A literature review of textile industry carbon emissions research: research hotspots, themes and emerging trends

DOI: 10.35530/IT.077.02.202596

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ABSTRACT – REZUMAT

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As global climate change issues became increasingly severe, the textile industry, characterised as a high-energy consumption and high-emission sector, attracted widespread attention regarding its carbon emission challenges. Exploring the current status of textile industry carbon emissions and identifying emission-reduction pathways has emerged as a prominent focus in environmental science research. To understand the research status of textile industry carbon emissions and clarify the research trajectories and future directions of textile carbon reduction, this study employed bibliometric methods, utilising literature on textile industry carbon emissions from the Web of Science database (2005–2025) as the analytical subject. CiteSpace visualisation software was used to analyse the research domains and core content of textile industry carbon emissions over 20 years. Through examining citation frequencies, the study assessed research hotspots in textile industry carbon emissions and predicted development trends in textile carbon reduction research. The research findings indicated that since 2012, the volume of research on textile industry carbon emissions has demonstrated exponential growth. Research outcomes were predominantly published in environmental science and sustainability journals, whilst traditional textile journals exhibited lower publication volumes, suggesting that interdisciplinary and multidisciplinary research in textile industry carbon emissions remained relatively weak, with research quality requiring improvement. The development of clean production technologies and circular economy models influenced and promoted the green transformation of the textile industry, leading the direction towards a low-carbon textile era.

Keywords: *textile industry, carbon emissions, carbon footprint, visualisation analysis, low-carbon textile era*

O analiză a literaturii de specialitate privind cercetarea emisiilor de carbon din industria textilă: domenii de interes, teme și tendințe emergente

Pe măsură ce problemele legate de schimbările climatice la nivel global au devenit din ce în ce mai grave, industria textilă, caracterizată ca fiind un sector cu consum energetic ridicat și emisii semnificative, a atras o atenție sporită în ceea ce privește provocările legate de emisiile de carbon. Analizarea situației actuale a emisiilor de carbon din industria textilă și identificarea căilor de reducere a emisiilor au devenit un punct central al cercetării în domeniul științelor mediului. Pentru a înțelege stadiul cercetării privind emisiile de carbon din industria textilă și pentru a clarifica traiectoriile de cercetare și direcțiile viitoare ale reducerii emisiilor de carbon din industria textilă, acest studiu a utilizat metode bibliometrice, folosind literatura de specialitate privind emisiile de carbon din industria textilă din baza de date Web of Science (2005–2025) ca subiect de analiză. Software-ul de vizualizare CiteSpace a fost utilizat pentru a analiza domeniile de cercetare și conținutul principal al emisiilor de carbon din industria textilă pe o perioadă de 20 de ani. Prin examinarea numărului de citări, studiul a evaluat punctele de interes ale cercetării privind emisiile de carbon din industria textilă și a prevăzut tendințele de dezvoltare ale cercetării privind reducerea emisiilor de carbon din industria textilă. Rezultatele cercetării au indicat că, începând cu 2012, volumul studiilor de cercetare privind emisiile de carbon din industria textilă a înregistrat o creștere exponențială. Rezultatele cercetării au fost publicate în principal în reviste de științe ale mediului și de sustenabilitate, în timp ce revistele tradiționale din domeniul textil au înregistrat un volum mai redus de publicații, ceea ce sugerează că cercetarea interdisciplinară și multidisciplinară privind emisiile de carbon din industria textilă a rămas relativ redusă, calitatea cercetării necesitând îmbunătățiri. Dezvoltarea tehnologiilor de producție ecologice și a modelelor de economie circulară a influențat și a promovat transformarea ecologică a industriei textile, orientând-o către o eră a textilelor cu emisii reduse de carbon.

Cuvinte-cheie*: industria textilă, emisii de carbon, amprenta de carbon, analiza vizualizării, era textilelor cu emisii reduse de carbon*

INTRODUCTION

Carbon emissions from manufacturing industries have become an important area of focus within global climate change research [1–3], with the textile sector receiving increasing attention due to its significant environmental footprint, encompassing production process carbon emissions, product life cycle carbon footprints, clean production technologies, carbon reduction strategies, and green supply chain management [4]. Identifying and analysing textile industry carbon reduction research pathways to achieve green transformation and sustainable development of the textile industry represented a critical issue in the current global transition of the textile industry from high-carbon emissions to low-carbon development stages [5, 6]. Textile industry carbon emissions management proved essential for both industrial green upgrading and environmental protection [7]. Following nearly four decades of development, textile industry carbon emissions research has established a relatively comprehensive research framework [8, 9]. As global climate change pressures intensified and environmental policies became increasingly stringent [10–12], the textile industry needed to undergo technological transformation to address carbon reduction and green development challenges [13–15]. Within this context, textile enterprises, research institutions, and related organisations were required to appropriately utilise carbon emissions management approaches to reduce environmental impacts, enhance green competitiveness, and address climate risks [16–18]. Teixeira (2025) highlighted the importance of financial mechanisms and policy instruments in supporting industrial decarbonization efforts [19], while Li (2025) further demonstrated that green credit policies can significantly influence the corporate value of high-polluting enterprises [20]. These findings provide valuable insights for the textile industry's carbon management and inter-regional collaboration.

In the practical application of the textile industry carbon reduction, numerous technological approaches were employed to improve the environmental performance of textile manufacturing, including carbon footprint accounting and clean production technologies [21, 22]. Among these, carbon emissions monitoring technology was recognised as an important means for enhancing textile industry environmental management and served as the technological foundation for achieving the green transformation of the textile industry [23, 24]. Advanced technologies, including artificial intelligence, have shown promising potential in enhancing industrial sustainability and emission monitoring [25], offering new opportunities for precision carbon management in textile manufacturing. Furthermore, the waste-to-energy-coupled systems investigated by He and Qu (2025) provide a strategic framework for textile industrial parks to improve grid resilience and energy efficiency by converting manufacturing by-products into sustainable power for these high-demand digital infrastructures [26].

Literature analysis serves as an important approach for investigating carbon emissions development in manufacturing sectors and constitutes a tool for understanding the frontiers of industrial carbon reduction research. Through literature analysis, the research status of the textile industry carbon emissions field could be understood, future development trends predicted, and related fields explored and developed [27]. In literature research, the emergence or decline of various publications was consistently related to breakthroughs achieved in the field or significant events occurring in related areas. For instance, the signing of the Kyoto Protocol in 1997 directly promoted the development of carbon emissions research, leading to the emergence of substantial research related to carbon accounting and emission reduction technologies in the textile carbon emissions field, with research outcomes proliferating continuously. Similarly, the signing of the Paris Agreement in 2015 promoted research in areas such as low-carbon textiles, green manufacturing, and circular economy, with extensive textile industry carbon emissions research related to climate change response and green development emerging.

As carbon peak and carbon neutrality goals were implemented more deeply, the volume of related literature continued to grow and became increasingly diversified [20, 28, 29]. These phenomena clearly demonstrated that literature analysis could effectively capture hotspot issues in textile industry carbon emissions research and provide effective pathways for addressing current environmental problems [30]. Within environmental science and sustainable development research fields, the textile industry's carbon emissions represented an important discipline that combined environmental theory with practical applications. Textile industry carbon reduction constituted an important research area within environmental science. Unlike traditional environmental research, Hasanbeigi and Price (2015) noted that modern textile industry carbon emissions research relied more heavily on developments in environmental science, data science, and clean technologies [31]. Facing complex textile supply chains and diverse emission reduction requirements, the textile industry's carbon emissions management could be optimised through precise and systematic approaches [32]. Based on carbon data analysis, various environmental problems could be diagnosed, providing optimal solutions for textile enterprises to reduce carbon emissions, improve environmental performance, and enhance green competitiveness.

Due to the rapid development of computers and the internet, bibliometrics has experienced substantial advancement and has been widely applied in disciplines including environmental science, sustainable development, clean production, carbon management, and climate change [33]. Rousseau and Rousseau (2021) employed bibliometric indicators, utilising improved journal impact factor hierarchical regional assignment methods whilst introducing contribution rate indicators for differently ranked authors, establishing mathematical models for quantitative evaluation of textile industry carbon emissions papers [34]. This provided a new evaluation method for textile industry environmental management work that could complement peer review processes. Daraio and Bonaccorsi (2017) comprehensively investigated the developmental status of textile industry environmental impact fields, providing comprehensive descriptions of textile industry carbon emissions research fields through combined quantitative and qualitative research methods [35]. Moazzem et al. (2021) employed bibliometric methods to examine and analyse the development of textile industry life cycle assessment research [36]. Through basic statistical analysis and co-citation network analysis of literature samples, they discovered that the latest hotspots in textile industry carbon emissions research concentrated on carbon footprint assessment and green supply chains, effectively demonstrating the characteristics of textile industry carbon emissions research through bibliometric approaches [37–39]. This clearly indicated that bibliometrics represented a continuously developing literature analysis method that was widely welcomed by scholars in the textile industry and environmental science.

DATA SOURCES AND RESEARCH METHODS

Data sources

All data utilised in this study were derived from the Web of Science Core Collection (SCI-E and SSCI). The data retrieved from the platform primarily comprised abstracts, keywords, citations, authors, research institutions, countries and regions, and download records of papers related to carbon emissions in the textile industry. It should be particularly noted that when downloading and analysing the data, the data from Hong Kong and Taiwan were not merged with mainland China's data for analysis, but were instead analysed separately by classification. A total of 349 data records were downloaded, with the data acquisition date being 27 June 2025.

Research methods

This study was based on bibliometric methods, primarily utilising CiteSpace literature data visualisation software developed by Drexel University in the United States for analysis. Following the approach established by Merigó et al. (2015) [40], the specific analytical methodology for this research was constructed as follows:

Search terms: "textile carbon emissions" OR "textile industry carbon footprint" OR "carbon emissions textile" OR "textile sustainability carbon"; Time period: "2000–2025"; Data source: Web of Science. CiteSpace's relationship strength algorithms primarily include the Cosine algorithm, Jaccard algorithm, and Dice algorithm, as detailed below:

Cosine algorithm:

$$\text{Cosine}\,(c_{ij}, s_i, s_j) = \frac{c_{ij}}{\sqrt{s_i s_j}} \tag{1}$$

Jaccard algorithm:

$$\text{Jaccard}\,(c_{ij}, s_i, s_j) = \frac{c_{ij}}{s_i + s_j - c_{ij}} \tag{2}$$

Dice algorithm:

$$\text{Dice}\,(c_{ij}, s_i, s_j) = \frac{2\,c_{ij}}{s_i + s_j} \tag{3}$$

Studies typically use the Cosine algorithm, which normalises the values between 0 ~ 1, with c_{ij} being the number of occurrences of i and j, s_i being the number of occurrences of i, and s_j being the number of occurrences of j, and which can be expressed based on the generalised similarity index as follows:

$$s_G(c_{ij}, s_i, s_j, 1) = \frac{2\text{Jaccard}\,(c_{ij}, s_i, s_j)}{\text{Jaccard}\,(c_{ij}, s_i, s_j) + 1} = \text{Dice}\,(c_{ij}, s_i, s_j) \tag{4}$$

In this paper, we use Cite Space software to implement these similarity algorithms and analyse them computationally using both inter- and intra-time slices.

REVIEW OF TEXTILE CARBON EMISSIONS RESEARCH

Trends in the number of textile carbon emissions research publications

According to figure 1, which presents a time series analysis of the annual publication volume in textile industry carbon emissions journals (2000–2025), the temporal trends in publication numbers (2000–2025) could be constructed. Several important characteristics were observed from the graph:

- Developmental stage characteristics: Embryonic period (2000–2012): Research commenced relatively late, with extremely limited publication volumes. The annual number of published papers remained essentially between 0 and 3 articles, indicating that this field had not yet received widespread attention from the academic community.
- Gradual growth period (2013–2018): Publication volumes began to increase, growing progressively from 2 articles in 2013 to 12 articles in 2018. The annual growth remained relatively modest, reflecting emerging research interest in the field.
- Rapid development period (2019–2024): Publication volumes experienced explosive growth, particularly escalating rapidly from 12 articles in 2019 to a peak of 69 articles in 2024. This period demonstrated the most significant growth, with 48 articles published in 2021 and reaching a historical high point in 2024.
- Decline and adjustment period (2025): Publication volumes decreased to 44 articles, which may have been related to the data collection timepoint or reflected a natural adjustment in research intensity.
- Overall trend analysis: The general pattern exhibited exponential growth, particularly with accelerated growth after 2019. This trend was closely related to increased global attention to climate change, the establishment of carbon neutrality targets, and heightened policy and academic attention towards the textile industry as a high-energy-consuming and high-pollution sector. The rapid increase in research intensity reflected the growing importance and urgency recognised in this field.

Analysis of author collaboration and co-citation networks

The examination of author collaboration networks is a critical approach for assessing research capabilities and evaluating the development of an academic

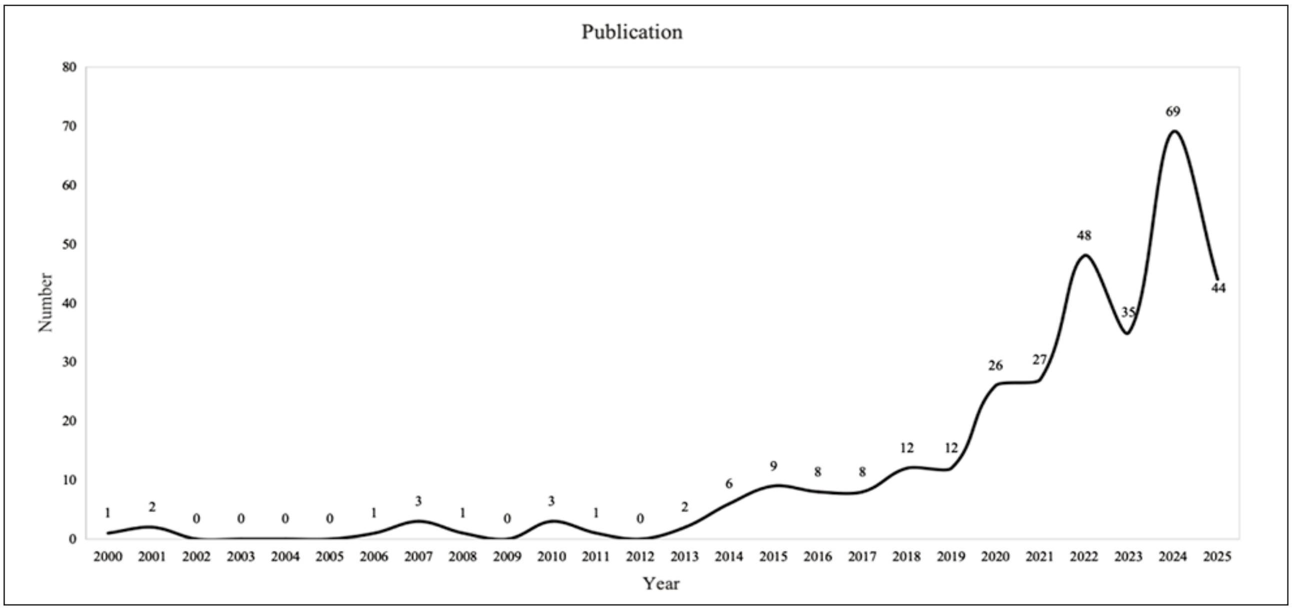

Fig. 1. Annual publication trend

field. Based on the visualisation of author collaboration networks generated using CiteSpace software (time span: 2005–2023), the following salient characteristics were observed within the field of carbon emissions in the textile industry:

• Characteristics of core collaborative groups: The network diagram revealed the formation of several distinct collaborative groups within this research domain. Most notably, a prominent collaboration network centred around Nimtmaki K (2020) was identified, positioning this scholar at the core of the network with numerous intensive cooperative ties. Similarly, researchers such as Li Lin G (2018), Peters G (2021), and Cheng Y (2021) emerged as key nodes of collaboration, constituting the primary research force in the field.

• Temporal evolution: The time-labelled nodes indicated a clear temporal evolution of the collaboration network. In the early phase (2012–2017), cooperation was predominantly centred around scholars such as Dahlbo H (2017) and Kanemoto K (2012). In the more recent period (2020–2023), the network expanded to include researchers such as Nimtmaki K, Luo Y (2022), and Chen S (2023), thereby forming a more complex and densely connected collaborative structure. This trend reflected the rapid development of the field and the deepening of academic cooperation.

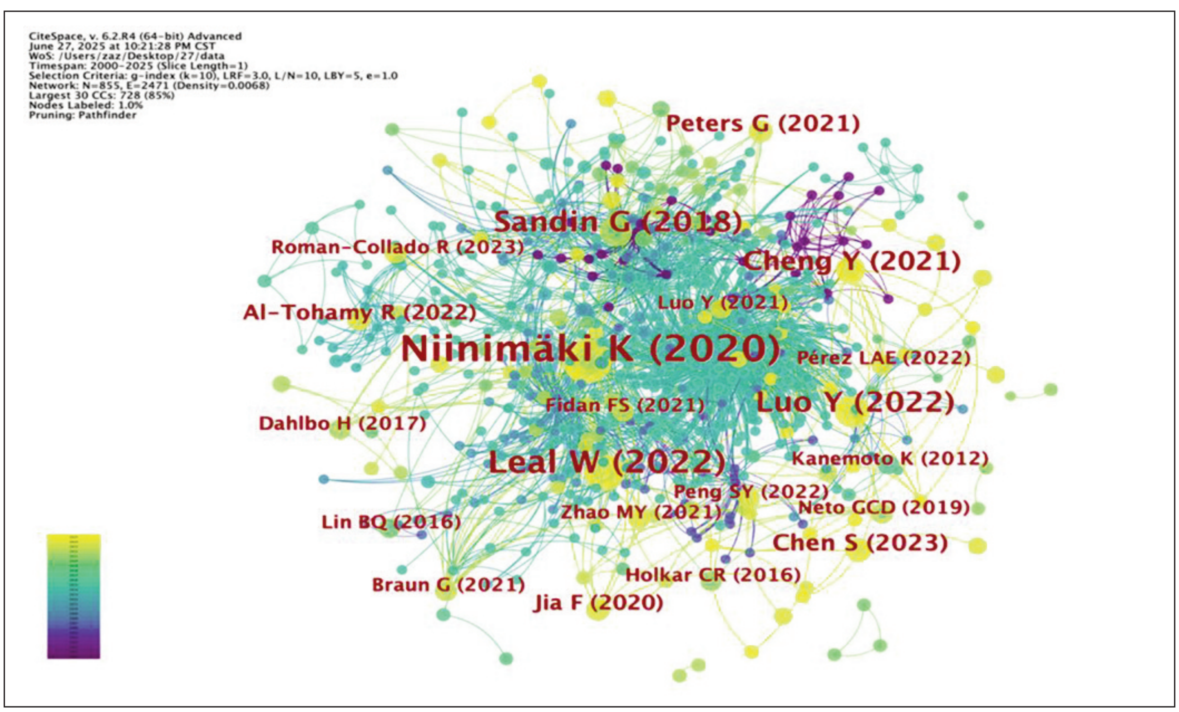

Fig. 2. Co-citation network of references

• Network density: The visualisation demonstrated a relatively high connection density, suggesting that collaboration among scholars in this domain was active. In particular, a highly interconnected research cluster centred on Nimtmaki K was evident in the core area of the network. Dense linkages among these nodes reflected frequent academic exchanges and cooperation. Additionally, scholars such as Roman-Collado R (2023) and Al-Tohamy R (2022) maintained multiple connections with the core network, further contributing to its cohesion.

• Distribution of research groups: Beyond the principal collaborative clusters, the network also exhibited a multi-layered structure. Scholars such as Peters G (2021), Luo Y (2022), and Leal W (2022) formed secondary collaboration centres that remained connected to the core network while maintaining relatively independent research orientations. On the periphery, researchers such as Holkar CK (2016) and Jia F (2020), although less connected, contributed to the diversity of research within the field.

• Overall assessment: The author collaboration network displayed a centralised structure with Nimtmaki K at its core, alongside a multi-centre, multi-layered distribution pattern. This suggested that the field of carbon emissions research in the textile industry had developed into a relatively mature international academic community. Core authors, through sustained collaborative efforts, made significant contributions to the theoretical development and practical applications in the field. Furthermore, the network's temporal progression clearly illustrated a trajectory from dispersed research efforts towards more centralised collaboration.

Prominent research themes based on keyword co-occurrence

The frequency of keyword co-occurrence provided a direct and effective means of illustrating the research areas and core content within a specific discipline. In this study, the keyword analysis function of CiteSpace was employed to construct a keyword co-occurrence network, thereby outlining the principal research hotspots in the field of carbon emissions within the textile industry. The knowledge domain map of the keyword co-occurrence network, generated by CiteSpace (parameters: time span 2000–2025; node type: keyword; network density: 0.0158), presented four major thematic clusters. These clusters centred on themes such as carbon emissions accounting, the impact of the textile industry, environmental assessment, and sustainable development.

Cluster #1 (Red Zone): Centred on the core nodes "carbon emissions" and "CO_2 emissions", this cluster predominantly encompassed research on the direct measurement and accounting of carbon emissions. Representative keywords included "greenhouse gas emissions", "carbon footprint", and "emissions". This cluster focused on the quantitative assessment and calculation methodologies related to carbon emissions in the textile industry, and represented the foundational core of research in this domain.

Cluster #2 (Green Zone): This cluster was organised around the core node "textile industry", linking keywords such as "textile", "consumption", "international trade", and "environmental impact". It emphasised systemic research across the textile value chain, highlighting carbon emissions throughout the entire process from production to consumption. This reflected the complexity of the textile industry as a globalised sector.

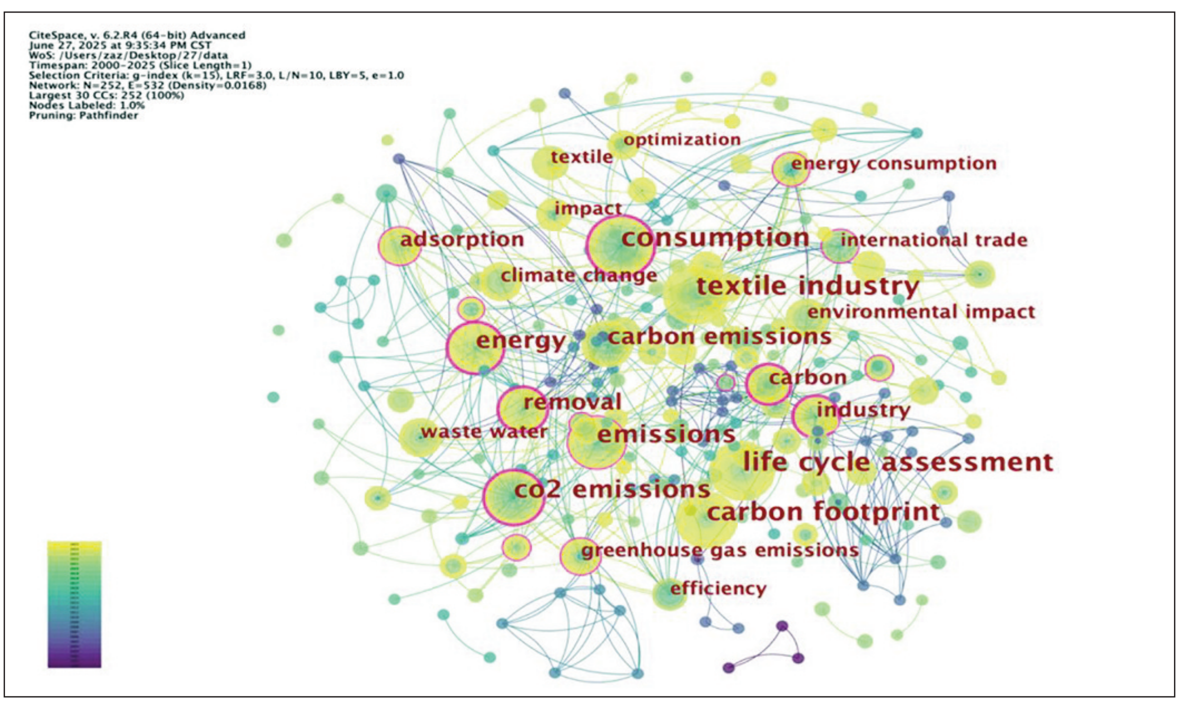

Fig. 3. Keyword co-occurrence map

Cluster #3 (Blue Zone): Centred on "life cycle assessment", this cluster represented the methodological direction of environmental evaluation. Key associated terms included "impact", "industry", "energy consumption", and "efficiency". The cluster underscored system-level approaches to environmental assessment and highlighted studies on the environmental footprint of the textile sector from a full life cycle perspective.

Cluster #4 (Yellow Zone): With "climate change" and "optimisation" as its central nodes, this cluster encompassed topics related to climate change mitigation, wastewater treatment, removal technologies, and adsorption processes. It reflected a shift in textile industry carbon emission research towards solution-oriented approaches and sustainable development strategies.

Interdisciplinary integration: The network diagram revealed dense interconnections among the clusters. Notably, the node "energy" functioned as a critical bridging point linking multiple clusters, underscoring the central role of energy consumption in the field of textile carbon emissions. In addition, the central positioning of nodes such as "consumption" and "environmental impact" highlighted the importance of end-user behaviour and environmental evaluation in this research area.

Overall assessment: The keyword co-occurrence network demonstrated a clear shift in textile industry carbon emissions research from singular emission accounting to integrated evaluations across the entire value chain and life cycle. The close interconnections among clusters further illustrated the interdisciplinary nature and systemic focus that had become characteristic of this evolving research field.

Keyword clustering analysis

Keywords represented the core content of academic publications and commonly occurring terms within a study. They provided an efficient and accurate means of understanding the primary focus of the literature, thereby serving as a crucial element in tracing the evolution of research on carbon emissions in the textile industry. This study conducted a keyword clustering analysis, as illustrated in the figure.

Using CiteSpace's clustering function, eleven primary research clusters were identified (parameter settings: modularity Q = 0.6736; mean silhouette score S = 0.8316), indicating a well-structured clustering outcome with high internal homogeneity.

The keyword clustering analysis revealed the current research hotspots and thematic directions in textile industry carbon emissions research, which mainly included the following key domains:

• Core research on carbon emissions: Cluster #0, labelled "carbon intensity", emerged as the largest cluster and was located at the centre of the network. This cluster primarily focused on the measurement of carbon intensity, accounting methodologies, and the assessment of emission reduction potential, reflecting the central concerns of this research field.

• Technological innovation and intelligent analysis: Clusters #1 "machine learning" and #2 "structural path analysis" reflected the extensive application of modern data analytics and econometric methods in textile carbon emission studies. These clusters represented the increasing trend toward technological sophistication and intelligent analysis in research methodologies.

• Environmental impact of chemicals and dyes: Cluster #3 "cationic dyes" highlighted environmental

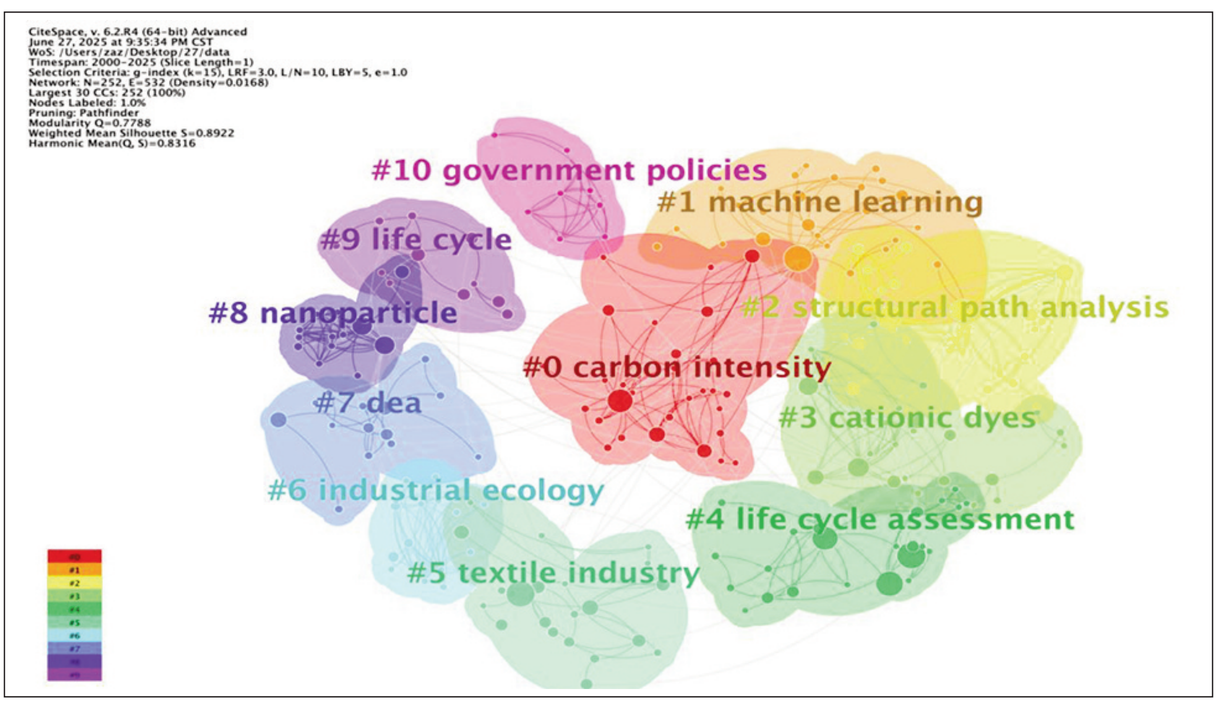

Fig. 4. Keyword clustering mapp

concerns related to the use of chemicals during textile production, indicating a research perspective focused on emission control at the production stage.

• Life cycle assessment approaches: Clusters #4 "life cycle assessment" and #9 "life cycle" emphasised the importance of systematic environmental assessment methods. These clusters illustrated a research orientation encompassing entire processes and supply chains, aligning with holistic sustainability principles.

• Industrial ecology and circular economy: Clusters #5 "textile industry" and #6 "industrial ecology" demonstrated a macro-level perspective on the textile sector's carbon emissions, concentrating on material and energy flows, as well as resource circulation between industries from an ecological systems viewpoint.

• Emerging technology applications: Cluster #7, "DEA (data envelopment analysis)" and cluster #8 ", nanoparticles" represented studies on efficiency assessment and the application of nanotechnology in the pursuit of low-carbon development within the textile industry.

• Policy and governance research: Cluster #10 "government policies" reflected investigations into the influence of policy frameworks on carbon emissions in the textile industry, underscoring the role of governance mechanisms in driving sectoral emission reductions.

The visualisation clearly depicted the research hotspots currently attracting scholarly attention. The spatial distribution and connection strength between clusters illustrated the interrelated nature of various research themes. It was evident that research on carbon emissions in the textile industry had increasingly focused on quantitative assessment, technological innovation, and policy governance. This indicated an interdisciplinary orientation combining theoretical inquiry with practical applications, and technical methods with policy tools. Moreover, it underscored the field's transition from examining isolated environmental impacts to pursuing a comprehensive and systemic approach to sustainable development.

Evolution of research hotspots and future trends

Based on the selection of "Keyword" as the node type and the use of the "Burstness" function in CiteSpace, the top 25 keywords with the highest burst intensities were identified, as shown in the figure. A higher burst intensity indicated a period of heightened academic activity and research interest. By analysing the temporal evolution of research hotspots in the field of textile industry carbon emissions between 2000 and 2025, distinct developmental stages and emerging trends were revealed.

• Initial exploration stage (2001–2014): During this period, research was primarily focused on foundational concepts and methodological development. "Energy consumption" began to surge in 2001 with a burst intensity of 2.02, continuing until 2017, which reflected the early interest in energy use within the textile sector. The keyword "reuse" exhibited a burst in 2008 with an intensity of 1.33, indicating the initial diffusion of circular economy concepts. "Consumption"

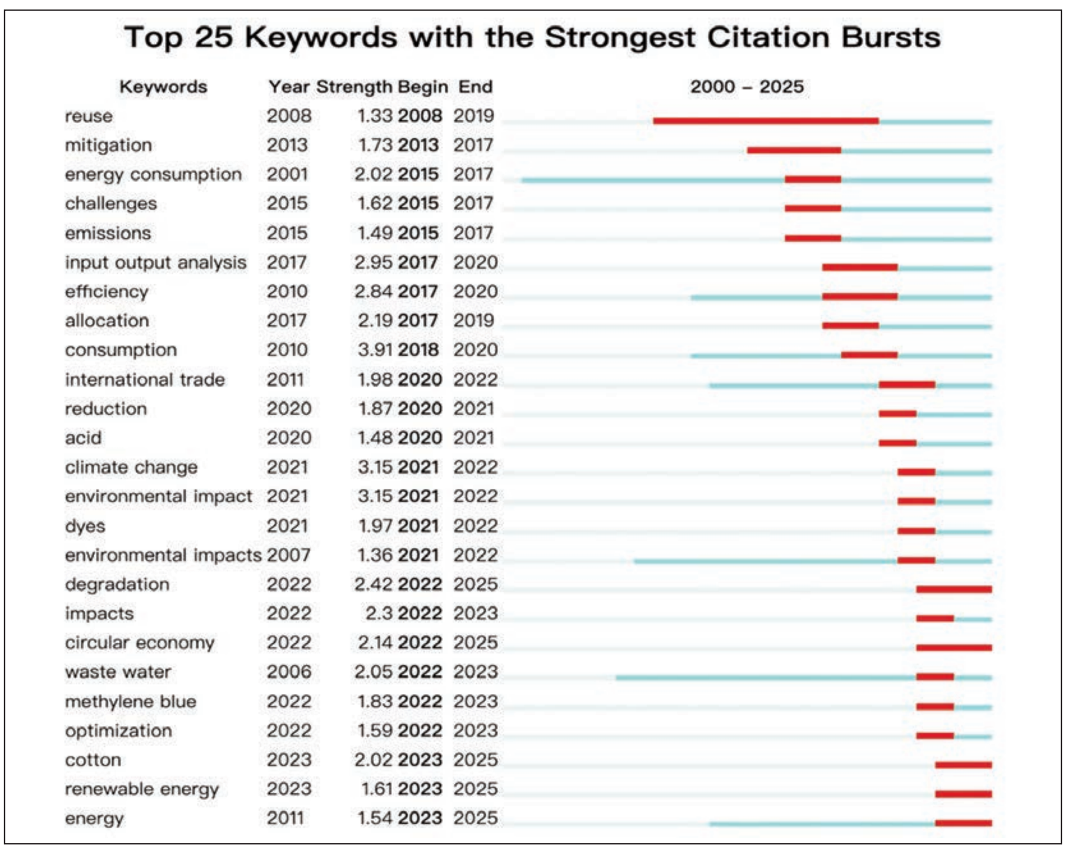

Fig. 5. Keyword burst map

surged in 2010 with a burst intensity of 3.91, signifying a research shift from the production side to consumption-related emissions.

• Rapid development stage (2013–2020): Between 2013 and 2020, keywords such as “mitigation”, “challenges”, “emissions”, “efficiency”, and “allocation” experienced notable bursts. Notably, “consumption” reached its highest burst intensity of 3.91 in 2018. “Input-output analysis” and “efficiency” both surged in 2017, with intensities of 2.95 and 2.84, respectively. Research during this period demonstrated increasing systematisation and methodological diversification, marking a transition from isolated issues to complex system-level analysis within the field.

• Mature development and frontier breakthrough stage (2020–2025): Post-2020, research hotspots reflected clear policy orientation and technological innovation. “Climate change” and “environmental impact” both experienced bursts in 2021, each with an intensity of 3.15, highlighting the influence of global climate policy on academic inquiry. The year 2022 represented a pivotal point, with simultaneous bursts in several keywords such as “degradation”, “circular economy”, “wastewater”, “methylene blue”, and “optimisation”. Among these, “degradation” recorded the highest burst intensity of 2.42, indicating growing interest in environmental remediation and waste management technologies.

• Emerging hotspots and future directions (2023-2025): Since 2023, research interests have increasingly centred on technological applications and sustainable development. “Cotton” and “renewable energy” began to surge in 2023, with burst intensities of 2.02 and 1.61, respectively, both projected to remain active through 2025. Although “energy” initially surged in 2011, it exhibited renewed interest in 2023, with a burst intensity of 1.54, reaffirming its persistent significance in textile-related carbon emission research.

Analysis of developmental trends: The overall evolution of research in this domain followed a trajectory from “problem identification” to “systemic analysis” and ultimately to “solution-oriented approaches”. Early studies emphasised energy consumption and waste treatment at individual production stages. The mid-stage progressed towards system-wide life cycle assessment and policy evaluation. In recent years, research has increasingly focused on technological innovation and the exploration of circular economy models. The simultaneous surge of multiple keywords post-2022 suggested a rapid maturation of the field and an urgent need for practical applications.

This evolutionary trajectory demonstrated that carbon emission research in the textile industry had transitioned from theoretical exploration to practical implementation. Future research was expected to place greater emphasis on integrated studies involving technological innovation, policy coordination, and industrial transformation. In particular, the integration of renewable energy, circular economy strategies, and intelligent emission reduction technologies was likely to remain at the forefront of academic inquiry in the years ahead.

Network analysis of core research institutions

In addition, this study conducted a clustering analysis of the core research institutions involved in the study of carbon emissions in the textile industry, as illustrated in the figure (parameter settings: modularity Q = 0.6736; average silhouette value S = 0.8316). The institutional collaboration network revealed a multipolar international research structure, predominantly centred in China, Europe, and North America. The network demonstrated clear geographical clustering and strong characteristics of transnational collaboration.

Chinese research cluster: The core institutions included Zhejiang Sci-Tech University, Donghua University, Jiangnan University, Xiamen University, Peking University, Minjiang University, and major research institutes such as the Chinese Academy of Sciences. These institutions formed a closely-knit collaborative network focused on carbon emission accounting, life cycle assessment, and emission reduction technologies in the textile industry. This underscored China’s leading role in environmental research within the global textile sector, reflecting its status as a major textile-producing country.

European research cluster: Centred around Nordic universities such as Aarhus University and Chalmers University of Technology, this cluster also included prominent institutions like the French National Centre for Scientific Research (Centre National de la Recherche Scientifique, CNRS). The European group demonstrated a distinct advantage in environmental policy analysis, sustainability assessment, and the study of the environmental impacts of international trade. This reflected the European Union’s leadership in environmental governance and sustainable development policy.

North American research node: The Lawrence Berkeley National Laboratory, under the United States Department of Energy, played a pivotal role in energy systems analysis and carbon emission modelling. This node highlighted North America’s research strength in environmental science and technological innovation.

Emerging research actors: Institutions such as Adana Alparslan Turkes Science & Technology University in Türkiye and Guangdong University of Technology in China represented the expanding international participation in this field. Their involvement illustrated the increasing engagement of emerging economies in global environmental research.

Transnational collaboration characteristics: The network visualisation revealed dense transnational linkages, with particularly close collaborations between China and Europe, as well as between China and the United States. The presence of multinational research frameworks, such as the National Institute of Technology (NIT) system, further illustrated the institutionalisation of international cooperation. This pattern of collaboration underscored the inherently

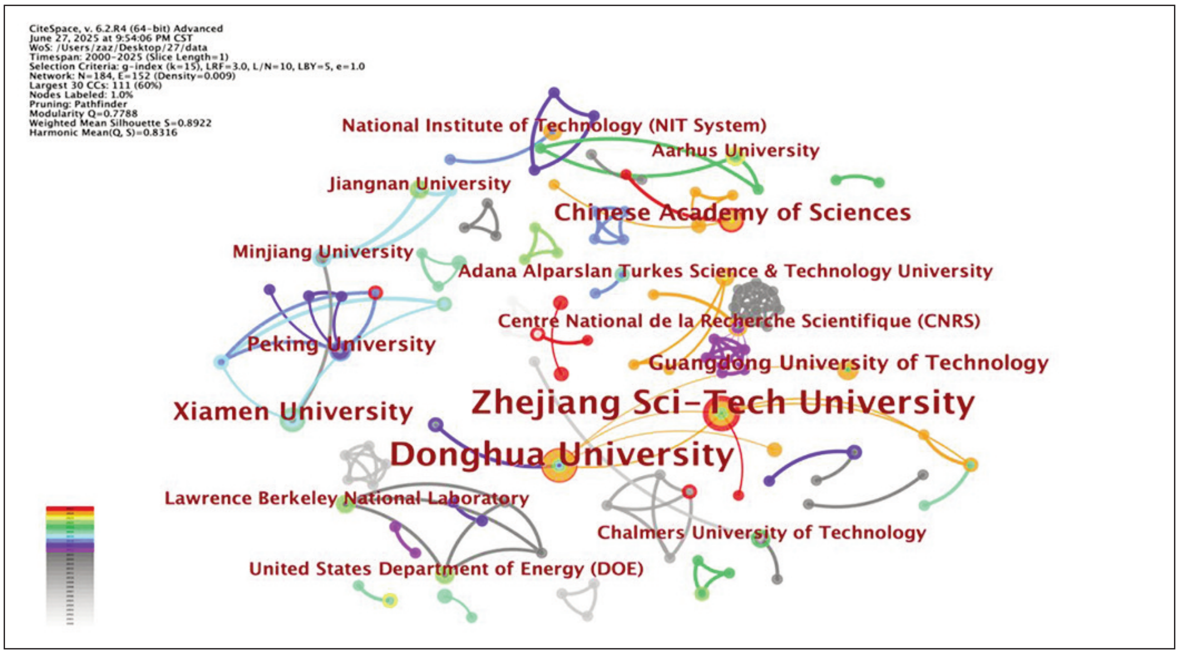

Fig. 6. Institutional collaboration map

global nature of textile industry carbon emissions and the necessity for coordinated international research efforts.

Integration of research and industrial application: The network encompassed both traditional academic institutions and industrial technology research platforms, highlighting the field's transition from theoretical exploration to practical implementation. The diversification of institutional partnerships provided crucial support for the industrial application of carbon reduction technologies in the textile sector.

In summary, the density and strength of connections within the network indicated the emergence of a relatively mature international collaborative system in textile industry carbon emission research. This framework offered a robust scientific foundation and cooperative platform to support the green transformation of the global textile industry and the achievement of carbon neutrality goals.

Timeline clustering analysis of keywords

This study also conducted a timeline clustering analysis of key information, resulting in the visualisation shown in the figure. In bibliometric analysis, a timeline view illustrates the chronological development and interconnections among various research topics. The larger the co-citation cluster, the higher its centrality within the network. The timeline diagram clearly depicted the evolutionary trajectory of research on carbon emissions in the textile industry from 2000 to 2025, as well as the developmental pathways of major research themes.

As shown in the figure, clusters #0 to #4 exhibited the highest centrality. These clusters corresponded to carbon intensity, machine learning, structural path analysis, cationic dyes, and life cycle assessment, respectively. These topics maintained high levels of academic attention throughout the entire time period, indicating their foundational role in shaping the core content and methodological approaches of textile industry carbon emission research.

• Early exploration stage (2000–2010): Research during this phase primarily focused on the establishment of fundamental concepts and the identification of key problems. Core topics included energy consumption, greenhouse gas emissions, and CO_2 emissions. The importance of carbon intensity began to emerge during this period, laying the groundwork for subsequent in-depth studies. Environmental management topics such as wastewater removal also attracted early attention.

• Methodological development stage (2010–2018): Specialised methodological approaches such as life cycle assessment and structural path analysis became increasingly mature, resulting in a more comprehensive analytical framework. Systemic research themes, including consumption, international trade, and carbon emissions, were significantly developed. The introduction of machine learning techniques marked a technological upgrade in methodological applications within the field.

• System integration stage (2018–2022): This period saw the emergence of integrated research themes, such as the textile industry, industrial ecology, and data envelopment analysis (DEA). Notably, concepts such as carbon footprint, environmental impact, and climate change experienced strong growth after 2020, reflecting a shift in the field towards system-oriented and policy-driven approaches.

• Frontier innovation stage (2022–2025): Emerging research topics such as circular economy, government policies, and optimisation demonstrated robust growth in recent years. Technological themes, including degradation and methylene blue, also appeared

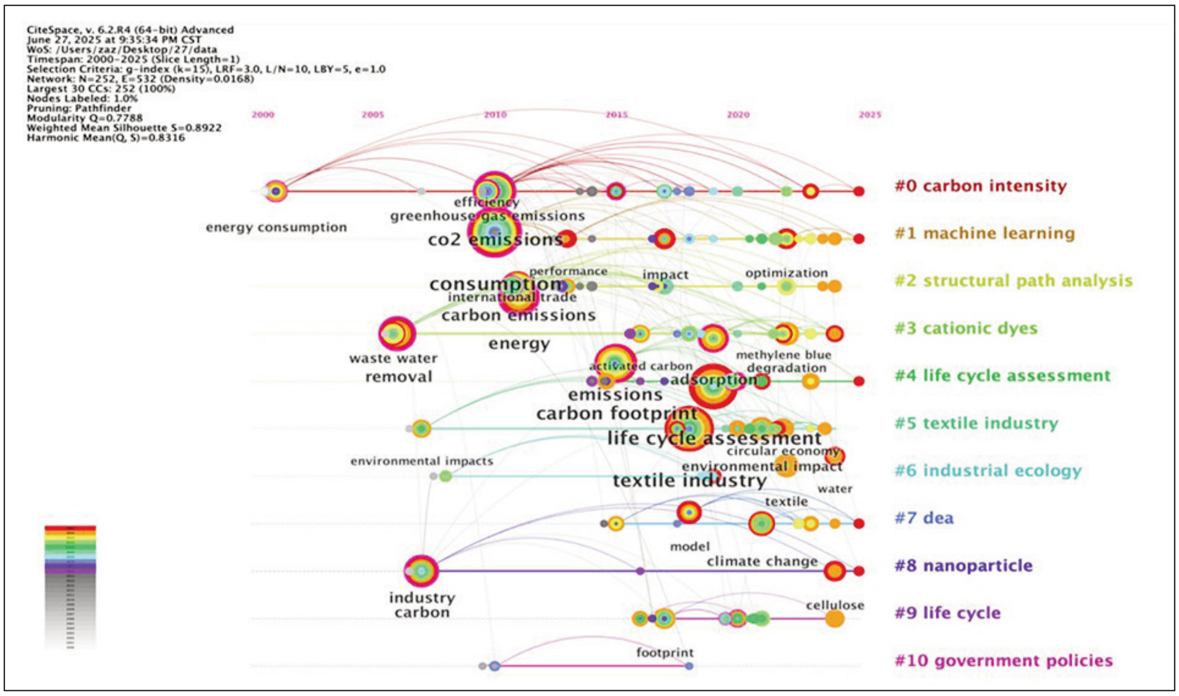

Fig. 7. Cluster timeline

during this stage, indicating a transition from theoretical research to technological application and innovation.

Cross-temporal persistent themes: Keywords such as textile, nanoparticle, and life cycle persisted throughout the entire study period, suggesting their sustained research value. In particular, life cycle research evolved from an early-stage methodological exploration into a central analytical framework underpinning the field.

Future research directions: Based on the trajectory shown in the timeline, it was anticipated that future research would focus on circular economy models, intelligent optimisation technologies, and collaborative policy mechanisms. These areas were expected to drive the evolution of carbon emission research in the textile industry from isolated environmental assessments towards integrated sustainable development solutions. Such advancements would provide a scientific foundation for promoting the green transformation of the textile sector and achieving carbon neutrality goals.

Analysis of disciplinary integration and interdisciplinarity

The study of carbon emissions in the textile industry involved extensive interdisciplinary integration. In this research, the CiteSpace software was used to generate a subject co-occurrence map to examine the connections between textile industry carbon emissions research and other academic disciplines, as illustrated in the figure. The dual-map overlay clearly demonstrated the interdisciplinary nature of this research area, highlighting the necessity of integrating multiple fields to achieve more comprehensive and robust outcomes.

In the figure, the coloured lines represent citation paths and knowledge flows among various disciplines. The following disciplinary clusters showed the strongest associations with textile industry carbon emissions research:

- Engineering and technology cluster: This cluster originated from disciplines such as physics, materials science, and chemistry (#5 PHYSICS, MATERIALS, CHEMISTRY) and extended to areas including plant science, biology, genetics, genetic engineering, and biotechnology (#10 PLANT, BIOLOGY, GENETICS, BIOCHEMISTRY, BIOTECHNOLOGY), as well as environmental science, ecology, and geography (#11 ENVIRONMENTAL, TOXICOLOGY, NUTRITION). The concentration of knowledge flow in this cluster reflected the developmental trajectory from material science foundations to applications in biotechnology and environmental assessment within the textile sector.
- Medical and health cluster: Fields such as health sciences, nursing, and medicine (#6 HEALTH, NURSING, MEDICINE), along with dermatology, dentistry, and surgery (#9 DERMATOLOGY, DENTISTRY, SURGERY), contributed to the understanding of the impact of textile-related carbon emissions on human health. This was particularly evident in research concerning occupational health and environmental health risk assessment.
- Economic and management cluster: The intersection of psychology, education, health, and sociology (#7 PSYCHOLOGY, EDUCATION, HEALTH, SOCIAL) highlighted the socio-economic dimensions of textile carbon emissions research. This included investigations into consumer behaviour, policy-making, and social impact assessments, underscoring the need for research that addresses broader societal implications.

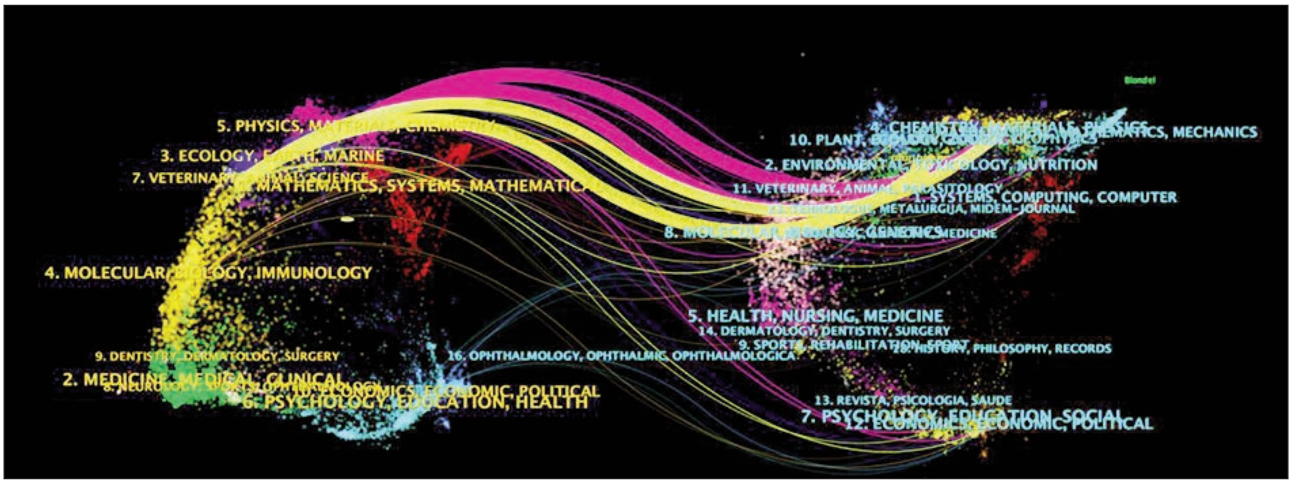

Fig. 8. Journal dual-map overlay

• Ecological and environmental cluster: This cluster included ecology, earth sciences, and marine sciences (#3 ECOLOGY, EARTH, MARINE), integrated with veterinary science and zoology (#8 VETERINARY, ANIMAL, SCIENCE). It represented comprehensive assessments of carbon emissions' impacts on ecosystems – spanning terrestrial, marine, and animal health perspectives.

• Molecular biology cluster: Disciplines such as molecular biology and immunology (#4 MOLECULAR, BIOLOGY, IMMUNOLOGY) provided essential theoretical foundations for exploring the biological mechanisms of textile-related carbon emissions, environmental toxicology evaluations, and the development of bioremediation technologies.

Knowledge flow characteristics: The figure revealed a clear trend of knowledge flow from foundational sciences to applied sciences and from isolated disciplines towards interdisciplinary integration.

Particularly notable was the active flow from core disciplines such as physics and chemistry to applied fields, including environmental science and biotechnology. This suggested a transition in carbon emission research within the textile industry from theoretical exploration to practical application.

In terms of disciplinary coupling strength, textile industry carbon emissions research exhibited the strongest associations with environmental science, materials science, and biotechnology. Connections with medical and health sciences, as well as social sciences, also continued to strengthen. This trend of multidisciplinarity reflects the complex nature of carbon emissions as an environmental issue, demanding integrated and holistic solutions. It also indicated that future research in this domain would increasingly prioritise cross-disciplinary collaboration and the application of systemic research methodologies.

CONCLUSION AND RECOMMENDATIONS

Based on a bibliometric analysis of textile industry carbon emissions research from 2000 to 2025, the field underwent a significant evolution from its nascent stage (2000–2012) to a period of rapid development (2019–2024). The volume of research increased dramatically after 2019, rising from an annual average of fewer than three publications to a peak of 69 in 2024. This surge reflected the strong influence of global climate policies and carbon neutrality targets on academic research agendas.

The research focus experienced a profound paradigm shift, transitioning from early investigations centred on energy consumption and waste management to a systematic carbon footprint evaluation framework. Key thematic areas emerged, including carbon accounting methodologies, innovations in clean production technologies, the construction of circular economy models, and the management of green supply chains. Methodologically, the field evolved from traditional statistical approaches to the application of advanced techniques such as machine learning, data envelopment analysis, and structural path analysis.

The pattern of international collaboration revealed a multipolar structure, with China playing a leading role alongside significant contributions from Europe and North America. In China, institutions such as Zhejiang Sci-Tech University, Donghua University, Jiangnan University, and the Chinese Academy of Sciences formed robust research networks. European clusters, particularly those led by Aarhus University and Chalmers University of Technology, demonstrated strong capabilities in environmental policy analysis. Meanwhile, North American institutions contributed significantly to energy system modelling and technological innovation. The field exhibited a high degree of interdisciplinary integration, extending beyond environmental and materials sciences to intersect deeply with biotechnology, information science, economics, and sociology. This reflected the complex and multifaceted nature of carbon emissions in the textile industry and the necessity of comprehensive, interdisciplinary solutions.

The evolution of research hotspots followed a clear trajectory: beginning with the establishment of foundational concepts and issue identification, progressing to systemic life cycle assessment and policy analysis, and advancing in recent years toward technological innovation and the exploration of circular economy models. Notably, after 2022, there was a marked increase in research focused on circular economy, wastewater treatment, and optimisation technologies, indicating a pivotal shift from theoretical exploration to practical application.

Future research should prioritise the following directions:

• Based on the current research status and development trend of carbon emissions in the textile industry, the future research direction should focus on technological innovation and interdisciplinary integration: at the technical level, it is necessary to develop digital carbon management technology based on the Internet of Things, big data and artificial intelligence to achieve accurate carbon footprint tracking throughout the life cycle, and promote the research and development and application of low-carbon new materials such as bio-based fibers and recycled fibers and energy-saving and emission reduction dyeing and finishing processes; In terms of discipline integration, we should strengthen in-depth collaboration between environmental science, materials science, data science, economics and other disciplines, promote the cross-publication of traditional textile journals and environmental science journals, and improve the quality of cross-disciplinary research. At the level of supply chain optimisation, build a digital management platform for green supply chains based on blockchain technology, deepen the circular economy model, and explore the high-value utilisation of textile waste. In terms of policy and standardisation construction, establish a unified carbon emission accounting methodology and international standards for the textile industry, and design effective carbon emission reduction incentive mechanisms. In the cutting-edge application field, expand the research on carbon management on the consumer side, explore regional differentiated emission reduction paths, and the application prospects of carbon capture, utilization and storage technology in the textile industry, and finally form a comprehensive research system covering technological innovation, policy guidance, standards and norms, and market mechanisms, providing all-round scientific support for the green transformation of the textile industry and the realization of carbon peak and carbon neutrality goals.

• Technological innovation: Emphasis should be placed on the integration of renewable energy, application of nanomaterials, development of intelligent emission reduction technologies, and advancement of digital monitoring systems.

• Systemic transformation: Greater efforts are needed to embed circular economy principles across the entire textile value chain, from fibre production to garment recycling, aiming to establish a closed-loop system.

• Policy frameworks: It is essential to develop more comprehensive carbon accounting standards and mechanisms for policy coordination, ensuring effective integration between industrial and environmental policies.

• Through the deep integration of digital and green technologies, and the dual driving forces of technological and business model innovation, the textile industry may achieve a fundamental transformation from traditional high-carbon production to a low-carbon, high-efficiency model. This transition will provide strong scientific and practical support for the sustainable development of the global textile sector and the realisation of carbon neutrality goals.

ACKNOWLEDGEMENT

The work was supported by the Key Project of Educational Reform Research in Higher Education in Heilongjiang Province for the Year 2024. [Project Number: SJGZB2024250].

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