis and its application under carbon neutralization target: a bibliometric perspective

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Abstract

Material flow analysis (MFA) could provide methodological support for quantifying material carbon flow and carbon emissions in the pursuit of carbon neutrality. Despite the extensive publication of MFA studies in academic journals, significant challenges remain on MFA and its application in carbon emission (MFA-CE) research, including identifying emerging research trends. This paper reviews MFA and MFA-CE research based on bibliometric analysis of data from WOS (Web of Science) platform, spanning from 1991 to 2022. We find that over the last 32 years: (1) Both MFA and MFA-CE research share similar article characteristics, such as rapid and active fluctuations in trends, with high-output countries primarily being the USA, China, and others; (2) MFA and MFA-CE are multidisciplinary fields, showing the fastest growth in Environmental Studies and Economics research; (3) Highly cited papers mainly focus on global material flow, environmental impact, and recycling. Notably, high citation analysis shows that both MFA and MFA-CE research have garnered substantial attention since 2014; and (4) Combining MFA with other methods would help identify material flow, such as carbon material flow. Additionally, the future perspectives of MFA-CE research were summarized: increasing interdisciplinary cooperation; a growing emphasis on multi-scale research; and enhanced availability and application of data.

Keywords: Bibliometric analysis, material flow analysis, carbon emission

INTRODUCTION

As carbon neutrality has become a widespread international consensus, material flow analysis (MFA) in carbon emission (MFA-CE) research has attracted much attention. Carbon neutrality is one of the main strategies taken by the international community to address climate risks and mitigate ecological crises[1]. As of November 2023, about 145 countries have announced or are considering achieving net zero targets, covering nearly 90% of global emissions[2]. In this context, quantitative analysis of carbon emissions could help provide a solid data foundation for achieving carbon neutrality goals. Based on the inherent characteristics of MFA, it could effectively analyze the carbon flow of material/product in the operation of the social system. Igarashi *et al.* examined the reduction potential of CO_2 emissions from stainless steels using dynamic MFA[3]. Krausmann *et al.* investigated the global socio-economic metabolism of material demand from 1900 to 2015 through MFA[4]. Liu *et al.* employed MFA to quantify petroleum-related CO_2 emissions in China and analyze their spatial distribution[5]. Li *et al.* developed a stock-driven dynamic MFA to estimate power generation infrastructure in China from 1993 to 2060 and explore the nexus of material-energy-carbon emissions[6].

After decades of development, MFA is widely used in many fields. From the systematic boundary of MFA, it is mainly applied to the research at the global, regional, national, city or community levels within a certain period. For instance, some researchers have focused on global material extraction and consumption, and material flows in different sectors including agricultural systems, transportation, construction, and waste[7-11]. Additionally, based on MFA, some studies analyze the characteristics of waste, food waste, economic growth, and environmental impact across various income levels, regions, and cities[12-15]. Focusing on the research object, MFA is mainly applied to resource exploitation, import and export, domestic material output and hidden flow, e.g., material, energy, carbon emission, and others[7,9,16-20]. In addition, some scholars have reviewed MFA from a literature perspective, highlighting its use as a strategic tool for managing e-waste and exploring its application, trends, and future research directions[21]. They also analyze the application of MFA in industrial ecosystems through bibliometric analysis[22].

The increasing volume of research publications reflects researchers' recognition of this field[22-24], including its various applications and methods. Unlike previous review studies, bibliometric analysis offers valuable insights into the current state and emerging trends in research[23,25]. As a powerful tool for analytical science research, bibliometric analysis quantitatively describes the demand for specific research topics and illustrates research distribution through knowledge maps[25,26]. However, there are few systematic reviews on MFA, especially from the perspective of bibliometrics or scientometrics. This gap is significant given that the primary contribution of MFA in carbon emissions research is its provision of a systematic, comprehensive and multi-scale analytical method. As a result, several key questions arise: What is the current status of the international MFA and MFA-CE field? What are the current research hotspots? And what are the future research directions? To address these questions, this paper assesses global trends and scales, discipline structures, discipline layouts, and frontier hotspots through a literature analysis of MFA and MFA-CE research. The remainder of the paper is organized as follows: Section 2 details the data and methodology, Section 3 presents the research results, and Section 4 discusses the findings and draws a conclusion.

MATERIALS AND METHODOLOGY

Web of Science (WoS) database encompasses various academic journals with international influence, comprehensive coverage, and interdisciplinary scope, making it one of the world's authoritative citation databases. We selected the WoS platform as our data source, including SCIE (Science Citation Index Expanded) and SSCI (Social Science Citation Index). The literature retrieval strategy for MFA research was

TI (title) or AK (keyword) equals "material* flow analys*" or "material* flow analyz*" or "substance flow analys*" or "substance flow analyz*" or "goods flow analys*" or "goods flow analyz*" or "material flow account*" or "substance flow account*" or "goods flow account*" or "material* flow model*"or "flow* and flux*" or "stock* and flow*" or "process* and stock*" or "hidde* flow*" or "local system* analys*" or "material system analys*" or "material system analyz*". For the application of MFA in carbon emission (MFA-CE) research, the search strategy was expanded with additional terms: "CO_2 emission*" OR "CO_2 footprint*" OR "CO_2 emit*" OR "carbon dioxide emission*" OR "carbon dioxide footprint*" OR "carbon dioxide emit*" OR "carbon emission*" OR "carbon footprint*" OR "carbon emit*" OR "Energy emission*" OR "Energy footprint*" OR "carbon fluxes". As of November 30, 2023, a total of 1309 publications were collected for MFA research and 782 publications for MFA-CE research, covering the period from 1991 to 2022.

The research framework is shown in Figure 1. We begin by searching for relevant publications on MFA and MFA-CE in the WOS database using the above-mentioned retrieval strategy. Next, we employ DDA software for data cleaning to include publications from various regions such as China, including Mainland China, Hong Kong, Macao, and Taiwan, as well as from the UK, including England, Scotland, Wales, and Northern Ireland. Additionally, to ensure data comparability, we select only English-language articles and exclude non-English articles. Irrelevant literature is also removed by reviewing titles, abstracts, and other details. Following these data cleaning procedures, we finally analyze 1235 papers on MFA and 719 papers on MFA-CE. We examine trends in publication, subject distributions, and journal evaluations to reveal the research status. Research hotspots are identified through an analysis of research areas, highly cited papers, high-frequency keywords, and frontier analysis. We utilize software tools such as DDA (Derwent Data Analyzer), CiteSpace, and VOSviewer to mine textual data and visualize research on MFA and MFA-CE.

RESULTS

Characteristics of articles

Global trends in publications

Analysis of MFA research [Figure 2] reveals a significant increase in the number of related publications from 1991-2022, rising from 4 to 142, with a cumulative total of 1,235. The trend can be divided into three distinct stages of growth: Initial stage (1991-2003), during which the average annual number of publications was 6, with a total of 58 publications, accounting for only 4.70% of the overall count; Slow growth stage (2004-2013), which saw a moderate increase in publications, with an average of 33 publications per year. The cumulative total reached 325, representing 26.32% of the total; rapid growth stage (2014-2022), which experienced a significant surge, with an average of 99 publications annually. The cumulative total reached 852, making up 68.99% of the overall total. This amount is 13.69 times greater than that of the initial stage.

For MFA-CE research [Figure 2], three distinct stages of growth in publication volatility were identified. Annual publications increased from 4 to 89 during 1991-2022, with a total of 719 articles (58.22% of all MFA research articles). During the first stage (1991 to 2003), there were 33 cumulative articles, representing 4.59% of the total, with an average of 4 articles published annually. In the second stage (2004 to 2013), the number of cumulative articles increased to 201, accounting for 27.96% of the total, with an average of 20 articles published per year. In the third stage (2014 to 2022), the cumulative number of articles reached 485, making up 67.45% of the total, with an average of 54 articles published annually. The number of articles in the third stage was 13.70 times higher than that of the first stage.

Both MFA and MFA-CE research exhibited rapid growth over the past 32 years [Figure 2], showing similar exponential growth trends. Interestingly, both fields can be divided into similar three stages based on annual

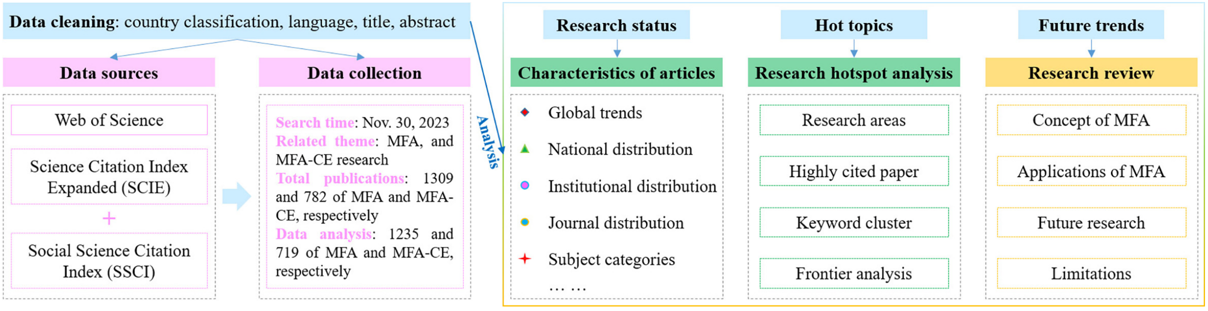


Figure 1. The research framework.

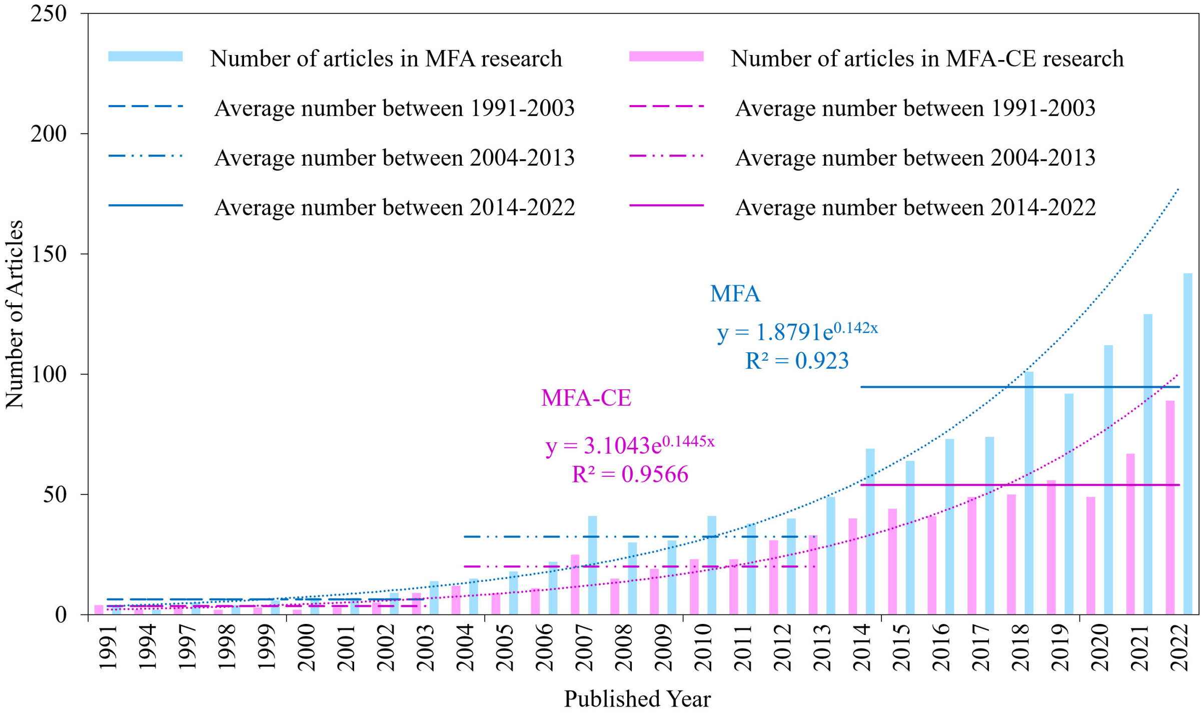


Figure 2. The number of annual publications from 1991 to 2022.

publications. The increasing trends revealed that these fields are widely recognized and have garnered significant attention.

National distribution characteristics

Articles on MFA and MFA-CE research from different countries during the past 32 years were analyzed [Figure 3]. Research in MFA originated from 73 countries/territories and MFA-CE research was from 64 different countries/territories. For MFA research, the top 10 productive countries published about 95.22% (1,176) of the total articles, as shown in Figure 3. For MFA-CE research, the top 10 productive countries contributed nearly 95.69% (688) of the total. Notably, the USA ranked first in the first stage (1991-2003) and second stage (2004-2013) and China ranked first in the third stage (2014-2022). Overall, a comparative analysis of the top 10 productive countries reveals that China, the USA, and Japan are the most active areas in MFA and MFA-CE research.

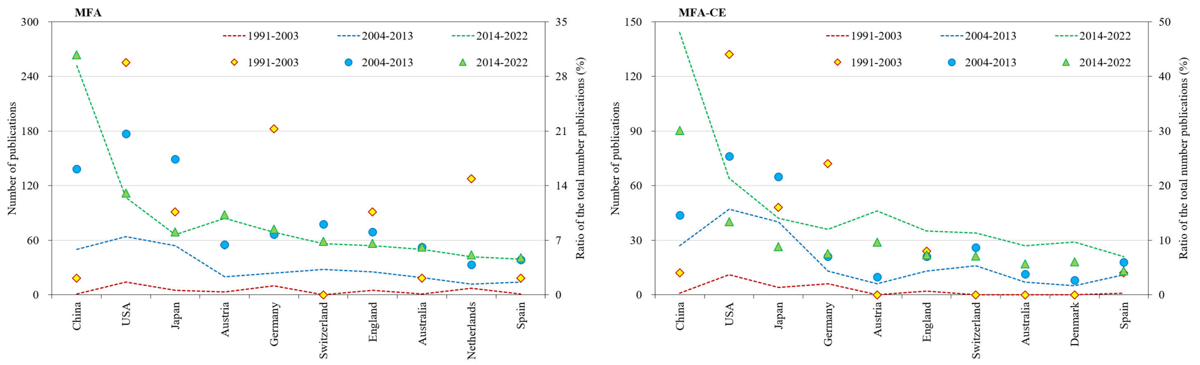


Figure 3. Number of publications by top 10 countries in different research periods.

Based on the VOSviewer software, the national cooperation network on MFA and MFA-CE research was drawn [Figure 4]. Based on MFA research, five clusters could be divided [Figure 4A]. The first cluster (the largest one) included 8 countries (Netherlands, Spain, Denmark, Belgium, France, Italy, Portugal, and India); the second cluster included 6 countries (Colombia, England, Germany, Sweden, Switzerland, and Thailand); the third cluster included 4 countries (Australia, Austria, the Czech Republic, and Finland); the fourth cluster included 3 countries (Canada, China, and the USA); the fifth cluster included 3 countries (Japan, South Korea, and Vietnam). Based on an analysis in MFA-CE research, the national cooperation network relationships could also be divided into five clusters [Figure 4B]. The first one (red, 6 countries) included Denmark, Spain, England, Italy, Portugal, and Belgium. The second one (green, 6 countries) included Japan, South Korea, France, Vietnam, India, and the Netherlands. The third one (blue, 5 countries) included China, the USA, Austria, Australia, and Canada. The fourth one (yellow, 4 countries) included Norway, Sweden, the Czech Republic, and Finland. The fifth one (purple, 4 countries) included Germany, Switzerland, Colombia, and Thailand.

The national cooperation network diagram of MFA and MFA-CE research offers an intuitive understanding of and effectively identifies the intensity of international cooperation[25,27]. On the whole, in terms of total link strength for both MFA and MFA-CE research, the USA and Japan were dominated in the early stage, while China and the USA took the lead in the later stage. Notably, since China set the goal of achieving carbon neutrality by 2060, its prominence in both MFA and MFA-CE research has become more pronounced.

Institutional distribution characteristics

During the study period, the WoS platform indicated that 1107 research institutions published articles on MFA and 381 institutions published on MFA-CE. The top 10 institutions contributed 13.80% and 15.31% of the total papers in these fields, respectively [Supplementary Table 1]. In MFA research, only 108 institutions (9.76% of the total) published ≥ 5 articles, accounting for 46.36% of the total publications. The top 10 most productive institutions in MFA research were: the Chinese Academy of Sciences (71, 2.73%), Tsinghua University (50, 1.92%), Yale University (42, 1.61%), the University of Tokyo (37, 1.42%), Norwegian University of Science and Technology (32, 1.23%), Vienna University of Technology (28, 1.08%), Leiden University (27, 1.04%), University of Southern Denmark (25, 0.96%), National Institute Environmental Studies (24, 0.92%), and Northeastern University (23, 0.88%). In MFA-CE research, only 54 institutions (14.17% of the total) published ≥ 5 articles, representing 37.29% of the total publications. The top 10 most productive institutions in MFA-CE research were: the Chinese Academy of Sciences (41, 2.71%), Tsinghua University (32, 2.11%), Yale University (31, 2.05%), the University of Tokyo (24, 1.58%), Vienna University

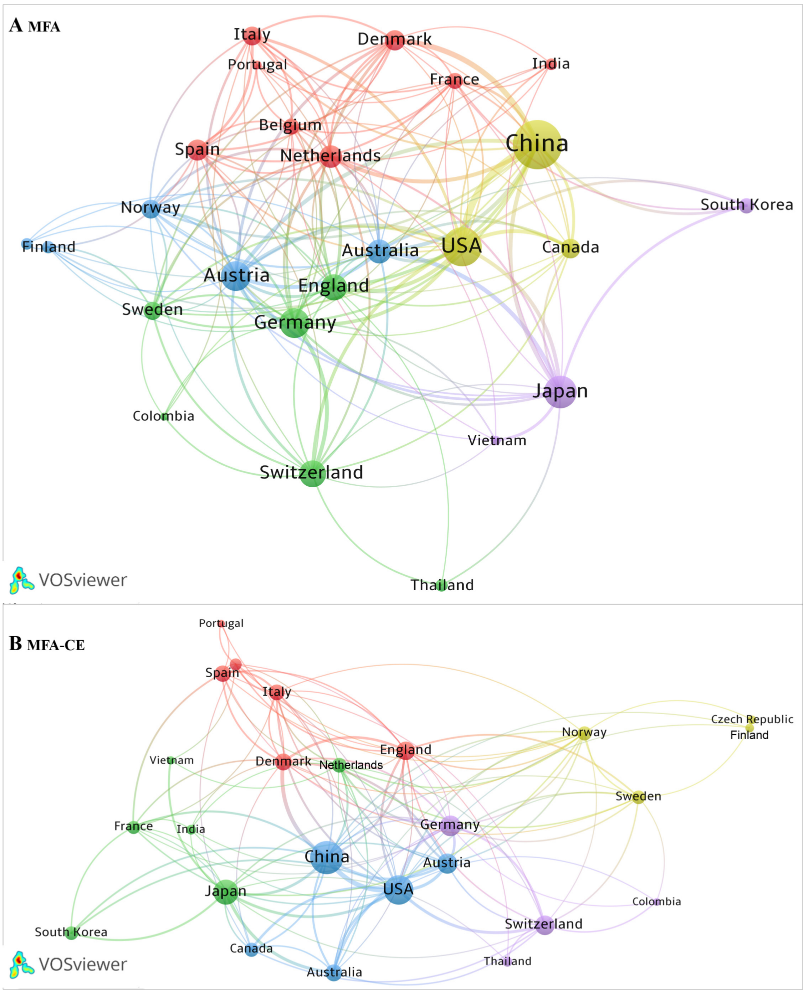


Figure 4. The national cooperation network map of MFA research (A) and MFA-CE research (B).

of Technology (20, 1.32%), National Institute Environmental Studies (19, 1.25%), Norwegian University of Science and Technology (18, 1.19%), University of Southern Denmark (17, 1.12%), Swiss Federal Laboratories for Materials Science and Technology (15, 0.99%), and Tohoku University (15, 0.99%).

In MFA research, the institutional cooperation network relationships could be divided into five clusters [Figure 5A]. The first one (red, 6 institutions) included Yale University, Leiden University, Norwegian University of Science and Technology, Vienna University of Technology (TUWien), Swiss Federal Laboratories for Materials Science and Technology (EMPA), and The Swiss Federal Institute of Technology. The second one (green, 4 institutions) included the University of Tokyo, National Institute Environmental Studies, Tohoku University, National Taiwan University. The third one (blue, 4 institutions) included University of Southern Denmark, Vienna University of Technology, Beijing Normal University, and Technical University of Denmark. The fourth one (yellow, 3 institutions) included Tsinghua University, Northeastern University, and Shanghai Jiao Tong University. The fifth one (purple, 3 institutions) included the Chinese Academy of Sciences, University of Chinese Academy of Sciences, and Nanjing University.

In MFA-CE research, the institutional cooperation network relationships could also be divided into five clusters [Figure 5B]. The first one (red, 4 institutions) included Vienna University of Technology, Technical

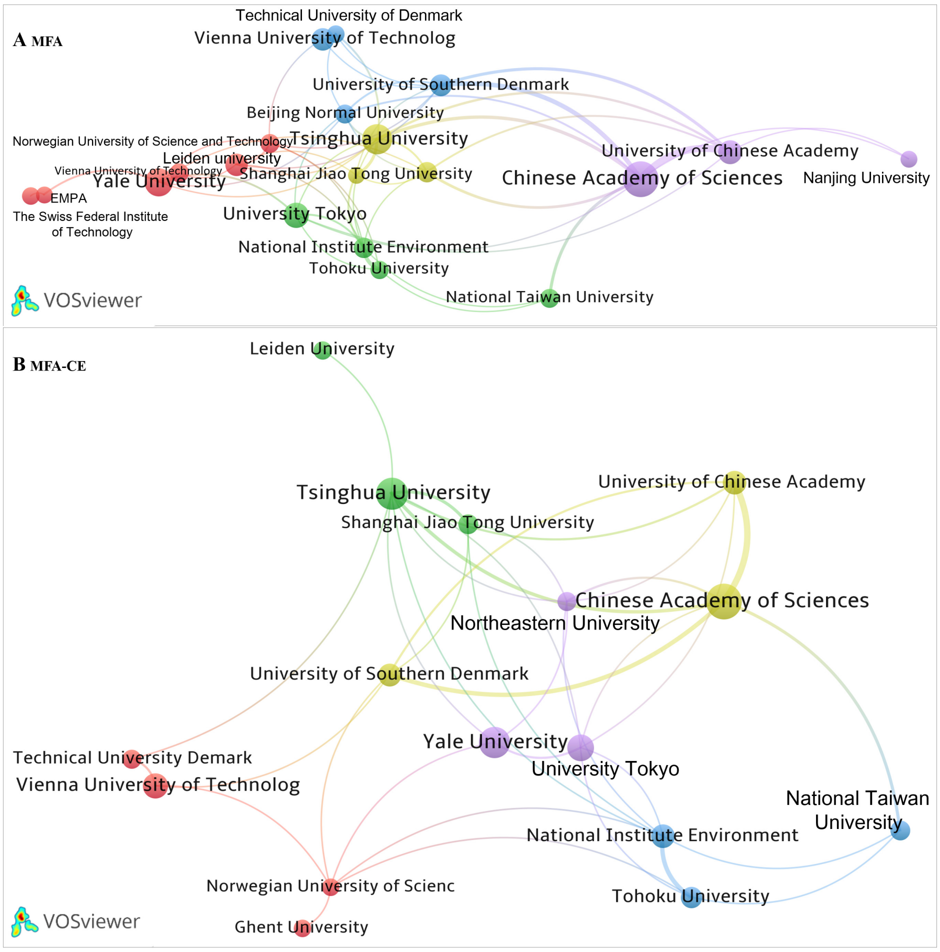


Figure 5. The institutional cooperation network map of MFA research (A) and MFA-CE research (B).

University of Denmark, Norwegian University of Science and Technology, and Ghent University. The second one (green, 3 institutions) included Tsinghua University, Shanghai Jiao Tong University, and Leiden University. The third one (blue, 3 institutions) included National Institute Environmental Studies, Tohoku University, and National Taiwan University. The fourth one (yellow, 3 institutions) included Chinese Academy of Sciences, University of Chinese Academy of Sciences, and University of Southern Denmark. The fifth one (purple, 3 institutions) included Yale University, the University of Tokyo, and Northeastern University.

Overall, based on the total link strength, Yale University and National Institute Environmental Studies played an important role in the early research of both MFA and MFA-CE. In the later stage, the Chinese Academy of Sciences and Tsinghua University assumed a dominant position.

Journal distribution characteristics

During the study period, from the WoS platform, there were 287 and 201 journals that published papers on MFA and MFA-CE research, respectively. The top 10 active institutions accounted for 57.46% and 56.88% of the total publications in MFA and MFA-CE research, respectively [Supplementary Table 2]. In MFA research, only 108 journals (9.76% of the total journals) published ≥ 5 articles, which accounted for 73.42% of the total publications. The top 10 most productive journals were: Resources Conservation and Recycling

(191, 15.48%), Journal of Industrial Ecology (164, 13.29%), Journal of Cleaner Production (131, 10.62%), Science of the Total Environment (45, 3.65%), Sustainability (35, 2.84%), Ecological Economics (33, 2.67%), Waste Management (32, 2.59%), Environmental Science & Technology (31, 2.51%), Waste Management & Research (28, 2.27%), and Journal of Environmental Management (19, 1.54%). In MFA-CE research, only 20 journals (9.95% of the total journals) published ≥ 5 articles, representing 66.62% of the total publications. The top 10 most productive journals were: Resources Conservation and Recycling (111, 15.44%), Journal of Industrial Ecology (101, 14.05%), Journal of Cleaner Production (78, 10.58%), Environmental Science & Technology (28, 3.89%), Science of the Total Environment (20, 2.78%), Waste Management (19, 2.64%), Waste Management & Research (17, 2.36%), Ecological Economics (15, 2.09%), Journal of Material Cycles and Waste Management (11, 1.53%), and Environmental Science and Pollution Research (9, 1.25%).

In MFA research, the journal cooperation network relationships could be divided into four clusters based on the total link strength [Figure 6A]. Environmental Science & Technology, Waste Management, and Science of the Total Environment were most closely related in the first cluster (red, 11 journals). Resources Conservation and Recycling, Journal of Cleaner Production, and Energy and Energy Policy were most closely related in the second cluster (green, 9 journals). Journal of Industrial Ecology, Ecological Economics, Nature, and Science were most closely related in the third cluster (blue, 6 journals). Journal of Environmental Management, Sustainability, and Ecology Modelling were most closely related in the fourth cluster (yellow, 4 journals). In MFA-CE research, the journal citation network relationships could be divided into four clusters based on the total link strength [Figure 6B]. Journal of Cleaner Production, Science, and Energy Policy were most closely related in the first cluster (red, 10 journals). Environmental Science & Technology, Science of the Total Environment, and Environmental Science and Pollution Research were most closely related in the second cluster (green, 9 journals). Resources Conservation and Recycling, Journal of Industrial Ecology, and Ecological Economics were most closely related in the third cluster (blue, 7 journals). Waste Management, Waste Management & Research, and Sustainability were most closely related in the fourth cluster (yellow, 4 journals). Overall, based on the total link strength, Resources Conservation and Recycling, Journal of Cleaner Production, Journal of Industrial Ecology, and Environmental Science & Technology hold important positions in journal publications within both MFA and MFA-CE research.

Research hotspot analysis

Analysis of research areas

Based on the data from WoS database, MFA research spans 103 disciplines. The top 10 research categories over different periods were mainly distributed across Environmental Sciences, Engineering, Environmental, Green & Sustainable Science & Technology, Environmental Studies, Economics, Ecology, Metallurgy & Metallurgical Engineering, Energy & Fuels, Water Resources, and Materials Science Multidisciplinary [Figure 7A], which collectively accounted for 88.01% of the total publications during 1991-2022. Notably, research in Environmental Studies and Economics related to MFA grew the fastest, with increases of 2.84 and 3.63 times, respectively, when comparing the periods 2004-2013 and 2014-2022. For MFA-CE research, the data span 84 disciplines. The top 10 research categories over different periods were distributed across Environmental Sciences, Engineering, Environmental, Green & Sustainable Science & Technology, Environmental Studies, Metallurgy & Metallurgical Engineering, Multidisciplinary Materials Science, Economics, Energy & Fuels, Management, and Ecology [Figure 7B]. These categories comprised 86.57% of the total publications from 1991 to 2022. Among these, research in Environmental Studies and Multidisciplinary Materials Science related to MFA-CE showed the most significant growth, with increases of 2.79 and 4.83 times, respectively, when comparing the periods 2004-2013 and 2014-2022.

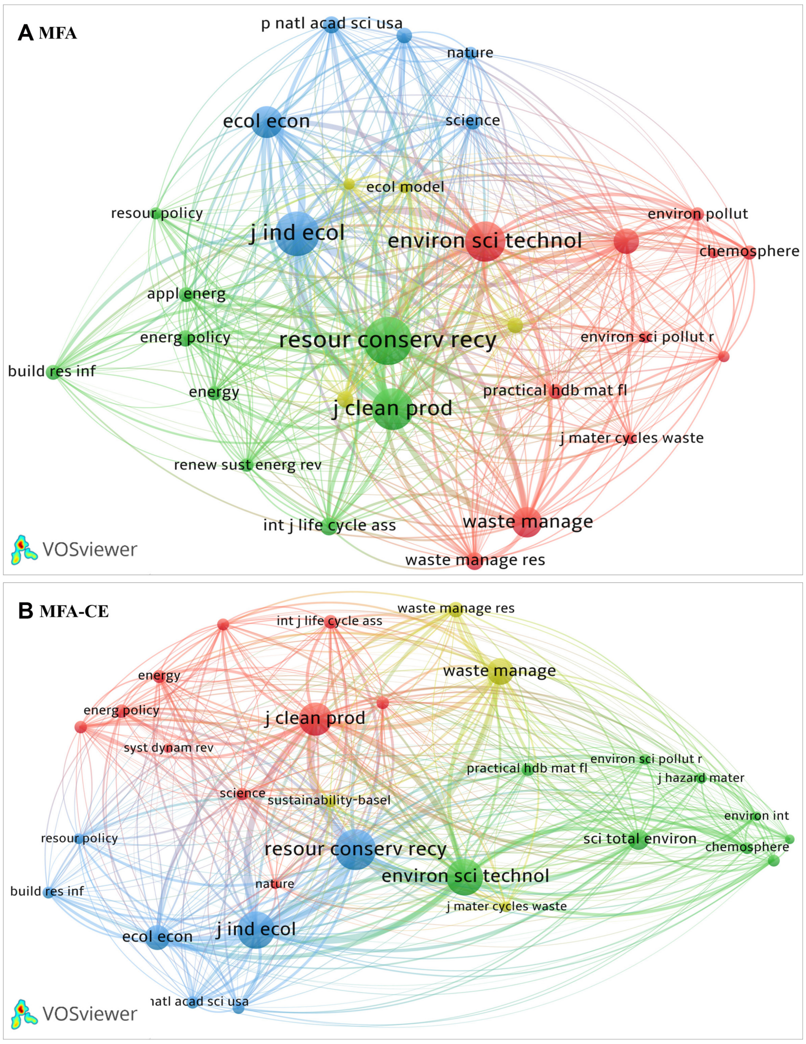


Figure 6. The journal citation network map of MFA research (A) and MFA-CE research (B).

Analysis of highly cited papers

High citation records reflect the impact and quality of publications[28]. In this study, we identified 7 highly cited papers on MFA and 3 on MFA-CE research, with 3 of these articles overlapping between the two categories, according to JCR (Journal Citation Reports) [Supplementary Table 3]. The analysis revealed the following key points: (i) The most cited paper among these was published by Haas *et al.* (2015) in Journal of Industrial Ecology, which was cited 484 times[29]. This study examined material flows, waste pollution, and recycling from a global economic perspective. The second most cited paper was authored by Krausmann *et al.* (2017) in PNAS, receiving 270 citations[26]. This work highlighted that global material stocks increased 23-fold from 1900 to 2010; (ii) The 7 highly cited papers predominantly focused on global material flows, regional resource waste, food waste and its reduction, as well as the stocks/flows of natural and human resources within ecosystem services; (iii) Notably, none of the highly cited articles were published before 2014, suggesting that MFA gained widespread application across various fields only after this year; and (iv) Additionally, the related articles were primarily published in journals such as Journal of Industrial Ecology, PNAS, Nature Geoscience, Global Environmental Change, Waste Management, Land Use Policy, and Resources Conservation and Recycling.

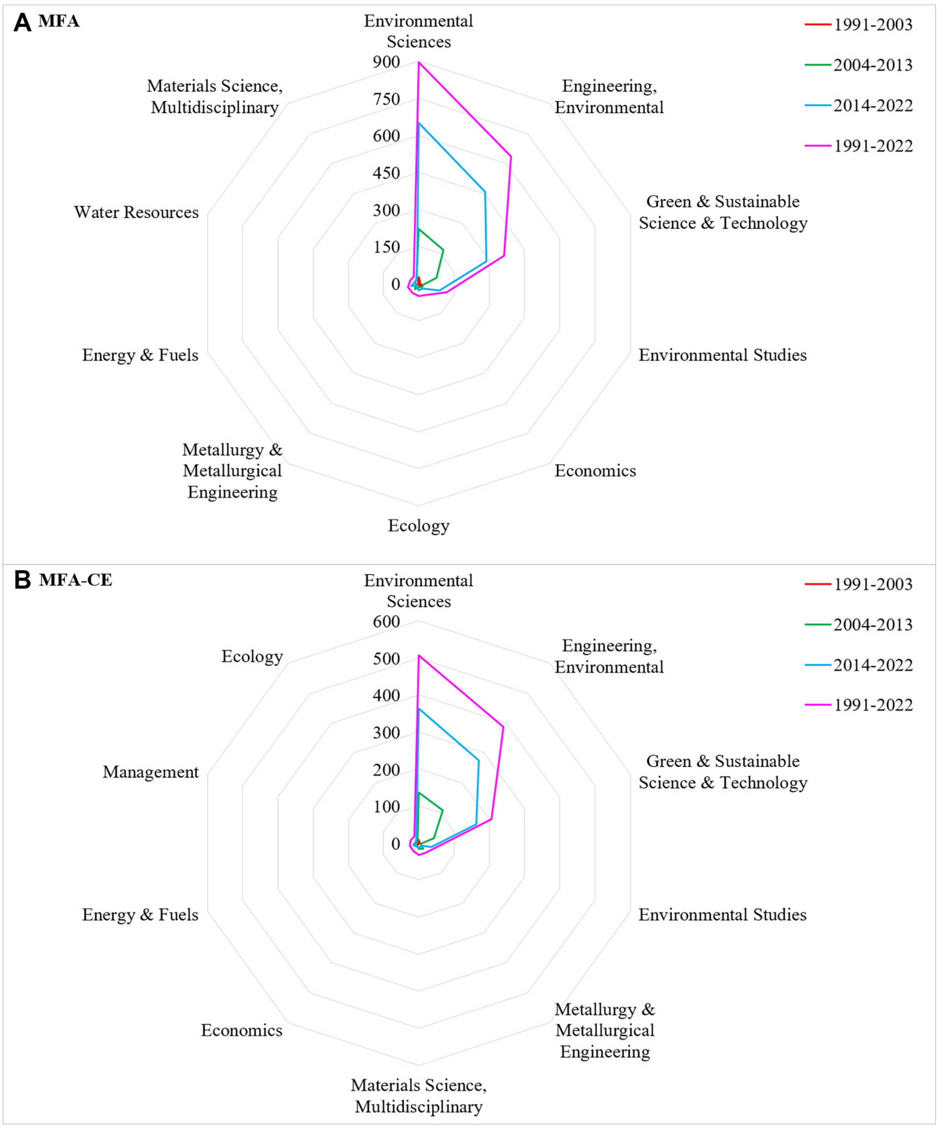


Figure 7. Top10 research categories of MFA research (A) and MFA-CE research (B).

Keyword cluster analysis

A total of 2920 keywords appeared in MFA research. Among these (92.47%), 2273 keywords appeared once, 315 twice, and 112 three times. Additionally, 220 keywords (7.53%) appeared more than 4 times. This distribution suggests that the frequency of keywords can indicate key research hotspots. A bibliometric analysis of the co-occurrence network for these keywords helps to identify relevant research trends and frontiers. Hence, this study removed the subject keywords related to retrieval strategies (such as MFA, substance flow analysis, *etc*.) and drew a related keyword co-occurrence network in MFA research [Figure 8A]. Results demonstrated that industrial ecology, circle economy, China, life cycle assessment, and phosphorous were the core of different clusters. The first cluster (red, 11) included China, dynamic material flow analysis, stocks and flows, scenario analysis, input-output analysis, resource efficiency, international trade, system dynamics, building stock, life cycle, and copper. The second cluster (green, 10) featured industrial ecology, urban metabolism, material flow accounting, uncertainty, economy-wide material flow analysis, steel, material efficiency, dematerialization, resource productivity, and social metabolism. The third

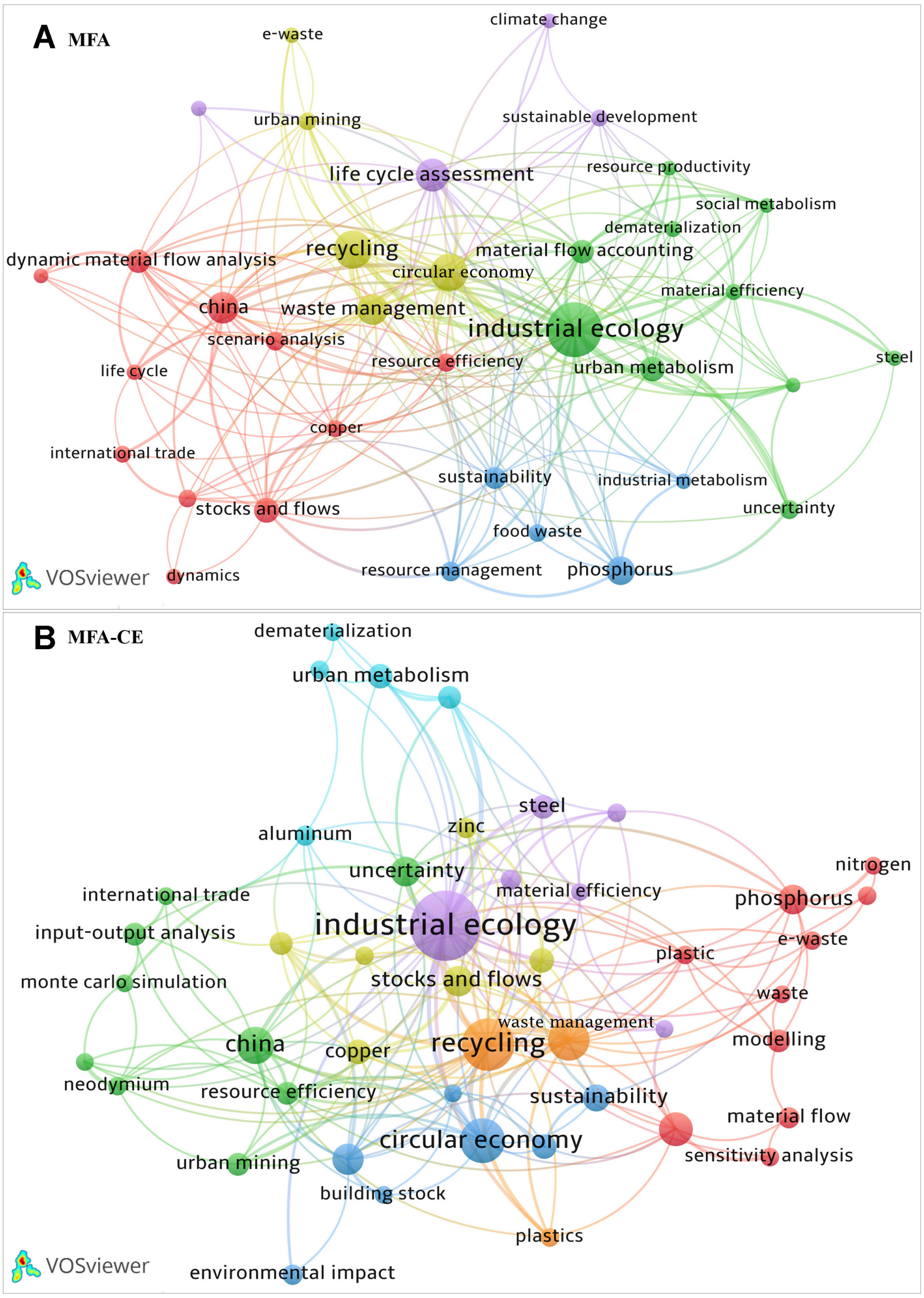


Figure 8. Keyword co-occurrence network map of MFA research (A) and MFA-CE research (B).

cluster (blue, 5) encompassed phosphorus, food waste, sustainability, resource management, and industrial metabolism. The fourth cluster (yellow, 5) included circular economy, recycling, waste management, urban mining, and e-waste. The fifth cluster (purple, 4) covered life cycle assessment, environmental impact, sustainable development, and climate change.

In MFA-CE research, a total of 1,806 keywords were identified. Of these (93.68%), 1,461 appeared once, 169 twice, and 62 three times. Only 114 keywords (6.31%) appeared more than four times. We excluded subject-specific keywords related to retrieval strategies (such as MFA, substance flow analysis, CO_2 emission, *etc.*)

and constructed a keyword co-occurrence network for MFA-CE research [Figure 8B]. The results demonstrated that industrial ecology, circle economy, China, life cycle assessment, recycling, urban metabolism, and phosphorous were the core of different clusters. The first one included 10 keywords: life cycle assessment, phosphorus, modeling, sensitivity analysis, plastic, e-waste, waste, material flow, heavy metals, and nitrogen. The second one included 9 keywords: China, resource efficiency, input-output analysis, international trade, uncertainty, Monte Carlo simulation, urban mining, rare earth, and neodymium. The third one included 7 keywords: circular economy, sustainability, energy efficiency, dynamic material flow analysis, environmental impact, building stock, and food waste. The fourth one included 6 keywords: stocks and flows, copper, life cycle, resource management, and zinc. The fifth one included 6 keywords: industrial ecology, steel, material efficiency, industrial metabolism, dynamic modeling, and decision support. The sixth one included 5 keywords: urban metabolism, economy-wide material flow analysis, decoupling, aluminum, and dematerialization. The seventh one included 3 keywords: recycling, waste management, and plastics.

Research frontier analysis

In the WoS database, we analyzed the top 20 and top 14 keywords with the strongest citation bursts (indicated by the red rectangles) in MFA and MFA-CE research, respectively [Figure 9]. The analysis in MFA research covered starting years from 1999 to 2007 and ending years from 2007 to 2022. The emerging words included materials flow analysis (MFA, 2007), resource manage, stocks and flows, European copper cycle, multi-level cycle, industrial ecology, cycle, stock, materials flow analysis (MFA, 2008), consumption, substance flow analysis (SFA, 2009), nitrogen, European Union, substance flow analysis (2012), food production, technology, product, time, tool, and sustainable development [Figure 9A]. The analysis in MFA-CE research covered the starting years from 2022 to 2020 and the ending years from 2007 to 2022. The emerging words included resource management, systems analysis, MFA (2007, 2022), iron and steel, substance flow analysis, data reconciliation, environment impact, food waste, circular economy, waste management, life cycle assessment (2020, 2022), and urban metabolism [Figure 9B].

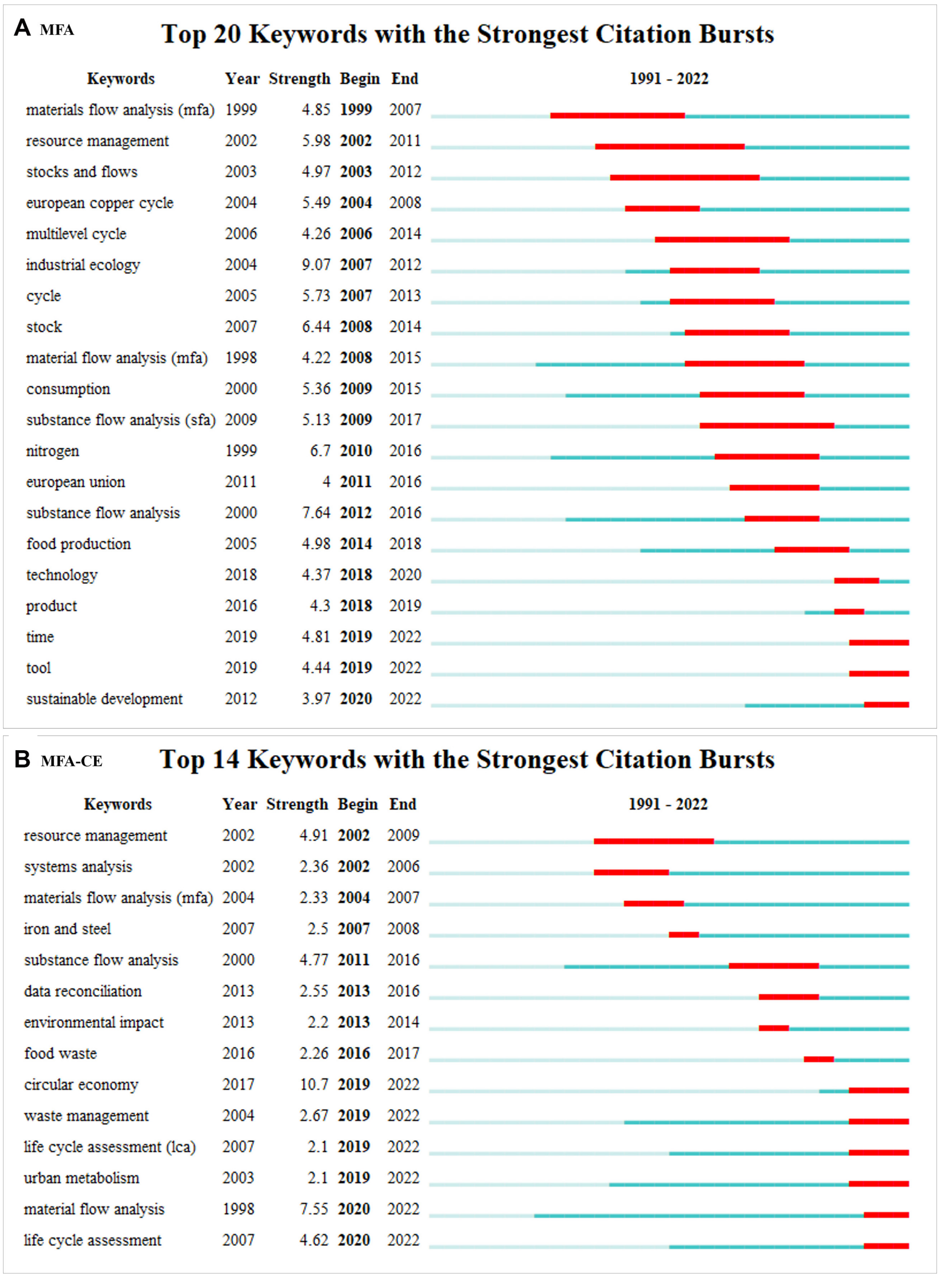
DISCUSSION

The concept and intension of MFA

The concept of MFA was based on the "metabolism" research, with its foundational ideas traceable to the 1850s[30]. In 1969, Ayres *et al.* performed the first country-scale MFA from an economic perspective[31]. In 1988, Udo de Haes *et al.* introduced the MFA concept on hazardous substances flowing through the economy and environment[32]. By the 1990s, the MFA framework had been largely established, and research on MFA began to gain momentum[18,33]. MFA serves as an assessment tool to evaluate the physical flows of natural resources and materials through their input, process and output stages[34-36]. As shown in Figure 10, MFA is widely used in socio-economic metabolism and industrial ecology to examine material flows between the environment and the economy[17,21,26,37]. With the growing global population, industrialization, and increased consumption driving the demand for material resources, MFA plays a crucial role in quantifying materials in production, consumption, trade, and disposal[4,18,26,38].

Applications of MFA

By sorting out the previous MFA research, it was found that MFA has gradually formed an accounting framework with all substances on the boundaries of socio-economic and natural environment systems as accounting objects, and conservation as accounting principles[15,34,39,40]. Within this framework, according to different research objects, MFA could be divided into substance flow analysis[41-43], goods flow analysis[44] and material system analysis[45-47], focusing on individual elements or compounds, as well as the overall amount and structure of substances within a certain range. Since the 1990s, MFA has been applied to study Japan's socio-economic system[48]. In 2001, the European Commission (EC) proposed the MFA system evaluation



A MFA

Top 20 Keywords with the Strongest Citation Bursts

Keywords	Year	Strength	Begin	End	1991 - 2022
materials flow analysis (mfa)	1999	4.85	**1999**	2007	
resource management	2002	5.98	**2002**	2011	
stocks and flows	2003	4.97	**2003**	2012	
european copper cycle	2004	5.49	**2004**	2008	
multilevel cycle	2006	4.26	**2006**	2014	
industrial ecology	2004	9.07	**2007**	2012	
cycle	2005	5.73	**2007**	2013	
stock	2007	6.44	**2008**	2014	
material flow analysis (mfa)	1998	4.22	**2008**	2015	
consumption	2000	5.36	**2009**	2015	
substance flow analysis (sfa)	2009	5.13	**2009**	2017	
nitrogen	1999	6.7	**2010**	2016	
european union	2011	4	**2011**	2016	
substance flow analysis	2000	7.64	**2012**	2016	
food production	2005	4.98	**2014**	2018	
technology	2018	4.37	**2018**	2020	
product	2016	4.3	**2018**	2019	
time	2019	4.81	**2019**	2022	
tool	2019	4.44	**2019**	2022	
sustainable development	2012	3.97	**2020**	2022	

B MFA-CE

Top 14 Keywords with the Strongest Citation Bursts

Keywords	Year	Strength	Begin	End	1991 - 2022
resource management	2002	4.91	**2002**	2009	
systems analysis	2002	2.36	**2002**	2006	
materials flow analysis (mfa)	2004	2.33	**2004**	2007	
iron and steel	2007	2.5	**2007**	2008	
substance flow analysis	2000	4.77	**2011**	2016	
data reconciliation	2013	2.55	**2013**	2016	
environmental impact	2013	2.2	**2013**	2014	
food waste	2016	2.26	**2016**	2017	
circular economy	2017	10.7	**2019**	2022	
waste management	2004	2.67	**2019**	2022	
life cycle assessment (lca)	2007	2.1	**2019**	2022	
urban metabolism	2003	2.1	**2019**	2022	
material flow analysis	1998	7.55	**2020**	2022	
life cycle assessment	2007	4.62	**2020**	2022	

Figure 9. Top keywords with the strongest citation bursts of MFA research (A) and MFA-CE research (B).

method, which provided important guidance for the economic systems of countries around the world[49]. Recently, MFA research has gradually shifted to dynamic flow analysis, aiming to explore the law of material flow. For example, MFA is widely used in e-waste management[21,50], environmental pollution for circular economy[51,52], construction stock and waste recycling, prediction of major metal supply and demand, as well as the environmental impact[9,38], sustainable development of agriculture-food-waste[8], and research related to CO_2 emissions[53-55].

Especially under the vision of carbon neutrality, MFA has played an important role in quantifying carbon emissions. According to the trend publications of MFA research in the previous section, it mainly showed a

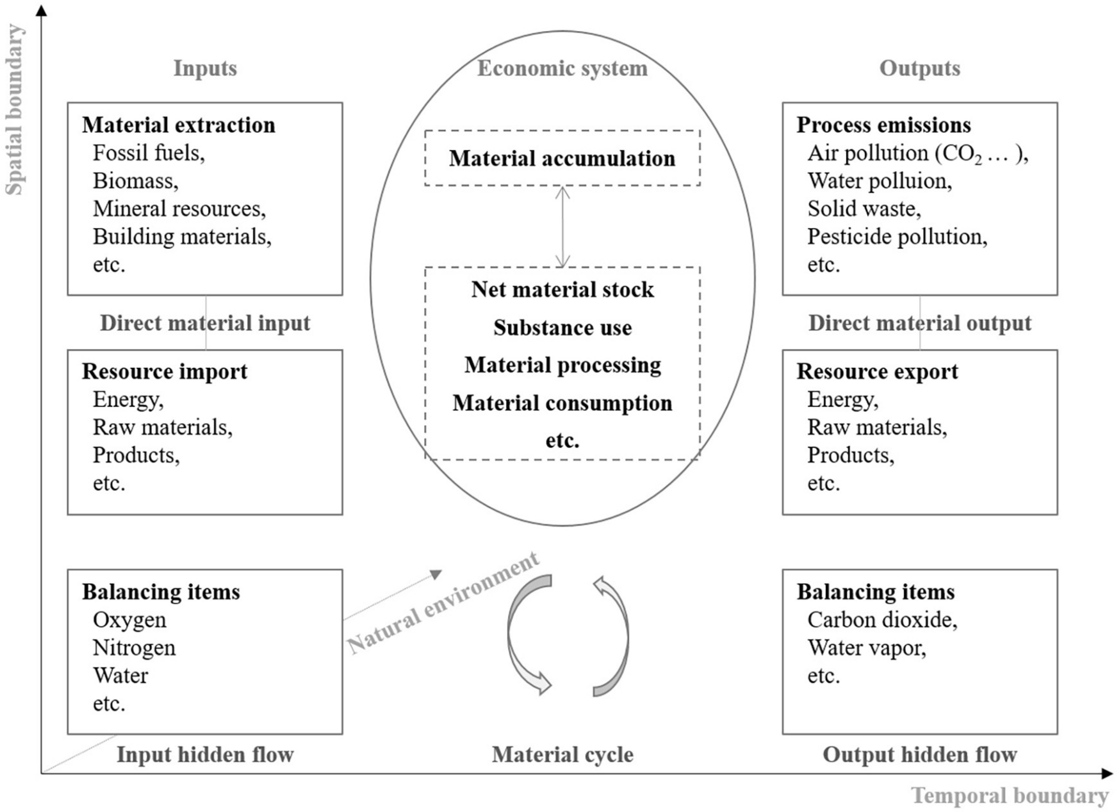
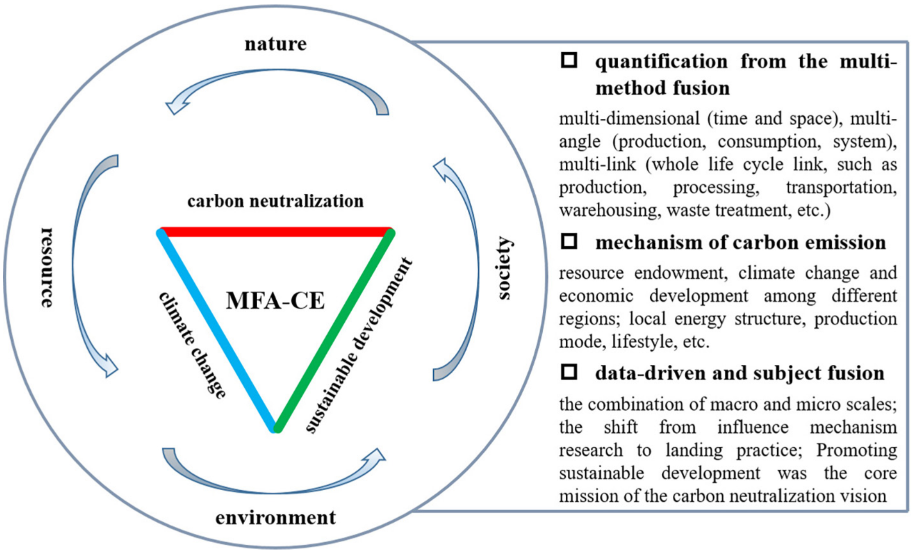


Figure 10. The framework of MFA research.

fluctuating upward trend. MFA-CE research focused on the core issues such as carbon emissions, climate change, and sustainable development. The quantification of carbon emission based on MFA is still one of the hot topics in future academic research. Such studies not only focus on how to accurately quantify carbon emissions, but also on finding effective ways to reduce emissions and achieve carbon neutrality. From a research methodology perspective, careful consideration of life cycle assessment[14], input-output analysis method[56], and MFA multi-method fusion evaluation could effectively avoid duplication and omission of the calculation content, which was suitable for evaluations of various scales, enhancing the accuracy and applicability of the results. From the perspective of research content, MFA focused on the evaluation of carbon emission characteristics. Researchers analyzed the emission characteristics from different scales (global, national, regional, and city), different fields (energy, construction, transportation, agriculture, *etc.*), and different links (production, consumption, waste treatment, *etc.*)[53,54,57-60]. These multi-level, multi-field, and multi-link studies will reveal the complexity and diversity of carbon emissions and provide a scientific basis for formulating effective emission reduction strategies. For example, Tan *et al.* pointed out that the functions of MFA in accounting, evaluation, and management can provide decision-making reference for the choice of carbon neutrality realization path[60].

Future research perspectives of MFA-CE

Based on the previous research, we summarized the following three research perspectives of MFA-CE research, as shown in Figure 11. Firstly, carbon emission quantification from the perspective of multi-method fusion deserves urgent attention. MFA, also known as socio-economic metabolic analysis, systematically evaluates the material stock and flow in the socio-economic system according to the law of conservation of mass, which is suitable for different scales of household metabolic accounting. Its primary



☐ **quantification from the multi-method fusion**

multi-dimensional (time and space), multi-angle (production, consumption, system), multi-link (whole life cycle link, such as production, processing, transportation, warehousing, waste treatment, etc.)

☐ **mechanism of carbon emission**

resource endowment, climate change and economic development among different regions; local energy structure, production mode, lifestyle, etc.

☐ **data-driven and subject fusion**

the combination of macro and micro scales; the shift from influence mechanism research to landing practice; Promoting sustainable development was the core mission of the carbon neutralization vision

Figure 11. Future research perspectives of MFA-CE.

advantage lies in analyzing changes in carbon flow and its environmental load throughout the production and consumption processes. It was suitable for the micro level, and most of them were analyzed by survey data or experimental data, which brought challenges to multi-scale and long-scale macro analysis. Considering multi-dimensional (time and space), multi-angle (production, consumption, system), and multi-link (whole life cycle link, such as production, processing, transportation, warehousing, waste treatment, *etc*.), the key scientific issue of carbon emission quantification with multi-method integration needed to be solved urgently.

Secondly, it was necessary to strengthen the research on carbon emission mechanisms from a multi-scale perspective. The comparative study of carbon emissions in multi-scale space provided data support and scientific support for carbon management, which became one of the main development trends in this research field[61]. There were significant differences in resource endowment, climate change, and economic development among different regions, which had different effects on local energy structure, production mode, lifestyle, *etc*., resulting in significant differences in carbon emissions[62]. It required a combination of IPAT (impact, population, affluence, and technology), EKC (Environment Kuznets Curve), KAYA identity (an index decomposition analysis), and other theoretical foundations, analyzed its specific influencing factors, and scientifically judged its key mechanism[55,63,64]. It would help to determine the future development path of carbon emissions, so as to provide scientific reference for formulating reasonable emission reduction schemes.

Thirdly, MFA-CE research needs to focus more on data-driven approaches and the integration of various subjects. Methodologically, more attention should be given to the combination of macro and micro scales, and there should be a stronger emphasis on the shift from theoretical research on influence mechanisms to practical implementation. Promoting sustainable development remains central to the vision of carbon neutrality[65]. Currently, MFA-CE research faces limitations related to data availability, accuracy, and consistency, relying heavily on assumptions and parameter estimates during the evaluation process, which introduces uncertainty into carbon emission accounting. Future research should prioritize enhancing data quality and accuracy while fostering interdisciplinary research and collaborative governance.

Limitations

On the one hand, there is inherent uncertainty within MFA research itself. Driven by the goal of carbon neutrality, MFA has proven to be an effective method for resource management, environmental protection, and sustainable development. However, current MFA research still faces many challenges, notably in data acquisition and quality control, complex system modeling, and interdisciplinary cooperation[66]. Additionally, in the modeling of complex systems, MFA research presents a set of difficulties. MFA encompasses multiple scales, from micro to macro, and establishing effective relationships between these scales remains a major issue[8-11]. Furthermore, MFA requires knowledge not only from engineering and environmental science but also from economics, sociology, and other disciplines. Interdisciplinary cooperation thus remains a major bottleneck in MFA research[39,55]. On the other hand, this study itself has some limitations. Although it analyzed the research landscape, hotspots, and some future trends in MFA and MFA-CE, certain areas for improvement remain. For example, future research should aim to expand the database to include papers in non-English languages. Moreover, as MFA research and its application in carbon emissions continue to evolve, new directions and technological breakthroughs are likely to emerge.

CONCLUSION

Both MFA and MFA-CE research exhibited similar article characteristics. They both followed consistent global publication trends, showing various degrees of exponential growth from 1991 to 2022. Additionally, research in both areas saw dominance from the USA in the early stage and China in the later stage, which correlates with the environmental and climate policies of those periods. For instance, with the establishment of international carbon neutrality targets, MFA has become one of the main methods to evaluate carbon emissions, leading to a rise in related research. Furthermore, the top 10 institutions in this field were mainly located in developed countries, such as the USA, Japan, Austria, and Norway, with the exception of China. The Chinese Academy of Sciences, Tsinghua University, and Yale University were the top 3 institutions in both MFA and MFA-CE research during the study period. Moreover, publications on MFA and MFA-CE research were mainly concentrated in journals such as Resources Conservation and Recycling, Journal of Cleaner Production and Journal of Industrial Ecology, whether considering the total number of publications or the strength of their association.

From the analysis of research areas, both MFA and MFA-CE are recognized as multidisciplinary fields. Between 1991 and 2022, the proportion of the top 10 subject categories in these fields accounted for over 85% of all publications, reflecting a significant advantage. The related disciplines primarily focused on various research fields, including Environmental Sciences, Engineering, Green & Sustainable Science & Technology, and Environmental Studies. Notably, the research in Environmental Studies and Economics related to MFA and MFA-CE grew the most rapidly, with increases ranging from 2.79 to 4.83 times during the periods 2004-2013 and 2014-2022, respectively.

The highly cited papers mainly focused on global material flow (including mineral resources, food resources, *etc.*), environmental impact (including environmental pollution and greenhouse gas emissions), and recycling. However, according to the WoS database, there are only 7 highly cited papers on MFA research and 3 on MFA-CE research. No highly cited articles were published before 2014, indicating that both MFA and MFA-CE research have received substantial attention only after 2014.

The combined use of MFA and other methods can enhance the identification of material flows, such as carbon material flows. As a prominent method in the field of carbon emissions, MFA is increasingly applied in the pursuit of carbon neutrality. For example, from 1991 to 2022, 58.22% of MFA-related publications focused on carbon emissions. MFA, a socio-economic metabolic analysis tool, systematically assesses the material stock and flow in the socio-economic system based on the law of conservation of mass. In the research of MFA-CE, the main advantage of MFA lies in analyzing changes in carbon material flows at a micro level. However, most related studies rely on specific research or experimental data, which can complicate multi-scale and long-term macro analysis of carbon emissions. Additionally, methods such as life cycle assessment and input-output analysis have emerged in keyword clusters and frontier subjects, highlighting that multi-method integration is crucial for identifying material flows.

Based on the previous research, three key research perspectives for MFA-CE research have been summarized: Firstly, there is a pressing need for better quantification of carbon emissions through multi-method fusion. Secondly, research on the mechanisms of carbon emissions requires strengthening from a multi-scale perspective. Thirdly, MFA-CE research should focus more on data-driven approaches and interdisciplinary integration.

DECLARATIONS

Authors' contributions

Conceptualization, methodology, visualization, writing and revising the manuscript: Liu L, Qu J
Resources, conceptualization, investigation, methodology: Li X, Liao Q, Niu Y

Availability of data and materials

The data presented in this work are available upon reasonable request from the corresponding author.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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