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Potentials and Challenges of Carbon Knowledge Graph in Sustainable Textile Production for Carbon Traceability: A Review

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Abstract: Textile production has received considerable attention owing to its significance in production value, the complexity of its manufacturing processes and the extensive reach of its supply chains. However, textile industry consumes substantial energy and materials and emits greenhouse gases that severely harm the environment. In addressing this challenge, the concept of sustainable production offers crucial guidance for the sustainable development of the textile industry. Low-carbon manufacturing technologies provide robust technical support for the textile industry to transition to a low-carbon model by optimizing production processes, enhancing energy efficiency and minimizing material waste. Consequently, low-carbon manufacturing technologies have gradually been implemented in sustainable textile production scenarios. However, while research on low-carbon manufacturing technologies for textile production has advanced, these studies predominantly concentrate on theoretical methods, with relatively limited exploration of practical applications. To address this gap, a thorough overview of carbon emission management methods and tools in textile production, as well as the characteristics and influencing factors of carbon emissions in key textile manufacturing processes is presented to identify common issues. Additionally, two new concepts, carbon knowledge graph and carbon traceability, are introduced, offering strategic recommendations and application directions for the low-carbon development of sustainable textile production. Beginning with seven key aspects of sustainable textile production, the characteristics of carbon emissions and their influencing factors in key textile manufacturing process are systematically summarized. The aim is to provide guidance and optimization strategies for future emission reduction efforts by exploring the carbon emission situations and influencing factors at each stage. Furthermore, the potential and challenges of carbon knowledge graph technology are summarized in achieving carbon traceability, and several research ideas and suggestions are proposed.

Key words: sustainable textile production; carbon knowledge graph; carbon traceability; low-carbon development; emission reduction

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0 Introduction

The Brudtland Report states that sustainable production is the ability to meet current needs without compromising the ability of future generations to meet their own needs. This mode of production emphasizes the balance of environment, society and economy to ensure the long-term sustainable use of resources and minimize environmental impact[1]. The United Nations defines the goal of sustainable production by 2030 as responsible consumption and production, which refers to eco-friendly production methods and a reduction in the waste volume within the context of a circular economy, while also avoiding the depletion of the Earth's energy resources[2]. The data published by the International Energy Agency (IEA) show that global energy-related carbon emissions are rapidly increasing at a rate of 0.9%, with carbon dioxide (CO_2) emissions surpassing 3.68 billion tons in 2022, and this trend is on the rise[3]. The statistical results of this study show that more than 100 countries are actively promoting the development of low-carbon technologies to address climate change[4]. China has committed to peaking CO_2 emissions before 2030 and achieving carbon neutrality before 2060 and is planning and driving technological innovation accordingly to support the global trend toward a low-carbon transition[5]. However, the manufacturing industry is a significant source of national economic revenue, and the full life cycle of manufacturing products includes multiple stages such as product design, production, transportation and sales, as well as recycling and disposal. Each is accompanied by considerable energy consumption and CO_2 emissions[6]. Particularly in the production phase, the carbon emissions generated account for 95% of the entire life cycle[7]. Sustainable production has increasingly become a key trend in the development of the manufacturing industry[8]. The core objective of this trend is to implement sustainable production strategies to reduce greenhouse gas emissions throughout the entire life cycle

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of products, from cradle to grave, thereby effectively addressing climate change and promoting the sustainable and healthy development of the environment[9]. The textile industry is a significant component of the manufacturing sector, and globally, it is the second-largest source of pollution next to the petrochemical industry[10]. Consequently, the transformation toward sustainable textile production is urgently needed.

However, the sustainable textile production process is complex and diverse, involving multiple stages from raw material cultivation and acquisition, spinning, production and manufacturing (weaving, dyeing and finishing), to garment making (cutting to sewing), each of which significantly impacts the environment and is challenging to quantify and manage[11]. In order to quantify and manage the environmental impact of these stages, assessment tools such as life cycle assessment (LCA), environmental footprint (EF) and eco-efficiency have been widely used to evaluate human activities related to products[12]. In the textile industry, carbon footprint is a widely used indicator for measuring the environmental impact of products[13]. Carbon footprint is an indicator that measures the direct and indirect greenhouse gas emissions of a product or service throughout its entire life cycle, including emissions from the acquisition of raw materials, manufacturing, storage, transportation, use, and the disposal and recycling stages. The unit of measurement for carbon footprint is CO_2 equivalent (CO_{2e}), which converts emissions of different greenhouse gases into an equivalent amount of CO_2 based on their global warming potential, allowing for comparison and summation. This concept is clearly defined and elaborated in the international standard ISO 14067 : 2018[14].

Unlike carbon footprint, carbon emissions generally refer to the absolute mass of CO_2 directly released by an activity or process within a specific time. The measurement of carbon emissions does not involve converting emissions of other greenhouse gases into CO_2 equivalents, nor does it consider the entire life cycle of a product or service. Consequently, carbon footprint offers a more comprehensive perspective for assessing and comparing the climate impact of different products or services throughout their entire life cycle. Many scholars employed various research methods to deeply analyze the environmental impact of sustainable textile production, aiming to provide scientific evidence and strategic guidance for the sustainable development of the textile industry. The carbon footprint values at different stages of the textile life cycle were calculated, and the results indicated that research on textile carbon footprints primarily focused on the stages of raw material cultivation and acquisition[15-16]. Wang et al.[17] used a bottom-up method to perform a full life cycle analysis on cotton-polyester knitted sweaters, establishing a carbon footprint emission model to resolve the inventory quantification and decomposition problems caused by the complexity of textile production processes, the multitude of materials and the extensive management style. The model was based on process analysis, using "number of garments" as the functional unit, and accounted for the carbon emissions during the raw material acquisition stage and transportation process. Hu et al.[18] focused on the key stages of textile enterprise production processes (weaving and dyeing stages) in terms of carbon emissions. Based on the emission factor method, they constructed separate carbon emission calculation models for the weaving and dyeing stages, addressing the issue of vague management in the textile production process, and providing references for factors affecting carbon emissions such as equipment energy consumption, material consumption and wastewater treatment. Zhang et al.[19] conducted systematic research on various aspects of clothing sewing production, including multi-objective management, simulation and low-carbon target management. Based on the evaluation criteria and accounting methods for carbon emissions, the factors affecting carbon emissions in clothing sewing production were analyzed, including fabrics, accessories, sewing equipment, transportation, personnel and lighting equipment, while separate carbon emission assessment models were established. This provides a theoretical reference for the stable and efficient operation of clothing enterprise production systems, reducing production costs and achieving low-carbon production. However, there is a lack of research on carbon emissions during the production stages, particularly the weaving and finishing stages, which contribute the most and have the highest proportion in the value of carbon footprint[20]. This is primarily due to the complexity of the production elements involved in specific process stages, the varying scales and lengths of production processes, and the lack of theoretical research and applied exploration into the carbon emissions generated in such stages.

However, previous studies primarily focused on the supervision and management of carbon emissions, with the main content being the use of carbon emissions as an indicator to analyze the environmental impact of sustainable textile production using different research methods, aiming to provide scientific evidence and strategic guidance for the sustainable development of the textile industry[21-22]. Moreover, compared to scientific theoretical guidance, practical application exploration has been an overlooked but important aspect in the field of low-carbon development. To reduce carbon emissions, in addition to clarifying the current level of carbon emissions in the production process, it is also necessary to study the root cause analysis of carbon emissions in sustainable production processes[23]. Only then can we address the specific high-pollution and high-emission processes within textile production, which are the bottlenecks of carbon emissions[24]. Carbon emission tracing and tracking is conducted to identify the direct and indirect driving factors related to high carbon emissions, providing theoretical support and practical reference value for energy conservation and emission reduction in sustainable textile production. However, the management, analysis and integration of related carbon emission data in sustainable textile production processes pose a critical challenge for achieving carbon emission tracing and tracking in sustainable textile production. Knowledge graph technology offers a viable approach to address this issue. The sustainable textile production line has a directed heterogeneous graph structure in spatial terms, and the advantage of knowledge graph technology lies in its use of graph structures to link the continuous textile production line with dense knowledge[25-26]. Research and work on knowledge graphs span various aspects, including the construction and representation of the knowledge engineering, the management and integration of data, as well as the analysis and communication of data, forming a systemic solution[27].

To address these issues, this research systematically reviews the research on reducing carbon emissions in the field of sustainable textile production. The purpose of this research is as follows.

1) Two new concepts of carbon knowledge graph (i.e., the knowledge graph of sustainable textile production) and carbon traceability (i.e., carbon emission traceability in textile production processes) are proposed, offering suggestions and application directions for the low-carbon development of sustainable textile production.

2) The characteristics and influencing factors of carbon emissions in the textile production process are systematically summarized based on seven key aspects of sustainable textile production. The potential and challenges of the carbon knowledge graph, as well as outlines of the future development direction, are introduced in the field of carbon traceability.

The structure of the rest of this research is as follows. Section 1 discusses the concept of carbon traceability and its distinction from carbon footprint, systematically summarizing the calculation methods and tools for carbon footprint. Section 2 systematically reviews the characteristics and influencing factors of carbon emissions in the textile production process, starting from the seven key aspects of the textile production. Section 3 summarizes the potential and challenges of the carbon knowledge graph in complex production processes and provides an outlook and summary of future trends. Section 4 draws the conclusions.

1 Carbon Emission Management Assessment Methods

To address the existing gaps in the development of carbon emission technologies in sustainable production, this research introduces the new concepts of textile production carbon traceability and the carbon knowledge graph in textile production, aiming to provide recommendations and expand the application direction for low-carbon development in sustainable textile production. Additionally, this section will systematically summarize the differences between carbon traceability and carbon footprint, the methods and tools for calculating carbon footprints and the definition and underlying principles of the carbon knowledge graph in textile production.

1.1 The difference between carbon footprint and carbon traceability

Carbon footprint was derived from the "ecological footprint" initially introduced by Wackernagel and others, representing the biologically productive land area needed or capable of absorbing human waste emissions to maintain the survival and economic development of a specific population[28]. As the understanding of the negative environmental impacts of CO_2 emissions during production processes deepened, carbon footprints were widely used to measure the direct and indirect greenhouse gas emissions of products or services over their life cycle, typically expressed as CO_2e[29]. This indicator has been widely applied in both industry and academia, although its definition is not uniform. Unlike the general concept of carbon emissions, the term typically refers to the absolute mass of CO_2 emitted.

However, theoretical research on carbon footprints often focuses on areas with simple structures and clear technological processes, leading to a greater emphasis on the stages of raw material cultivation and acquisition in the textile industry, while research on carbon emissions during production stages, especially weaving and finishing, is relatively scarce. These stages, although contributing the most to carbon footprints and accounting for the largest share, are unable to identify the driving factors of specific carbon emission bottlenecks or process nodes in sustainable textile production through traditional research approaches.

The concept of carbon traceability was subsequently introduced to address the complex and disordered nature of technological processes, aiming to trace the flow of carbon emissions during production and concurrently identify the various production resources that contribute to CO_2 emissions in each process. Carbon traceability has evolved from the concept of carbon footprint, providing a novel perspective to tackle the complex analysis of carbon emissions in production processes. Carbon traceability facilitates a more precise identification and quantification of carbon emission sources within the production process, thereby offering a scientific foundation for developing emission reduction strategies and optimizing production procedures.

1.2 Methods and tools related to carbon footprint

To further analyze and optimize sustainable production pathways and industrial structures, outstanding scholars both domestically and internationally have conducted a series of studies on quantifying carbon footprint data. Among these, the LCA method is currently the most widely used evaluation method, with its main principle being to assess the energy consumption and climate impact capacity of the assessed object throughout its entire life cycle from birth to death. However, sustainable textile production still lacks a unified quantification method[30-32]. This research takes the LCA method as the entry point and summarizes existing research methods which can be categorized into process-based LCA[33-34], input-output LCA[35] and hybrid LCA[36]. Among these, the process-based LCA method is currently the most mainstream, with its core being on-site monitoring and statistical analysis of all data inputs and outputs within the assessed object's life cycle, and a detailed explanation of the total carbon emissions of the assessed object. Internationally, the introduction of the Greenhouse Gas (GHG) Protocol emphasizes the harmonization of international accounting standard. This standard was co-proposed by the World Business Council for Sustainable Development (WBCSD) and the World Resources Institute (WRI), and had extensive application in international efforts to reduce energy consumption and emissions. In addition, the PAS 2050: 2008 emission standard was proposed by the Carbon Trust and the UK Department of Environment, Food and Agriculture, and commissioned by the British Standards Institution. The ISO standards series were developed by the International Organization for Standardization (ISO) to address the broad application of life cycle framework analysis[37]. Domestically, the Chinese life cycle database (CLCD)[38] is the first publicly released LCA carbon footprint basic database (first released in 2010) and is currently the only publicly accessible and self-consistent basic database in China. WebLCA[39] is an open and collaborative database platform where all users can develop their own intellectual property databases that adhere to CLCD specifications, and the data can be publicly released after review. WebLCA is an open-sharing database platform where various Internet platforms can access and use the platform database for a fee through the system interface. However, the setting of the system boundaries for this method is relatively subjective and lacks a unified set of rules. To overcome the above issues, the input-output LCA method uses regularly published input-output tables combined with impact assessment equations to uncover the latent relationships between economics and the assessed object. However, both methods are more inclined toward macro-level assessments and may not be appropriate for considering specific products or the entire product life cycle. Considering the limitations of these methods, the hybrid LCA method aims to enhance the accuracy of assessment calculations by combining their strengths. However, due to the complexity of the hybrid LCA method and its high data requirements, this method is still in the hypothetical stage[40-41]. Nonetheless, although carbon footprint accounting based on LCA is extensively utilized, the subjectivity in defining system boundaries is a crucial flaw of this method. Therefore, to address the issues, systematic LCA databases and tools have been developed to reduce human involvement and improve the efficiency and management performance of assessments through automation. The main commercial and free LCA softwares are summarized and classified in Table 1.

As shown in Table 1, eFootprint is an independently developed online LCA platform in China and is widely used to assess the carbon footprint of Chinese products and technologies. The carbon neutrality system (CNS) carbon emissions software is a commercial software developed by Shanghai University, designed to calculate carbon emissions at each stage of a product's life cycle. In academic and commercial fields, the most widely used and standardized database and platform software include GaBi developed by the University of Stuttgart in Germany[42]. Furthermore, internationally recognized mature software such as GaBi, SimaPro, OpenLCA and Umberto are widely utilized by researchers worldwide[43]. However, existing LCA software can only perform basic measurement calculations and advanced data analyses[44], essentially being a simple input and output of carbon emission data, akin to a black box, without supporting insights into internal mechanism models or customization to meet specific industrial scenario needs.

The "black box" issue mainly stems from the regionalization of carbon emission factor databases[45]. There are significant differences in carbon emission factor values for energy and materials among different countries and regions. For instance, calculating the carbon emissions from 1 kg of crude oil is not as simple as multiplying it by a universal carbon emission factor[46]. This factor is based on the carbon emission coefficient of standard coal equivalent to the calorific value of the crude oil, and its calculation depends on the weight of the standard coal that releases the same amount of heat as the crude oil. However, due to differences in fuel calorific values, this conversion coefficient varies by countries and regions. Therefore, when calculating energy carbon emissions, it is necessary to introduce a "conversion coefficient from crude oil to standard coal" to reflect the differences in fuel calorific values between different countries and regions. For example, in the carbon emission assessment of the dyeing process within the entire life cycle of the sustainable textile production, traditional management tools lack detailed management of the equipment properties, personnel status, and types and quantities of energy consumption involved in the current process[47-48]. Therefore, to further address the complexities, scales and fine-grained analysis requirements of industrial production processes, it is essential to construct transparent knowledge graphs for each specific process in sustainable production, meeting the needs for high accuracy and real-time carbon emission management. Consequently, this software still requires targeted development and optimization, and such targeted development is crucial for further enhancing the carbon emission reduction capabilities of sustainable production.

Table 1 Categorization of main commercial and free LCA software

Software	Free	Country	Year	Advantage	Disadvantage
CNS	No	China	2006	1) User-friendly and easy to operate 2) Supporting product supply chain management 3) Supporting multiple life cycle stage options	1) Only supporting China version 2) Functionality may be limited to China market
EQUER	No	France	1995	1) French national database	1) Limited international coverage
SimaPro	No	The Netherlands	1994	1) Comprehensive LCA tools	1) More time required for users to learn to use the software 2) License required
Umberto	No	Germany	1994	1) Computer performance exceeds other tools 2) Statistically rich	1) License required 2) Lack of reference data
GaBi	No	Germany	1990	1) Supporting multi-disciplinary assessment of atmosphere, water and soil 2) Abundant statistics	1) License required 2) Features may be limited to the German market
eBalance	Yes	China	2010	1) Using a high-quality life cycle database as a basis 2) Supporting multiple life cycle stage options	1) Only supporting China version 2) Functionality may be limited to the Chinese market
EIO-LCA	Yes	USA	1995	1) Better suited for generic items	1) Features may be limited to the US market
OpenLCA	Yes	USA	2006	1) Free and easy to use 2) Multi-language support 3) Continuously updated	1) Data reliability is not guaranteed 2) Functionality may be limited to the Dutch market
eFootprint	Yes	China	2021	1) Supporting CLCD database, ELCD database and global database 2) Carbon footprint and LCA survey, modeling and analysis for various products	1) Only supporting online version operation

Note: ELCD denotes European reference life cycle database.

1.3 Definition and principle of carbon knowledge graph in textile production

In China, researchers have published a significant number of studies predicting the carbon emission intensity, carbon emission efficiency, and their convergence across the country or in various sectors and regions. In 2014, China announced in a joint climate change statement with the USA that it aims to peak its carbon emissions around 2030, marking an important shift from relative emission reduction to absolute emission reduction[49-50]. With this transition, scholars' interest in the total amount of carbon emissions has been growing, and the research methods have become increasingly diverse. Over the past two decades, domestic research on carbon emissions has gradually become more detailed, and research into carbon footprints and carbon labels has also delved into various industries such as animal husbandry and tourism[51-52].

However, the carbon emission calculation methods described above have limitations in fine-grained prediction, particularly when applied to specific processes like textile production. Consequently, enhancing the fine-grained and interpretable prediction of carbon emissions in textile production is a challenging research issue. In this context, the carbon knowledge graph for textile production processes offers a new direction for addressing this issue. The strength of knowledge graph technology in the industrial field lies in knowledge integration, and thus it has been widely applied in industrial scenarios. Liu et al.[53] proposed a cognitive manufacturing data representation method based on knowledge graphs, which innovatively addressed the problem of handling massive, multidimensional, heterogeneous and time-series data in industrial scenarios. By employing a perception-cognition dual-system driven approach, the method optimized the allocation of manufacturing resources, laying the foundation for the advent of human-like cognitive processing and the era of cognitive manufacturing in cyber-physical production systems. They introduced a method that integrates industrial knowledge graphs (IKGs) with multi-agent reinforcement learning, which creatively solved the problem of moving toward Self-X cognitive manufacturing networks. Qin et al.[54] introduced a semantic representation method based on knowledge graphs, which creatively solved the problem of adaptive manufacturing control in large-scale personalized manufacturing. Therefore, knowledge graph technology offers a path for sustainable textile production. However, current research has not fully considered the needs for transparent management and fine-grained prediction in sustainable textile production. The improvement of fine-grained prediction and interpretability of carbon emissions is a key and challenging research issue, which is a major obstacle to achieving more efficient carbon emission management.

To address the issues, the construction of a carbon knowledge graph can enable detailed tracking and in-depth analysis of carbon emissions in the textile production process, thereby providing a scientific basis for formulating effective carbon emission reduction strategies. The carbon knowledge graph for textile production (i. e., the carbon knowledge graph for carbon emissions in the textile production process) is a professional tool based on knowledge graph technology[55-57], aiming to represent the information of personnel, materials, energy consumption and carbon emissions in a systematic and structured manner within the textile production process. Its main features include nodes and edges. Nodes represent entities such as personnel, materials and equipment, and edges represent the relationships between these entities, such as production, consumption and emission. The construction of the carbon knowledge graph involves multiple levels and dimensions, which can be categorized into two major types: the global carbon knowledge graph and the order carbon knowledge graph. The global carbon knowledge graph is composed of all order carbon knowledge graphs and describes a summary of carbon emission data across the entire textile production process. It provides a comprehensive view of the entire production process, allowing the visualization of carbon emission differences and overall trends between different orders, serving as a reference for enterprises in developing carbon emission reduction strategies. The order carbon knowledge graph starts with the order and correlates order information with the production process structure. It is divided into two layers: the order layer and the production process layer. In the order layer, basic order information is integrated and managed, such as planned deliveries, compositions and weights; while in the production process layer, the order's production process is decomposed into different processes, and the carbon emission of each process is modeled and described, including material carbon emissions, energy carbon emissions and personnel carbon emissions[58]. The establishment of the order layer not only effectively manages basic information but also combines with graph representation learning methods[59], and can be used for research on graph recommendation systems[60-62]. The production process layer manages spatial configurations and process flow trends, and by combining with graph convolutional network methods[63], it can tackle carbon emission prediction challenges[64]. Such research focuses on the prediction of carbon emissions at a fine-grained level for specific processes, which can further enhance the accuracy and granularity of the predictions compared to traditional global carbon emission predictions.

The ontological structure and relationship of production processes in a basic carbon knowledge graph for textile production, as shown in Fig. 1, are used for analyzing and optimizing carbon emissions in the textile production process, thereby supporting enterprises' carbon emission reduction strategies and sustainable development goals.

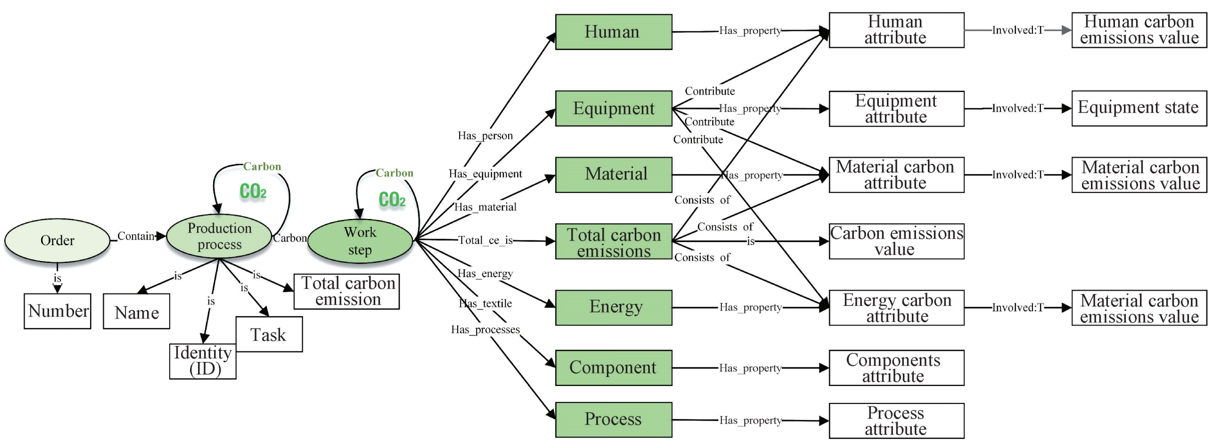

Fig. 1 Ontological structure and relationship of production processes in a basic carbon knowledge graph

In Fig. 1, the entity nodes include the order node, production process node, work step node, total carbon emission node, and other corresponding specific carbon emission and energy consumption nodes. The arrows between nodes represent the sequence relationships of the production process, the subordinate characteristic relationships of carbon emissions and the timing relationships of direct carbon emissions from production process processing. Specifically, "Contain" specifies that certain process steps and work steps are necessary components of the production process. "Total_ce_is" represents the total carbon emissions associated with a specific production work step. "Has_person" indicates the presence and involvement of personnel in a particular work step. "Has_equipment" signifies the equipment used during a specific work step. "Has_material" represents the materials consumed or utilized in a work step. "Has_energy" indicates the type and amount of energy consumed during a work step. "Has_textiles" represents the textiles consumed or utilized in a work step. "Has_processes" represents the processes involed in a work step. "Contribute" shows the contribution of the equipment's energy and material usage to the carbon emissions. "Has_property" describes the properties or characteristics of the production resources involved in the process steps. "Involved: T" represents the specific quantitative carbon emissions related to the timing in the production process, along with the states of equipment operation and personnel involvement, where T signifies the temporal sequence.

The sustainable textile production carbon knowledge graph is presented in Fig. 2.

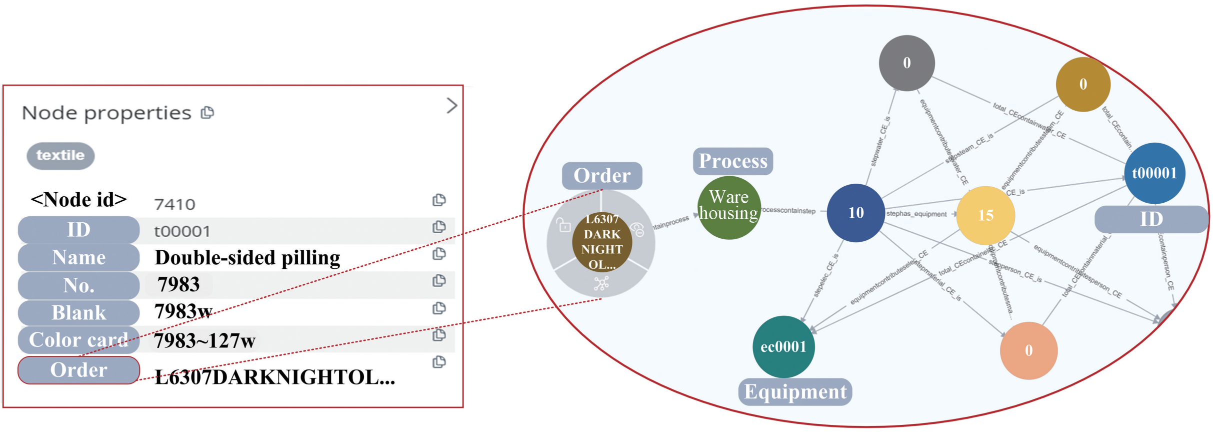

Fig. 2 Sustainable textile production carbon knowledge graph (partial)

In summary, the carbon knowledge graph G for textile production can be defined as

$$G = (V, E) = (N_s, R, N_t),$$

where V is a set of vertices representing entities (such as specific processes, personnel, materials and equipment); E is a set of edges representing the relationships between these entities (such as production, consumption and emission); N_s, R and N_t respectively denote the starting node entity, the relationship and the ending node entity within the carbon knowledge graph, and the data are stored in the form of triples for subsequent modeling of the carbon knowledge graph. During the construction of the carbon knowledge graph, it is necessary to pre-define process knowledge attributes and the carbon emission flow relationships between process nodes. The production process resources within the carbon knowledge graph encompass personnel, operational equipment, materials, carbon emissions and process methods, among other typical attributes. The carbon emission flow relationships toward the production process ontology models in the carbon knowledge graph can be further categorized into three types: 1) subordinate feature relationship of carbon emissions R_f that is used to represent the carbon emission-related attributes and the process operation attributes of the production process nodes, such as the energy consumed by equipment and material carbon, the number of equipment personnel and the quantity of material input; 2) temporal relationship of direct carbon emissions R_t that is used to describe whether the equipment is in an idle state or other temporal information; 3) sequential relationship of carbon flow R_q that is used to describe the causal relationship in the textile production process, for example, describing the continuity between the weaving and dyeing processes, indicating that the semi-finished fabric produced by the weaving process must be fully processed before dyeing can proceed.

2 Characteristics and Influencing Factors of Carbon Emissions in Textile Production Processes

The entire life cycle of textiles can be divided into eight stages, including raw material acquisition, spinning, weaving, dyeing and printhing, product processing, transportation and sales, use and end-of-life stage[65]. The end-of-life stage includes reuse, recycling, material recovery, incineration and disposal. Each of these stages encompasses more detailed processes and procedures[66-67], as shown in Fig. 3. The raw material acquisition stage involves collecting natural fibers from nature, such as cotton, linen and silk, as well as manufacturing synthetic fibers through chemical processes, such as polyester, nylon and polyacrylonitrile (PAN). Spinning is the process of converting fiber materials into yarn, including both short-fiber spinning and long-fiber spinning methods. Chemical fiber filaments, such as polyester, nylon and PAN synthetic fibers, are produced through chemical processing methods and can be used directly in weaving or first go through the spinning process to be made into yarn before weaving[22]. Weaving is the process of transforming yarn into fabric, including methods such as mechanical weaving, knitting and braiding. Dyeing and printing is the process of adding color and patterns to fabric, including methods such as printing, dyeing and bleaching. Product processing is the step of turning fabric into finished products, which can be divided into nonwoven fabrics, clothing, home textiles and industrial applications according to different usage scenarios, and typically includes processes such as cutting, sewing, finishing and packaging. Processes such as spinning, weaving, dyeing, finishing and product processing are all important components of sustainable textile production. This is due to the fact that they have a substantial impact on resource consumption, energy efficiency, environmental impact and the quality and performance of the final product[68]. To better elaborate on the characteristics and influencing factors of carbon emissions in the production process, this research specifically describes seven typical main processes in the textile industry, including spinning, chemical fiber filaments, knitting, dyeing and printing, nonwoven fabrics, clothing and home textiles, which are shown with a dark green background in Fig. 3. To reveal the potential applications of carbon knowledge graphs, this research further explores the construction of carbon knowledge graphs for these seven scenarios in the textile production process, including the potential of carbon knowledge graphs in the fields of spinning, chemical fiber filaments, knitting, dyeing and printing, nonwoven fabrics, clothing and home textiles.

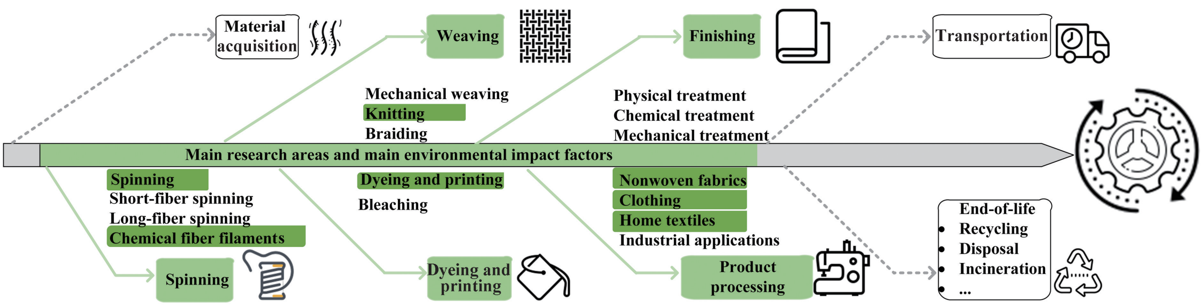

Fig. 3 Main research areas and key environmental impact assessment factors in sustainable textile production processes

2.1 Spinning carbon knowledge graph

The spinning stage mainly includes processes such as cleaning, carding, drawing and winding. The potential of the spinning carbon knowledge graph lies in its ability to track and monitor carbon emissions in the spinning process in detail. The spinning stage is a crucial link in textile production, involving the processing of raw materials such as natural fibers or chemical fiber filaments into yarns[69]. Carbon emissions in this process primarily stem from energy use, material handling, and the operation of mechanical equipment. By constructing a spinning carbon knowledge graph, it is possible to monitor the carbon emissions of each process in detail, thereby providing a scientific basis for optimizing production processes and reducing carbon emissions. At present, some studies have initiated the exploration of utilizing the Internet of Things (IoT) technology and big data analytics to build spinning carbon knowledge graphs, achieving a degree of advancement. The ontological structure and relationship of production processes in a typical spinning carbon knowledge graph are shown in Fig. 4, where the ontological structure is centered around production processes and their inter relationships. In Fig. 4, work processes are delineated in green within the process nodes. Subsequent work steps are indicated by a yellow coloration. Attribute characteristics related to carbon emissions are denoted in purple.

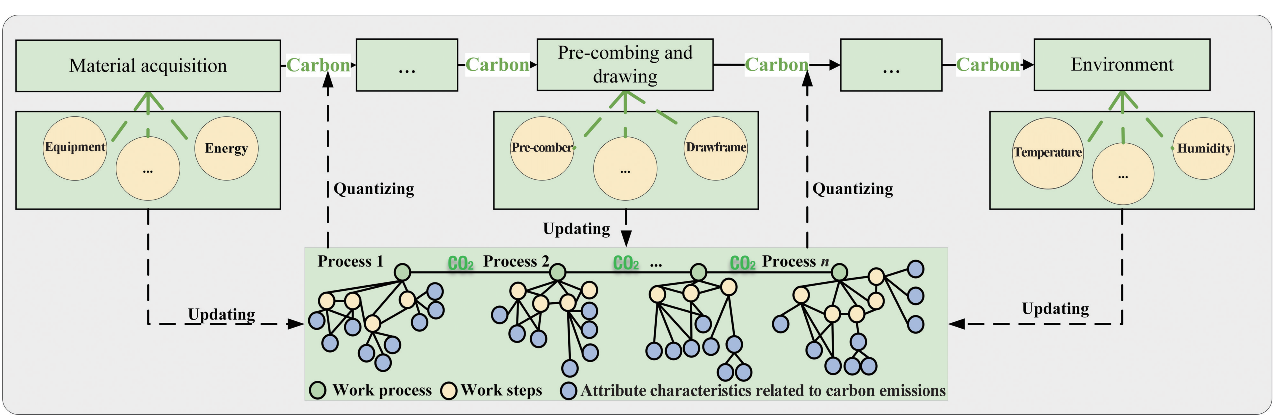

Fig. 4 Ontological structure and relationship of production processes in a typical spinning carbon knowledge graph

2.2 Chemical fiber filament carbon knowledge graph

The potential of the chemical fiber filament carbon knowledge graph lies in its ability to deeply analyze carbon emissions in the production process of chemical fiber filaments. Chemical fiber filaments are produced via chemical manufacturing processes and the related materials include polyester, nylon, PAN, etc. The production process of chemical fiber filaments includes various stages such as polymerization, spinning, drawing and heat treatment, with each stage potentially emitting a considerable amount of carbon[70]. The development of a chemical fiber filament carbon knowledge graph enables the meticulous tracing and dissection of the carbon footprint at each stage, which is instrumental in guiding manufacturers toward more environmentally friendly production techniques and effectively reducing greenhouse gas emissions.

2.3 Knitting carbon knowledge graph

The potential of the knitting carbon knowledge graph lies in its ability to track and monitor carbon emissions in the knitting process in detail. Knitting is the process of weaving yarn into fabric using knitting machinery, which involves aspects such as energy consumption, raw material processing and mechanical equipment operation. The establishment of a knitting carbon knowledge graph provides granular oversight of carbon release, which is pivotal for refining industrial practices and minimizing the environmental impact of knitting operations.

2.4 Dyeing and printing carbon knowledge graph

The potential of the dyeing and printing carbon knowledge graph lies in its ability to track and monitor carbon emissions in the dyeing and printing process in detail. Dyeing and printing is the process of adding color and patterns to fabrics. It involves aspects such as water consumption, chemical usage and energy consumption[71]. The implementation of a dyeing and printing carbon knowledge graph allows for a comprehensive examination of carbon-intensive steps, serving as a cornerstone for enhancing process efficiency and carbon mitigation strategies.

2.5 Nonwoven carbon knowledge graph

The potential of the nonwoven carbon knowledge graph lies in its ability to track and monitor carbon emissions in the nonwoven production process in detail. Nonwoven fabrics are produced by bonding, melting, or needling short fibers or filaments into fabrics. The production processes involve energy consumption, raw material processing and mechanical equipment operation, among other aspects[72]. Detailed visibility into the carbon dynamics throughout the production chain is gained through the nonwoven carbon knowledge graph, facilitating targeted interventions to streamline operations and lower carbon output.

2.6 Clothing carbon knowledge graph

The potential of the clothing carbon knowledge graph lies in its ability to track and monitor carbon emissions in the clothing production process in detail. Clothing production involves multiple processes such as design, cutting, sewing, finishing and packaging, each of which may result in significant carbon emissions[73]. A nuanced view of the carbon footprint associated with various stages of clothing manufacture is offered by the clothing carbon knowledge graph, providing a roadmap for eco-innovation and carbon reduction efforts in the apparel industry.

2.7 Home textile carbon knowledge graph

The home textile carbon knowledge graph is valuable for its detailed tracking and monitoring of carbon emissions throughout the production process of home textile products[74]. A detailed carbon audit across the production life cycle is provided by the home textile carbon knowledge graph, which is essential for identifying opportunities for green production and advancing the sustainability agenda within the home textile sector. This knowledge graph facilitates a comprehensive understanding of the carbon impact of home textile production, thereby promoting sustainable industry practices.

3 Challenges and Future Pathways of Carbon Knowledge Graph in Sustainable Textile Production

In the field of sustainable textile production, current commercial LCA tools can meet basic management and statistical needs, such as GaBi developed by the University of Stuttgart in Germany and SimaPro developed by PRé Sustainability (a company in the Netherlands). GaBi supports assessments across multiple domains including atmosphere, water and soil. SimaPro is adapted for complex building types and used in over 80 countries[75]. Nevertheless, these tools face limitations when addressing the challenges associated with carbon emission management during sustainable textile production. The key challenges comprise opacity of information, process complexity, scale grandeur and the necessity for bespoke customization. Specifically, traditional management tools often lack detailed management of equipment attributes, personnel status and types and quantities of energy consumption involved in the process[76]. In industrial production processes, due to the complexity and scale, coupled with the demand for high accuracy and real-time carbon emission management, the existing software is inadequate in delivering the necessary degree of customization and transparency.

In response to these issues, knowledge graph technology offers a solution. Knowledge graph technology possesses the ability to generate the transparent knowledge graph and can be tailored for individual process flows within sustainable production. It has found applications across sectors like healthcare, finance and e-commerce[77-79], and is utilized for purposes including knowledge management[80], intelligent recommendations[81] and intelligent search[82]. In textile production, knowledge graph technology can help resolve issues of opacity and complexity in carbon emission management, providing more accurate and real-time carbon emission management needs. Knowledge graph technology offers a new path for carbon emission management and traceability in sustainable textile production. To avoid duplication, the detailed process of developing the carbon knowledge graph is omitted here. This process is thoroughly explained in previous work, as referenced in Ref. [58]. Therefore, this research elaborates in Section 3 on the seven-line carbon knowledge graph for textiles (including spinning, chemical fiber filaments, knitting, dyeing and printing, nonwoven fabrics, clothing and home textiles), which demonstrates the significant applicability of the textile carbon knowledge graph in promoting sustainable textile production. Utilizing knowledge graph technology to consolidate carbon emission resources throughout the textile production process provides a fresh viewpoint for the traceability of carbon in sustainable textile production. This approach is particularly suitable for analyzing and resolving carbon emission bottlenecks in complex process flows and large-scale production pathways, thereby tracing the root causes[83]. Nevertheless, since the application of knowledge graph technology in sustainable textile production is currently in its nascent stage, there are a range of challenges and limitations. This section will delve into the challenges faced by the carbon knowledge graph in the sustainable textile production process and elaborate on future development directions.

3.1 Challenges and limitations of carbon knowledge graph

In the context of sustainable textile production, the carbon knowledge graph is an innovative instrument that provides a new viewpoint for fine-grained forecasting and the management and tracking of carbon emissions across production workflows. Nonetheless, while the carbon knowledge graph holds promise, it encounters a range of challenges and constraints during technical implementation and utilization. Initially, the creation of the carbon knowledge graph necessitates extensive data support, encompassing aspects such as material usage, energy consumption, equipment efficiency and emission factors during production. The acquisition of data may be restricted, particularly in terms of the standardization and consistency of data collection. The lack of high-quality data will impact the accuracy and reliability of the carbon knowledge graph.

Moreover, the intricacy and unpredictability of textile production processes present difficulties for the establishment of the carbon knowledge graph. Textile production involves multiple stages and processes, each with its own unique carbon emission characteristics and subject to various influencing factors. Consequently, while the carbon knowledge graph has potential in sustainable textile production, it still faces a series of challenges and limitations in terms of data acquisition, complexity management, dynamic updates, analytical methods and interpretability. Future research needs to delve into these aspects to advance the application of the carbon knowledge graph in sustainable textile production.

3.2 Future works

Carbon traceability is a pivotal trend in sustainable textile manufacturing, marking a crucial transition in low-carbon development and presenting a substantial global challenge. The core of future sustainable textile production will involve the deep integration of low-carbon manufacturing technologies such as the IoT, industrial Internet and digital twins[84-86]. The carbon knowledge graph in the textile production process is a crucial component of these low-carbon manufacturing technologies, and carbon traceability is an important direction for the application of these technologies in the field of low-carbon manufacturing. For instance, to address the issue of greenhouse gas emissions from various production factors, some scholars and research institutions have begun to integrate IoT technology with low-carbon technologies to measure and track greenhouse gas emissions across multiple industries. The utilization of the IoT in the pursuit of carbon neutrality has experienced exponential expansion recently[87]. Drawing from current research outcomes, this research will outline prospective technological approaches, with a detailed depiction provided in Fig. 5.

As shown in Fig. 5, from a macro perspective, future research and development should focus on the integration of product life cycle management with low-carbon manufacturing technologies, encompassing low-carbon design, manufacturing, logistics and recycling[6]. The primary research direction should be the development of the customized industrial carbon emission software for specific domains and the in-depth exploration of these software applications in specific industrial scenarios. The crux of this approach lies in analyzing the specific needs of industrial scenarios to guide the development of the customized software. In Fig. 5, this research uses a workshop case to highlight specific industrial scenarios, emphasizing their significance. Moreover, the carbon knowledge graph detailed in this research is designed to tackle the intricate production processes and predict carbon emission constraints in sustainable textile manufacturing, with carbon traceability acting as a practical application instance within this production framework.

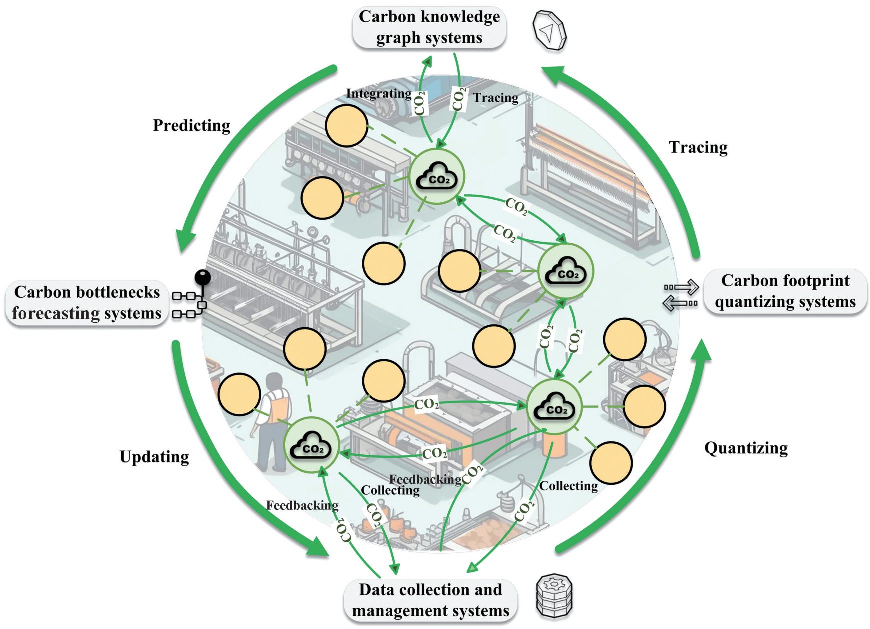

Fig. 5 Sustainable textile production technology pathways

From a micro perspective, the development of low-carbon technologies in sustainable textile production should focus on the following areas: 1) the domain of carbon emission data collection and management systems, encompassing the integration of IoT technology for automated data acquisition and real-time tracking, bolstering the automation of data gathering and ensuring the data's precision and timeliness, particularly in the industrial manufacturing sector, where the variety of materials and complex process flows pose significant challenges to data collection (to overcome this challenge, researchers and industry practitioners need to develop more standardized and unified methods to define system boundaries, enabling data integration and analysis across different studies); 2) the domain of carbon footprint quantification systems, encompassing the establishment of a comprehensive and unified carbon emission database and standards for sustainable textile production, the development of unified quantification software compatible with various quantification models to support the quantification needs of carbon footprints for different products and the promotion of data consistency and comparability; 3) the domain of the carbon knowledge graph system, encompassing customizing the intelligence of carbon emission traceability by integrating advanced analysis tools and algorithms, reducing dependence on manual input and enhancing the efficiency and precision of the traceback process.

In summary, future research and development should foster the deep integration of low-carbon manufacturing technologies such as the IoT, industrial Internet and digital twins with sustainable textile production. This will involve the development of theories and computational models for low-carbon data collection, quantification, management, analysis, recommendation and prediction that are applicable to complex scenarios and multi-objective requirements, to fully support the low-carbon needs throughout the product life cycle.

4 Conclusions

To address global climate change and promote the shift to a low-carbon economy in sustainable textile production, this research conducts a systematic review of research on carbon emission reduction in the field. It offers a thorough overview of management strategies, tools and key processes throughout the product life cycle, aiming to pinpoint prevalent challenges. This research aims to address the challenges posed by the complexity of processes, the vast scale and the high demand for the fine-grained analysis in sustainable textile production. The issues of information opacity and the lack of personalized customization for specific scenarios result from the existing carbon emission management methods and tools, which operate similarly to "black boxes". The specific contributions of this research are as follows.

Initially, this research introduces two new concepts, carbon knowledge graph and carbon traceability, to provide recommendations and application directions for the low-carbon development of sustainable textile production. The carbon knowledge graph is designed to illustrate carbon emissions throughout the textile production process, facilitating a clearer understanding of the carbon footprint for manufacturers and offering a foundation for developing emission reduction strategies. Carbon traceability focuses on identifying the sources of carbon emissions within the textile production process, enabling businesses to comprehensively assess their emissions sources and implement specific measures for reduction. Furthermore, this research discusses the concept of carbon traceability, distinguishes it from carbon footprint, and systematically summarizes the calculation methods and tools for carbon footprint. This helps enterprises accurately calculate their carbon emissions during production and provides data support for the formulation of emission reduction strategies. Subsequently, the study systematically analyzes the features and determinants of carbon emissions throughout the textile production process, focusing on seven aspects of sustainable textile production, which encompass spinning, chemical fiber filaments, knitting, dyeing and printing, nonwoven fabrics, clothing and home textiles. Through in-depth research on the carbon emission situation and influencing factors of each link, specific guidance and optimization plans can be provided for future emission reduction efforts. In conclusion, this research summarizes the potential and challenges of the carbon knowledge graph in complex production processes and looks forward to future development trends. The construction and application of the carbon knowledge graph face numerous challenges, including data acquisition, model development and standard setting, yet it holds immense potential for practical use.

In the future, as technologies continue to advance and standards are gradually refined, the carbon knowledge graph will become an indispensable tool in sustainable textile production, providing solid support for the industry's low-carbon transformation.

References

[1] GONÇALVES A, SILVA C. Looking for sustainability scoring in apparel: a review on environmental footprint, social impacts and transparency [J]. *Energies*, 2021, 14(11): 3032.

[2] CAI Y J, CHOI T M. A united nations' sustainable development goals perspective for sustainable textile and apparel supply chain management [J]. T*ransportation Research Part E: Logistics and Transportation Review*, 2020, 141: 102010.

[3] PARHAMFAR M, SADEGHKHANI I, ADELI A M. Towards the net zero carbon future: a review of blockchain-enabled peer-to-peer carbon trading [J]. *Energy Science & Engineering*, 2024, 12(3): 1242-1264.

[4] CHEN R. A review of knowledge mapping-based research on peak carbon and carbon neutrality [J]. *Green Finance and Accounting*, 2022(7): 3-9. (in Chinese)

[5] WANG S H, YANG ZW, ZHANG W, et al. A review of domestic and foreign research on carbon emission under the background of "double carbon": based on visualization of scientific knowledge map and combing of development context [J]. *Ecological Economy*, 2023, 39(12): 222-229. (in Chinese)

[6] HE B, YUAN X, QIAN S S, et al. Product low-carbon design, manufacturing, logistics, and recycling: an overview [J]. *WIREs Energy and Environment*, 2023, 12(5): e479.

[7] WANG C X, WANG L H, LIU X L, et al. Carbon footprint of textile throughout its life cycle: a case study of Chinese cotton shirts [J]. *Journal of Cleaner Production*, 2015, 108: 464-475.

[8] HE B, LIU Y J, ZENG L B, et al. Product carbon footprint across sustainable supply chain [J]. *Journal of Cleaner Production*, 2019, 241: 118320.

[9] SILIŅA L, DĀBOLIŅA I, LAPKOVSKA E. Sustainable textile industry-wishful thinking or the new norm: a review [J]. *Journal of Engineered Fibers and Fabrics*, 2024, 19: 15589250231220359.

[10] HAUKKALA T, NIINIMÄKI K, TURUNEN L L M. Fashion in turmoil: impact of the COVID-19 pandemic on Finland's textile and fashion industry [J]. *Sustainability: Science, Practice and Policy*, 2023, 19(1): 2173424.

[11] CHEN S, ZHU L S, SUN L R, et al. A systematic review of the life cycle environmental performance of cotton textile products [J]. *Science of the Total Environment*, 2023, 883: 163659.

[12] JHANJI Y. Life cycle analysis of textiles and associated carbon emissions [M]//Sustainable Fibres for Fashion and Textile Manufacturing. Amsterdam: Elsevier, 2023: 403-431.

[13] LUO Y, WU X Y, DING X M. Carbon and water footprints assessment of cotton jeans using the method based on modularity: a full life cycle perspective [J]. *Journal of Cleaner Production*, 2022, 332: 130042.

[14] LIU J R, LI X, ZHU L S, et al. Discussion on key issues of carbon footprint accounting for bast fiber textiles [J]. *Science of the Total Environment*, 2023, 897: 166272.

[15] PENG S Y, LIU J Y, GENG Y. Assessing strategies for reducing the carbon footprint of textile products in china under the shared socioeconomic pathways framework [J]. *Climate Change Economics*, 2022, 13(1): 2240004.

[16] CHENG Y, LIANG H E. Calculation and evaluation of industrial carbon footprint of cotton denim jacket [J]. *Journal of Engineered Fibers and Fabrics*, 2021, 16: 15589250211020387.

[17] Wang W L. Development of software for carbon footprint assessment and accounting of terylene cotton hoodie [D]. Hangzhou: Zhejiang Sci-Tech University, 2024. (in Chinese)

[18] Hu K L. Study on carbon emissions in key segments of textile enterprises' production processes [D]. Xi'an: Xi'an Polytechnic University, 2019. (in Chinese)

[19] ZHANG X J. Analysis and technology of objective management for low carbon emissions in garment sewing process [D]. Suzhou: Soochow University, 2021. (in Chinese)

[20] MAIR S, DRUCKMAN A, JACKSON T. Global inequities and emissions in Western European textiles and clothing consumption[J]. *Journal of Cleaner Production*, 2016, 132: 57-69.

[21] XIAO Y Y, NORRIS C B, LENZEN M, et al. How social footprints of nations can assist in achieving the sustainable development goals[J]. *Ecological Economics*, 2017, 135: 55-65.

[22] LEAL FILHO W, DINIS M A P, LIAKH O, et al. Reducing the carbon footprint of the textile sector: an overview of impacts and solutions[J]. *Textile Research Journal*, 2024 [2024-04-23]. https://journals. sagepub. com/doi/abs/10. 1177/00405175241236971.

[23] SUN C W, CHEN L Y, ZHANG F. Exploring the trading embodied CO_2 effect and low-carbon globalization from the international division perspective [J]. *Environmental Impact Assessment Review*, 2020, 83: 106414.

[24] GIACOMIN A M, PACCA S A. Input-output analysis as guidance for the Brazilian textile supply chain[J]. *Environment, Development and Sustainability*, 2024: 1-20.

[25] FRACCASCIA L, GIANNOCCARO I, ALBINO V. Green product development: what does the country product space imply? [J]. *Journal of Cleaner Production*, 2018, 170: 1076-1088.

[26] MA X G. Knowledge graph construction and application in geosciences: a review [J]. *Computers & Geosciences*, 2022, 161: 105082.

[27] ZHOU B, BAO J S, CHEN Z Y, et al. KGAssembly: knowledge graph-driven assembly process generation and evaluation for complex components [J]. *International Journal of Computer Integrated Manufacturing*, 2022, 35 (10/11): 1151-1171.

[28] WACKERNAGEL M, YOUNT J D. The ecological footprint: an indicator of progress toward regional sustainability[J]. *Environmental monitoring and assessment*, 1998, 51: 511-529.

[29] MOHAN S, OKE N. Waste management in textile industry: a novel application of carbon footprint analysis [C]//Sustainable Environmental Geotechnics: Proceedings of EGRWSE 2019. Berlin: Springer, 2020: 125-130.

[30] ZAMANI B, SVANSTRÖM M, PETERS G, et al. A carbon footprint of textile recycling: a case study in Sweden[J]. *Journal of Industrial Ecology*, 2015, 19(4): 676-687.

[31] BEVILACQUA M, CIARAPICA F E, GIACCHETTA G, et al. A carbon footprint analysis in the textile supply chain [J]. *International Journal of Sustainable Engineering*, 2011, 4(1): 24-36.

[32] Q IAN W, JI X, XU P, et al. Carbon footprint and water footprint assessment of virgin and recycled polyester textiles[J]. *Textile Research Journal*, 2021, 91(21/22): 2468-2475.

[33] ZHANG Y, KANG H, HOU H, et al. Improved design for textile production process based on life cycle assessment [J]. *Clean Technologies and Environmental Policy*, 2018, 20 (6): 1355-1365.

[34] CASTELLANI V, SANYÉ-MENGUAL E, SALA S. Environmental impacts of household goods in Europe: a process-based life cycle assessment model to assess consumption footprint [J]. *The International Journal of Life Cycle Assessment*, 2021, 26(10): 2040-2055.

[35] WOOD R, MORAN D, STADLER K, et al. Prioritizing consumption based carbon policy based on the evaluation of mitigation potential using input output methods [J]. *Journal of Industrial Ecology*, 2018, 22(3): 540-552.

[36] HE B, CAO X, GU Z. Kinematics of underactuated robotics for product carbon footprint [J]. *Journal of Cleaner Production*, 2020, 257: 120491.

[37] GARCIA R, FREIRE F. Carbon footprint of particleboard: a comparison between ISO/TS 14067, GHG protocol, PAS 2050 and climate declaration[J]. *Journal of Cleaner Production*, 2014, 66: 199-209.

[38] HU Y, DU H, XU L, et al. Life cycle environmental benefits of recycling waste liquor and chemicals in production of lignocellulosic bioethanol[J]. *Bioresource Technology*, 2023, 390: 129855.

[39] PANG B, SUN Z, WANG L, et al. Improved value and carbon footprint by complete utilization of corncob lignocellulose [J]. *Chemical Engineering Journal*, 2021, 419: 129565.

[40] PERKINS J, SUH S. Uncertainty implications of hybrid approach in LCA: precision versus accuracy [J]. *Environmental Science & Technology*, 2019, 53(7): 3681-3688.

[41] YASIN S, BEHARY N, ROVERO G, et al. Statistical analysis of use-phase energy consumption of textile products [J]. *The International Journal of Life Cycle Assessment*, 2016, 21(12): 1776-1788.

[42] SHREE V, NAUTIYAL H, GOEL V. Carbon footprint estimation for academic building in India [M]//LCA Based Carbon Footprint Assessment.

Singapore: Springer Singapore, 2021: 55-70.
[43] ORMAZABAL M, JACA C, PUGA-LEAL R. Analysis and comparison of life cycle assessment and carbon footprint software[C]//Proceedings of the Eighth International Conference on Management Science and Engineering Management: Focused on Computing and Engineering Management. Berlin: Springer, 2014: 1521-1530.
[44] ZHENG H, YAN Y F. Research on carbon footprint analysis model of mechanical and electrical products from the perspective of LCA[C]//Proceeding of the 24th International Conference on Industrial Engineering and Engineering Management 2018. Singapore: Springer Singapore, 2019: 21-28.
[45] TURCONI R, BOLDRIN A, ASTRUP T. Life cycle assessment (LCA) of electricity generation technologies: overview, comparability and limitations[J]. *Renewable and Sustainable Energy Reviews*, 2013, 28: 555-565.
[46] WANG Y, CHAU C K, NG W Y, et al. A review on the effects of physical built environment attributes on enhancing walking and cycling activity levels within residential neighborhoods[J]. *Cities*, 2016, 50: 1-15.
[47] BOSCO S, DI BENE C, GALLI M, et al. Soil organic matter accounting in the carbon footprint analysis of the wine chain[J]. *The International Journal of Life Cycle Assessment*, 2013, 18(5): 973-989.
[48] CHEN J L, WEN Y H. Developing a simple carbon footprint calculation tool with the criteria of inventory data selection[C]//Leveraging Technology for a Sustainable World: Proceedings of the 19th CIRP Conference on Life Cycle Engineering. Berlin: Springer, 2012: 429-434.
[49] ABBATE S, CENTOBELLI P, CERCHIONE R, et al. Sustainability trends and gaps in the textile, apparel and fashion industries[J]. *Environment, Development and Sustainability*, 2024, 26(2): 2837-2864.
[50] SCRUCCA F, BARBERIO G, FANTIN V, et al. Carbon footprint: concept, methodology and calculation[M]//SUBRAMANIAN S M. Carbon Footprint Case Studies: Municipal Solid Waste Management, Sustainable Road Transport and Carbon Sequestration. Singapore: Springer Singapore, 2021: 1-31.
[51] MORRIS J, KOEP L, DAMERT M. Labels in the textile and fashion industry: communicating sustainability to effect sustainable consumption[M]//MATTHES A, BEYER K, CEBULLA H, et al. Sustainable Textile and Fashion Value Chains: Drivers, Concepts, Theories and Solutions. Berlin: Springer, 2021: 257-274.
[52] LI Y, LUO Y, HE Q. Chemical footprint of textile and apparel products: an assessment of human and ecological toxicities based on USEtox model[J]. *The Journal of the Textile Institute*, 2020, 111(7): 960-971.
[53] LIU M, LI X, LI J, et al. A knowledge graph-based data representation approach for IIoT-enabled cognitive manufacturing[J]. *Advanced Engineering Informatics*, 2022, 51: 101515.
[54] QIN Z, LU Y. A knowledge graph-based knowledge representation for adaptive manufacturing control under mass personalization[J]. *Manufacturing Letters*, 2023, 35: 96-104.
[55] SIDDHARTH L, BLESSING L T M, WOOD K L, et al. Engineering knowledge graph from patent database[J]. *Journal of Computing and Information Science in Engineering*, 2022, 22(2): 021008.
[56] LAI X. Bottleneck prediction and resilience improvement for manufacturing systems[D]. Ann Arbor: University of Michigan, 2022.
[57] TANG J, LIU Y, LIN K, et al. Process bottlenecks identification and its root cause analysis using fusion-based clustering and knowledge graph[J]. *Advanced Engineering Informatics*, 2023, 55: 101862.
[58] WU T, LI J, BAO J, et al. CarbonKG: industrial carbon emission knowledge graph-based modeling and application for carbon traceability of complex manufacturing process[J]. *Journal of Computing and Information Science in Engineering*, 2024, 24: 081001.
[59] VASWANI A, SHAZEER N, PARMAR N, et al. Attention is all you need[C/OL]. The 31st Annual Conference on Neural Information Processing Systems (NIPS). La Jolla: Neural Information Processing Systems (NIPS), 2017, 30[2024-03-01]. https://proceedings.neurips.cc/paper_files/paper/2017/file/3f5ee243547dee91fbd053c1c4a845aa-Paper.pdf.
[60] WU Z, PAN S, CHEN F, et al. A comprehensive survey on graph neural networks[J]. *IEEE Transactions on Neural Networks and Learning Systems*, 2021, 32(1): 4-24.
[61] WANG L. From intelligence science to intelligent manufacturing[J]. *Engineering*, 2019, 5(4): 615-618.
[62] ZHOU J, CUI G Q, HU S D, et al. Graph neural networks: a review of methods and applications[J]. *AI Open*, 2020, 1: 57-81.
[63] VELIČKOVIĆ P, CUCURULL G, CASANOVA A, et al. Graph attention networks[EB/OL]. (2018-02-04)[2024-07-13]. https://arxiv.org/abs/1710.10903.
[64] LUO L H, FANG Y X, LU M L, et al. GSim: a graph neural network based relevance measure for heterogeneous graphs[J]. *IEEE Transactions on Knowledge and Data Engineering*, 2023, 35

(12): 12693-12707.
[65] SENTHIL KUMAR P, JANET JOSHIBA G. Energy footprints of textile products [M]// SUBRAMANIAN S M. Energy Footprints of the Food and Textile Sectors. Singapore: Springer Singapore, 2019: 45-61.
[66] KARTHIK T, GOPALAKRISHNAN D. Environmental analysis of textile value chain: an overview [M]//SUBRAMANIAN S M. Roadmap to Sustainable Textiles and Clothing: Environmental and Social Aspects of Textiles and Clothing Supply Chain. Singapore: Springer Singapore, 2014: 153-188.
[67] ROY CHOUDHURY A K. Environmental impacts of the textile industry and its assessment through life cycle assessment [M]// SUBRAMANIAN S M. Roadmap to Sustainable Textiles and Clothing: Environmental and Social Aspects of Textiles and Clothing Supply Chain. Singapore: Springer Singapore, 2014: 1-39.
[68] ZAMAN S U, UMAIR M, JAVID A. Sustainable production practices in textiles[M]// BATOOL S R, AHMAD S, NAWAB Y, et al. Circularity in Textiles. Berlin: Springer, 2023: 129-157.
[69] KOPF S, ÅKESSON D, SKRIFVARS M. Textile fiber production of biopolymers: a review of spinning techniques for polyhydroxyalkanoates in biomedical applications[J]. *Polymer Reviews*, 2023, 63(1): 200-245.
[70] FARHANA K, KADIRGAMA K, MAHAMUDE A S F, et al. Energy consumption, environmental impact, and implementation of renewable energy resources in global textile industries: an overview towards circularity and sustainability[J]. *Materials Circular Economy*, 2022, 4(1): 15.
[71] RAJ A, CHOWDHURY A, ALI S. Green chemistry: its opportunities and challenges in colouration and chemical finishing of textiles[J]. *Sustainable Chemistry and Pharmacy*, 2022, 27: 100689.
[72] DE OLIVEIRA C R S, DA SILVA A H, MULINARI J, et al. Textile re-engineering: eco-responsible solutions for a more sustainable industry [J]. *Sustainable Production and Consumption*, 2021, 28: 1232-1248.
[73] MOAZZEM S, CROSSIN E, DAVER F, et al. Assessing environmental impact reduction opportunities through life cycle assessment of apparel products[J]. *Sustainable Production and Consumption*, 2021, 28: 663-674.
[74] STANESCU M D. State of the art of post-consumer textile waste upcycling to reach the zero waste milestone[J]. *Environmental Science and Pollution Research*, 2021, 28(12): 14253-14270.
[75] HE B, YUAN X, QIAN S S, et al. Carbon neutrality: a review[J]. *Journal of Computing and Information Science in Engineering*, 2023, 23(6): 060809.
[76] MA S Y, DING W, LIU Y, et al. Digital twin and big data-driven sustainable smart manufacturing based on information management systems for energy-intensive industries [J]. *Applied Energy*, 2022, 326: 119986.
[77] ZHAO X, MA X W, CHEN B Y, et al. Challenges toward carbon neutrality in China: strategies and countermeasures[J]. *Resources, Conservation and Recycling*, 2022, 176: 105959.
[78] HE B, MAO H Y. Digital twin-driven product sustainable design for low carbon footprint[J]. *Journal of Computing and Information Science in Engineering*, 2023, 23(6): 060805.
[79] KWON S, MONNIER L V, BARBAU R, et al. A new implementation of ontostep: flexible generation of ontology and knowledge graphs of express-driven data[J]. *Journal of Computing and Information Science in Engineering*, 2022, 22(2): 024502.
[80] GENG Z Q, ZHANG Y H, LI C F, et al. Energy optimization and prediction modeling of petrochemical industries: an improved convolutional neural network based on cross-feature[J]. *Energy*, 2020, 194: 116851.
[81] DING S, XU N, YE J, et al. Estimating Chinese energy-related CO_2 emissions by employing a novel discrete grey prediction model[J]. *Journal of Cleaner Production*, 2020, 259: 120793.
[82] ZHU J W, HAN X, DENG H H, et al. KST-GCN: a knowledge-driven spatial-temporal graph convolutional network for traffic forecasting[J]. *IEEE Transactions on Intelligent Transportation Systems*, 2022, 23(9): 15055-15065.
[83] HANS A, CHAUDHARI A M, BILIONIS I, et al. A Bayesian hierarchical model for extracting individuals' theory-based causal knowledge[J]. *Journal of Computing and Information Science in Engineering*, 2023, 23(3): 031011.
[84] ZHENG H B, LIU S M, ZHANG H J, et al. Visual-triggered contextual guidance for lithium battery disassembly: a multi-modal event knowledge graph approach[J]. *Journal of Engineering Design*, 2024: 1-26.
[85] FU T J, LI P Y, LIU S M. An imbalanced small sample slab defect recognition method based on image generation[J]. *Journal of Manufacturing Processes*, 2024, 118: 376-388.
[86] SHEN X W, LIU S M, ZHANG C, et al. Intelligent material distribution and optimization in the assembly process of large offshore crane lifting equipment[J]. *Computers & Industrial Engineering*, 2021, 159: 107496.

[87] SHI Y L, ZHANG N, SONG X L, et al. Novel approach for industrial process anomaly detection based on process mining[J]. *Journal of Process Control*, 2024, 136: 103165.

可持续纺织生产碳图谱在碳追溯领域的应用潜力和挑战：综述

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摘　要：纺织生产因其生产价值的重要性、工艺流程的复杂性、供应链的广泛性以及能源消耗的密集性等特点而备受关注。纺织行业不仅消耗大量的能源和物料，其排放的温室气体也对环境造成严重破坏。在应对这一挑战的过程中，可持续生产的理念为纺织行业的可持续发展提供了重要指导。低碳制造技术通过优化生产流程、提高能源利用效率和减少材料浪费，为纺织行业实现低碳转型提供了强有力的技术支持。因此，低碳制造技术已逐步被应用在可持续纺织生产的案例中。然而，尽管对纺织生产低碳制造技术的研究已经取得了一定的进展，但这些研究主要侧重于理论方法，对于实践应用的探索相对不足。针对这种情况，该文对纺织生产碳排放管理方法、工具和纺织生产关键工艺碳排放的特征与影响因素进行了全面总结，以识别其中的共性问题，并引入了“碳图谱”和“碳追溯”这两个新概念，为可持续纺织生产的低碳发展提供了策略建议，指出了应用方向。从可持续纺织生产的七个关键方面出发，系统性地总结了纺织生产过程中碳排放的特征与影响因素。旨在通过深入研究各环节的碳排放情况和影响因素，为未来的减排工作提供具体指导和优化方案。此外，总结了碳图谱技术在实现碳追溯方面的潜力和挑战，并提出了若干研究思路和建议。

关键词：可持续纺织生产；碳图谱；碳追溯；低碳发展；减排