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Hot Spots and Trends of Textiles with Herbal Dyes

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Article

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ABSTRACT

With the strengthening of environmental awareness and the concept of health, using non-toxic and environmentally friendly herbs on textiles has become an important research issue. It has attracted increasing attention from the academic community. This study systematically reviewed and visualized 474 papers related to herbal dyeing of textiles collected from the Web of Science and Scopus databases using the bibliometric tool CiteSpace to analyze the relevant literature in the past 10 years (2015-2024). This study constructed a knowledge graph framework for herbal dyeing research, focusing on the analysis of keyword co-occurrence knowledge graph, keyword clustering, keyword prominence, Cited References and Authors Analysis, and national cooperation network. The results show that the evolution trend in the field of herbal dyeing of textiles can be summarized into four main aspects: raw materials and dyeing technology, sustainability and new mordants, functional applications and medical textiles and bioactivity. Herbal dyeing is not only an environmentally friendly alternative, but also a new textile technology that combines science and technology, functionality and medical value. This study provides data support and theoretical reference for subsequent research by sorting out the core research directions and development context in this field.

KEYWORDS

textiles, herbal dyeing, citespace, hot spots, trends

INTRODUCTION

Clothing is our second skin and plays an important role in human life [1]. The European Commission studied the possible correlation between the chemicals used in textile finishing and allergic reactions, reporting that textile finish resins and other textile auxiliaries can induce allergic contact dermatitis [2]. According to research carried out by the Italian Contact and Environmental Dermatitis Research Group, clothing accounts for 8.5% of non-occupational contact dermatitis, with it being the fourth most important cause [3]. The potential unsafe factors of synthetic dye use have aroused widespread concern [4]. The word 'natural dye' covers all the dyes derived from natural sources like insects, and animals. Minerals, fungi, and various parts of the plants including roots, barks, leaves, flowers, skin, foliage, nuts, berries, and herbs [5], as shown in Figure 1. It follows that natural dyes include plant dyes, some plant dyes have medicinal properties and impart healing qualities to the fabric. For example, lotus seed [6], mint [7], red sandalwood powder (*Ptrecarpus santalinus*) [8], grape seed [9]

etc. (refer to Table 1). Textiles finished or dyed from extracts of various medicinal herbs are called herbal tex-tiles. Among technical textiles, medical textiles are a promising product, which plays an important role in maintaining human health [1]. Herbs were used to create different colours and to provide various health benefits. The natural/herbal fabrics are 100% organic, completely free of synthetic chemicals, and toxic irritants, and are biodegradable [10]. Herbal products derived from plants are gaining popularity worldwide for use in textiles because of their easy availability, green approach, low toxicity, biocompatibility, and eco-friendly nature [11-13]. Herbal extracts are being used successfully for imparting antimicrobial finish to textiles [12]. In these last few decades especially, researchers have been focusing more and more on the various aspects of herbal dyes [14]. Despite the increasing academic interest in herbal dyeing, there remains a gap in systematically mapping research hotspots and emerging trends in this field. While previous studies have explored the environmental and health benefits of herbal dyes, few have comprehensively analyzed the evolution of research themes, interdisciplinary collaborations, and global development patterns using bibliometric techniques. This study used CiteSpace to conduct a quantitative and visual analysis of scholarly publications related to herbal dyeing in textiles. By identifying key research clusters, major contributing institutions, and international collaborations, this study provides a structured overview of the field's trajectory, offering a valuable reference for future research and innovation in sustainable textile dyeing.

Table 1. Comparison of the main differences between natural dyes, plant dyes and herbal dyes

Name	Natural Dye	Plant Dye	Herbal Dye
Dye Source	Plants, minerals, insects	Only plants	Medicinal herbs with therapeutic properties
Functional Benefits	No	No (unless the plant has medicinal properties)	Yes (antibacterial, UV protection, anti-inflammatory, etc.)
Sustainability	High	High	High
Application Scope	Sustainable fashion, traditional dyeing crafts	Natural clothing, eco-friendly home textiles	Medical textiles, wellness clothing, Ayurvedic textiles
Example	Cochineal (animal-based red dye)[15]	Dried Papaya Leaves [16], Coconut Fiber [17], Date Palm Skin[18]	lotus seed [6], mint [7], red sandalwood powder (*Ptrecarpus santalinus*) [8], grape seed [9]

The word medication is used instead of dyeing because medicinal herbs are used to impart the required colour to fabric or yarn [19,20]. Several natural dyes have been demonstrated to possess antimicrobial activity. These natural antimicrobial agents may significantly reduce the risk of infections especially when they are used in close contact [1]. Herbal cloth production by a particular method is accomplished by utilizing extracts of selected herbs for dyeing cotton/silk/linen, yarn, and fabric [21].

Research has shown that natural dyes may lend several functional properties to textiles, such as antibacterial, antifungal, UV protective, insect repellent, and aromatic properties [3]. Improvement in UV protection characteristics of natural cellulosic fibres after treatment with natural dyes has been reported by various researchers [16-18]. Textiles dyed with such materials are also likely to show antimicrobial properties and the same has been reported by many researchers [22,23].

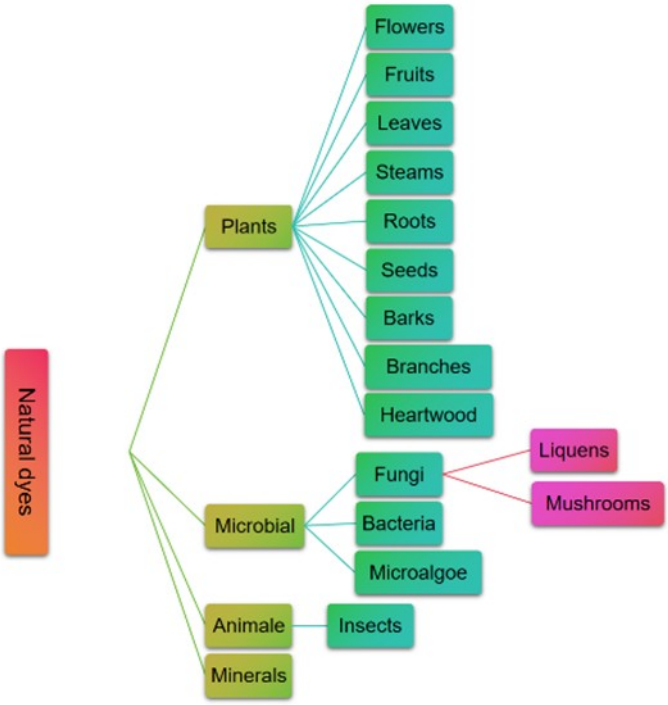

Figure 1. Classification of natural dyes based on their origin/s [24]

Traditional herbal dyeing of textiles usually follows the traditional dyeing process (refer to Figure 2). Modern methods of extraction and dyeing such as ultrasonic radiation, ultraviolet radiation, microwave radiation, and gamma rays have aided the green dyeing process by increasing colour strength and colourfastness [25]. Mordants are used to improve the colour quality and fastness of natural dyes. Mordants are essential for dyeing many natural dyes through the development/interaction between fibre, mordant and dye. Bio-mordants can better protect the environment and bring out the efficacy of herbal dyeing, so for herbs such as bio-mordant dyeing, turmeric rhizome, henna leaves, acacia bark, pomegranate peel, Amaltas bark, pomegranate peel, Anar phallic fruit and Arjun bark etc. are also highly concerned topics [8].

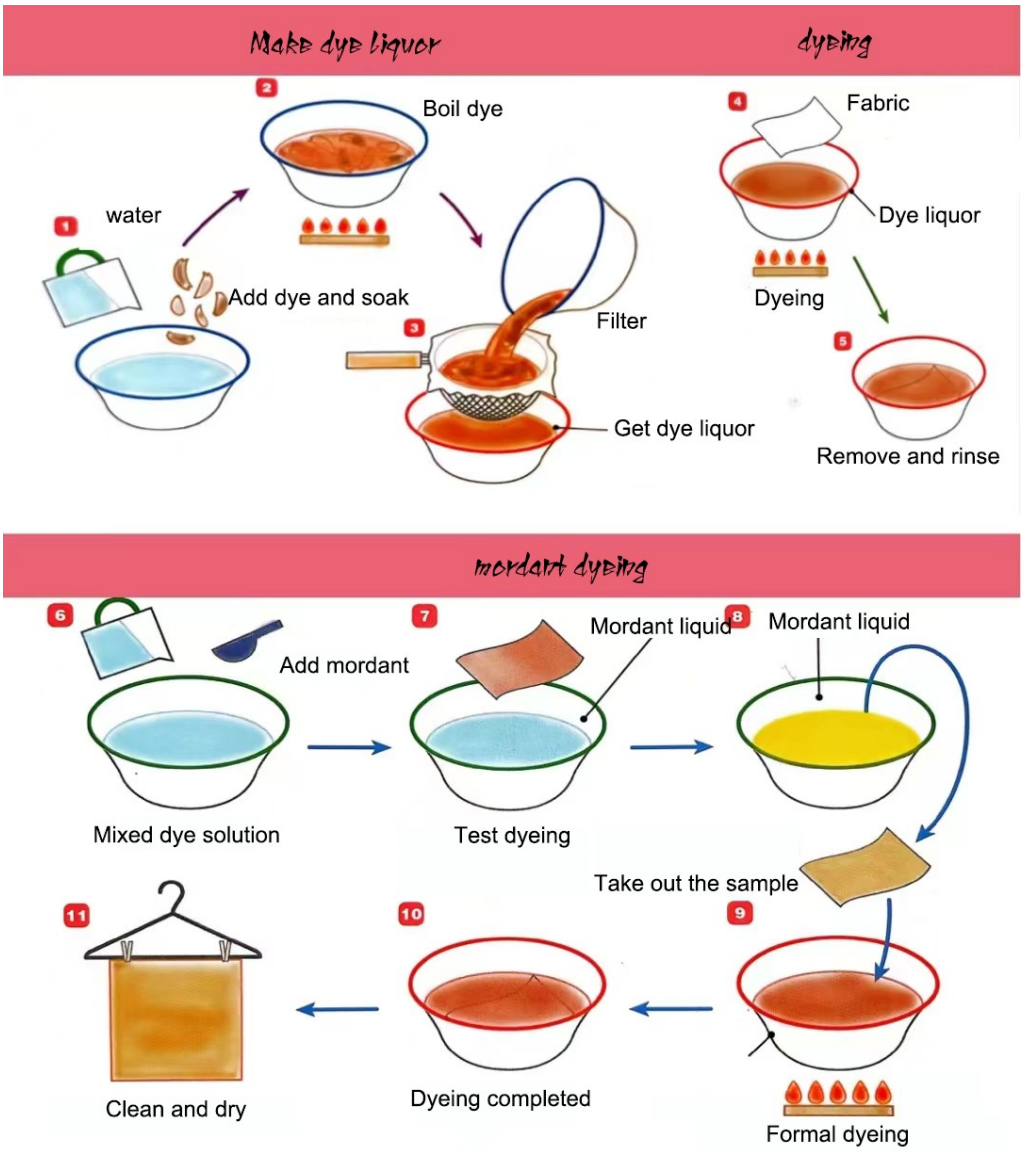

Figure 2. The traditional dyeing process

Recently, 'sustainability' and the erroneous assumptions that natural = harmless, and synthetic = toxic have prompted a voluminous research cited references that (re) examine natural dyes [26]. Against this backdrop, there has been a growing academic interest in the application of herbal dyes in textile dyeing. This study provides a comprehensive review of research on "herbal dyeing in textiles" since 2015 and conducts an in-depth analysis of the following four key questions:

Q1. What are the keywords studied in the cited references on herbal textile dyeing?

Q2. What are the research hotspots in the cited references on herbal textile dyeing?

Q3. What are the popular regions, institutions, and journals for studying herbal textile dyeing?

Q4. Based on the above analysis, what are the future research trends?

Based on the research findings of the above four objectives: 1) Analyze the research hotspots and development trends of herbal dyes. Utilize bibliometric methods to systematically review the research

themes of herbal dye applications in textiles, identifying key research directions, core keywords, and their temporal evolution. 2) Explore interdisciplinary collaboration and international research networks. Conduct co-citation and collaboration network analysis to examine interdisciplinary cooperation among chemistry, environmental science, and textile engineering, as well as assess academic collaborations between developing and developed countries. 3) Evaluate the sustainability and technological innovation pathways of herbal dyeing. Identify key advancements in green chemistry, technological innovations, and functional applications of herbal dyes, analyzing how current research contributes to the sustainable development of the textile industry. 4) Construct a systematic knowledge map to support future research and industrial practices. Develop a knowledge network through bibliometric analysis, summarizing the evolution of research findings to provide data-driven insights for academia and industry, promoting further advancements and applications of herbal dyeing technologies.

MATERIALS AND METHODS

This study used the bibliometric analysis tool CiteSpace to analyze the content of natural dye textile dyeing published in WOS and Scopus databases through keyword co-occurrence, keyword clustering, keyword prominence, document co-citation, publishing institution knowledge map, etc. Conduct a visual comprehensive analysis.

Data Collection

The methodological approach used is a systematic cited references review (SLR), which helps identify any of the academic cited references relevant to a particular research area, as well as for a critical evaluation and synthesis of an emerging yet already diverse research area, and critically evaluates the selected topic [27]. It aims to impartially unveil patterns, dynamics, and the impact of scientific publications, along with the interconnections between authors, institutions, and research topics [28]. To ensure rigour and appropriate literature collection, the selection of data followed the PRISMA protocol [29]. The study followed the instructions of the PRISMA protocol to ensure the methodological rigour and quality of the review [30-32]. As shown in Figure 3.

This article selects the Web of Science core database and Scoups as data sources, and the search conditions are keywords such as "herbal Textile Dying", "herbal Textile Dying", "herbal Textile", and "natural Textile Dying*herbal". The operator (that is OR and AND) searches for compatibility (represented by*) to identify related research documents. Herbal dyeing spans multiple disciplines, including agriculture, botany, chemistry, medicine, pharmacy, literature, and more. However, as this study focuses on the practical and theoretical aspects of herbal dyeing specifically within the textile industry, the research scope is limited to fields such as botany, pharmaceutics, environmental science,

social science, art, and commerce. Since 2015, the research on herbal-dyed textiles has increased significantly, showing a rapid upward trend. Therefore, this study defines the research timeline as January 1, 2015, to December 31, 2024. Based on the search criteria, a total of 357 relevant papers were retrieved from the Web of Science (WOS), and 326 papers from Scopus. The retrieved documents were carefully reviewed, and a second round of screening was conducted to exclude works unrelated to the research scope. After this screening process, only 474 articles aligned with the term "Herbal Textile Dyeing," with 239 articles from WOS and 235 from Scopus. These 474 papers were then exported for further analysis in this study.

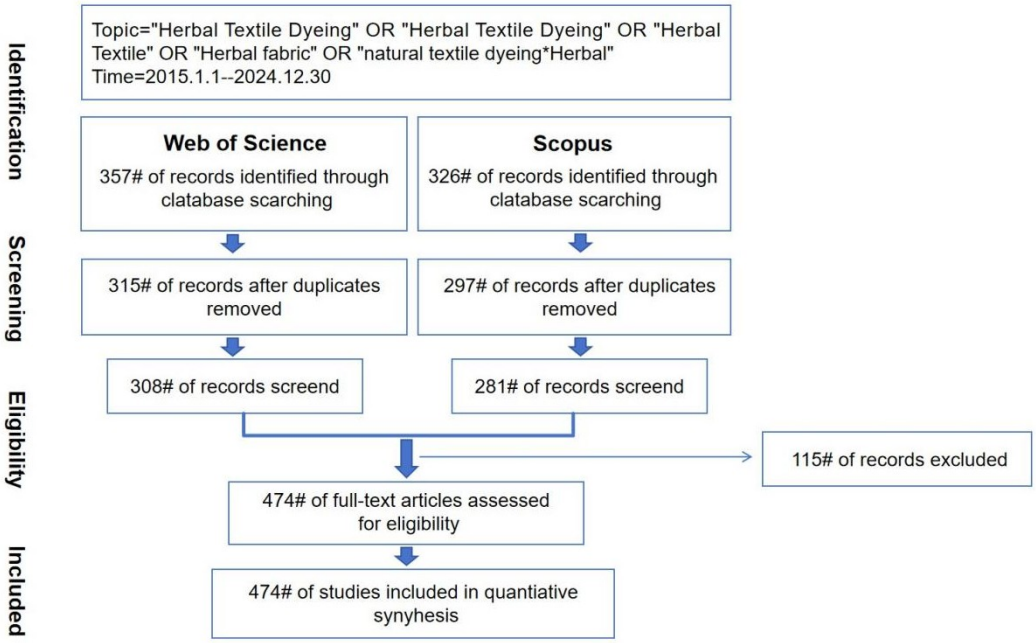

Figure 3. PRISMA flow

Tool Selection

Bibliometric methods are frequently employed across several academic disciplines such as business [33], management [34], and marketing [35,36], to examine scientific output and research patterns. CiteSpace is a citation visual analysis software, developed from the background of scientometrics and knowledge visualization, which is specifically used to identify potential knowledge contained in scientific cited references [37]. This study utilized Citespace version 6.3 to evaluate and analyze keyword co-occurrence, keyword clustering, keyword prominence, document co-citation, and the knowledge graphs of publishing institutions and countries. The study also summarized the connections between these elements and identified the underlying reasons for these trends. The findings were used to explore the primary research areas in herbal dyeing of textiles, as well as the new trends and shifts that have emerged over time.

Data Analysis

The data analysis of this paper includes the following steps: 1) Through the selection of 474 documents from WOS and Scopus, keyword clustering co-occurrence analysis and keyword prominence analysis were conducted to evaluate the research keywords of Chinese herbal dyeing for textiles and to review the research hotspots and development trajectory of research topics in the field of Chinese herbal dyeing for textiles in the past decade, to answer Questions 1 and Questions 2. 2) This study analyzes the co-cited documents and the countries with the most publications in this field and sorts out the associations between the journals with the highest publication volume and the countries. In this way, answer Question 3. 3) Based on the above analysis results, this study analyzes the future trend and upsurge of textile herbal dyeing.

RESULTS AND DISCUSSION

Keyword Co-Occurrence Analysis

The keywords were extracted from the article and refined to the core content of the article, revealing the main aspects covered by the content of the article. The repeated appearance of a keyword can reflect the research hotspot in a field [38]. This article conducts keywords in keywords in the keywords in herbal textile dyeing literature through Citespace. Calculate the frequency of keywords and Betweenness Centrality. If you have a knowledge map, you can obtain the main research content in the field of herbal textile dyeing research. Figure 4 is a keyword co-occurrence map in the field of herbal textile dyeing.

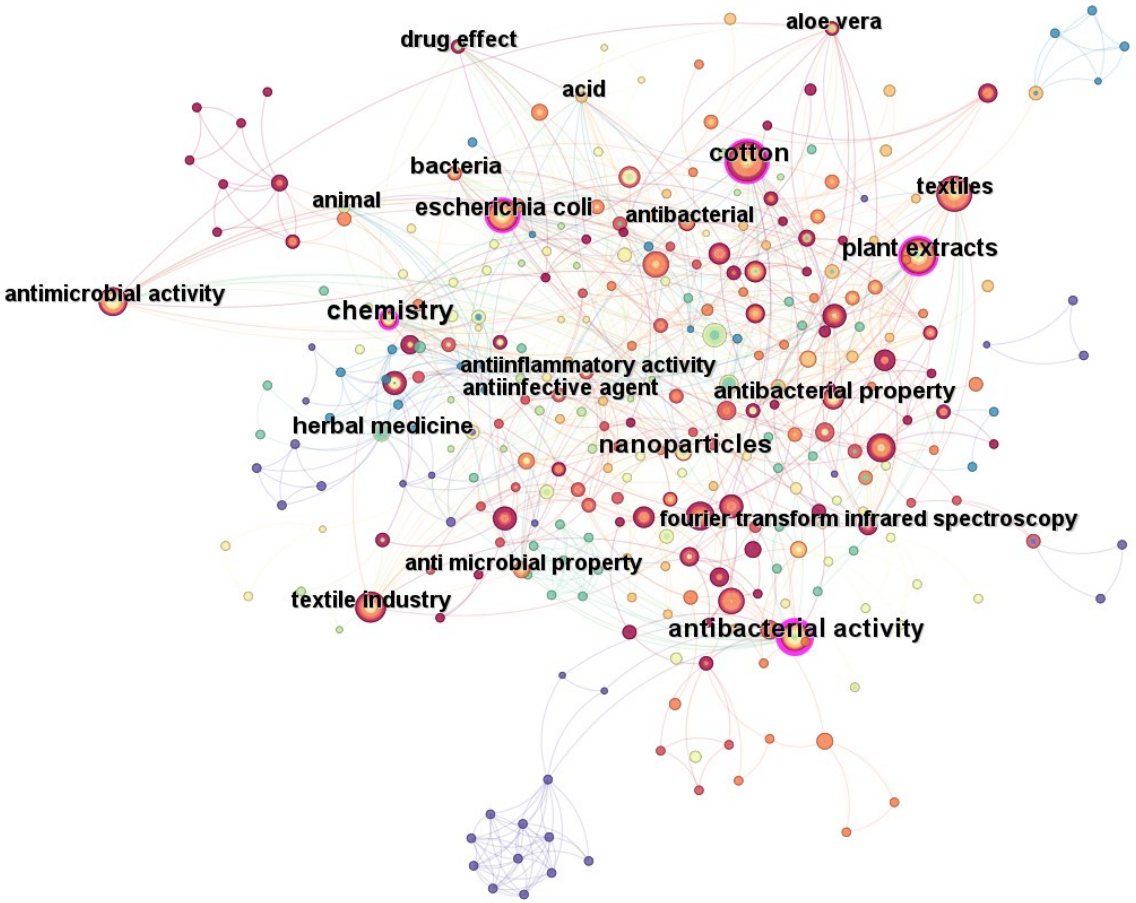

Figure 4. Keyword co-occurrence map in the field of herbal textile dyeing

When performing cluster analysis on keywords, representation words with similar semantics can be grouped into one category [39]. This study sorted the keyword nodes by usage frequency after merging synonyms. In addition to using the frequency of keywords to measure research hotspots, betweenness centrality is also an indicator for measuring the importance of nodes in the network. The betweenness centrality of a node is positively correlated with its link effect in the keyword network graph, that is, the higher the betweenness centrality of a node, the more keywords are associated with it, and the stronger its media function in the network graph. Nodes with a betweenness centrality exceeding 0.1 are called key nodes. It is generally believed that keywords with high frequency and strong betweenness centrality are research hotspots. As shown in Table 1. Comprehensively selecting keywords with a frequency greater than 15, in addition to cotton and plant extracts with high frequency and high betweenness centrality, antibacterial activity, chemistry, escherichia coli, textile industry, bacteria, nanoparticles, herbal medicine, Fourier transform infrared spectroscopy etc. are all hot topics of concern. This result shows that the main textile studied in herbal dyeing is cotton. Aiming at the antibacterial and other medicinal functions of fabrics, the innovative application of

nanoparticles, Fourier transform infrared spectroscopy and other scientific and technological means in the industrial production of textiles is also a hot research topic.

Table1. High-frequency keywords and betweenness centrality

No.	Keyword	Count	Centrality
1	cotton	61	0.15
2	plant extracts	46	0.10
3	textiles	42	0.07
4	chemisty	41	0.13
5	escherichia coli	41	0.14
6	antibacterial activity	28	0.06
7	textile industry	30	0.06
8	drug effect	29	0.07
9	bacteria	25	0.13
10	herbal medicine	23	0.05
11	nanoparticles	19	0.03
12	antibacterial property	17	0.09
13	essential oils	17	0.04
14	fourier transform infrared spectroscopy	15	0.04
15	staphylococcus aureus	15	0.03

Research Trend Analysis

By calculating the temporal distribution of keyword frequencies, we can identify the mutation terms with high growth rates and fast frequency increases. Analyzing these mutation terms allows for the identification of the frontier areas and development trends in textile herbal dyeing research. Figure 5 presents the mutation term knowledge map of textile herbal dyeing research from 2015 to 2024 (with minmumduration=2, r=0.2). Based on this analysis, the research on textile herbal dyeing can be roughly divided into three stages.

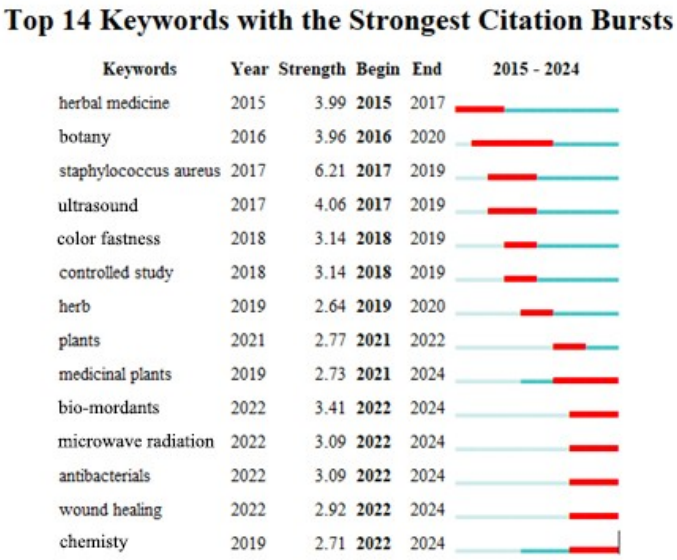

Figure 5. Keyword emergence from 2015-2024

Based on the keyword burst analysis, research on herbal dyeing in textiles over the past decade can be divided into three phases.

Phase 1 (2015-2017): Fundamental Research and Exploration of Herbal Sources. During this period, research primarily focused on the botanical sources and fundamental properties of herbal dyes. Keywords such as "herbal medicine" and "botany" indicate academic interest in extraction [40], chemical composition [41-43], and dyeability of plant pigments [44,45], laying the theoretical foundation for herbal dyeing.

Phase 2 (2018-2021): Process Optimization and Performance Enhancement. This phase saw advancements in dyeing techniques and sustainability improvements. Keywords such as "ultrasound", "colour fastness", and "bio-mordants" reflect efforts to enhance dye uniformity, colourfastness, and eco-friendliness through technologies like ultrasound-assisted dyeing [46-48], and plasma treatment [49]. Additionally, research into antibacterial properties [50-52] (staphylococcus aureus, antibacterials) gained traction, driving the application of herbal dyes in medical textiles.

Phase 3 (2022-2024): Functional Expansion and Interdisciplinary Integration. Recent research has shifted towards functional applications and chemical mechanisms. Keywords such as "wound healing" and "chemistry" highlight the growing interest in antibacterial [53] and wound-healing properties of herbal-dyed textiles. Increased interdisciplinary collaboration, involving green chemistry [54,55], materials science [56], such as Cashew (Anacardium occidentale L) [57], mangiferin [58] etc. and medical research, such as female vaginitis active ingredients of 16 kinds of natural herbal medicine extracts and dyeing effect on cotton fabric etc. [59], are further expanding their potential in medical and high-performance textiles.

The development of herbal dyeing research follows a trajectory from [44] fundamental exploration to process optimization and functional innovation. Future research is expected to focus more on sustainable dyeing processes and the development of functional textiles.

Keywords clustering Analysis

A single keyword can directly reflect the attention paid to the research. The cluster analysis of keywords can better reflect the structural characteristics of knowledge production. Its clustering logic is to classify relatively homogeneous keywords into the same group. In this paper, 474 papers formed 15 clustering indicators. The average S value is 0>0.8 (0>0.7), indicating that the clustering results are significant and efficient. These 15 clusters reflect the topic distribution of current research on herbal dyeing of textiles. The label of each cluster is the keyword in the co-occurrence network. The cluster number is #0 - #16. The larger the cluster number, the fewer keywords it contains. Conversely, the smaller the number, the more keywords it contains. Most of the connections in the graph are within the cluster, but there are still some connections across clusters. For example, there are many cross-cluster connections between the two clusters #0 Green chemistry and #5 Herbal extracts, indicating that the co-citation degree between these research directions is high (as shown in Figure 6).

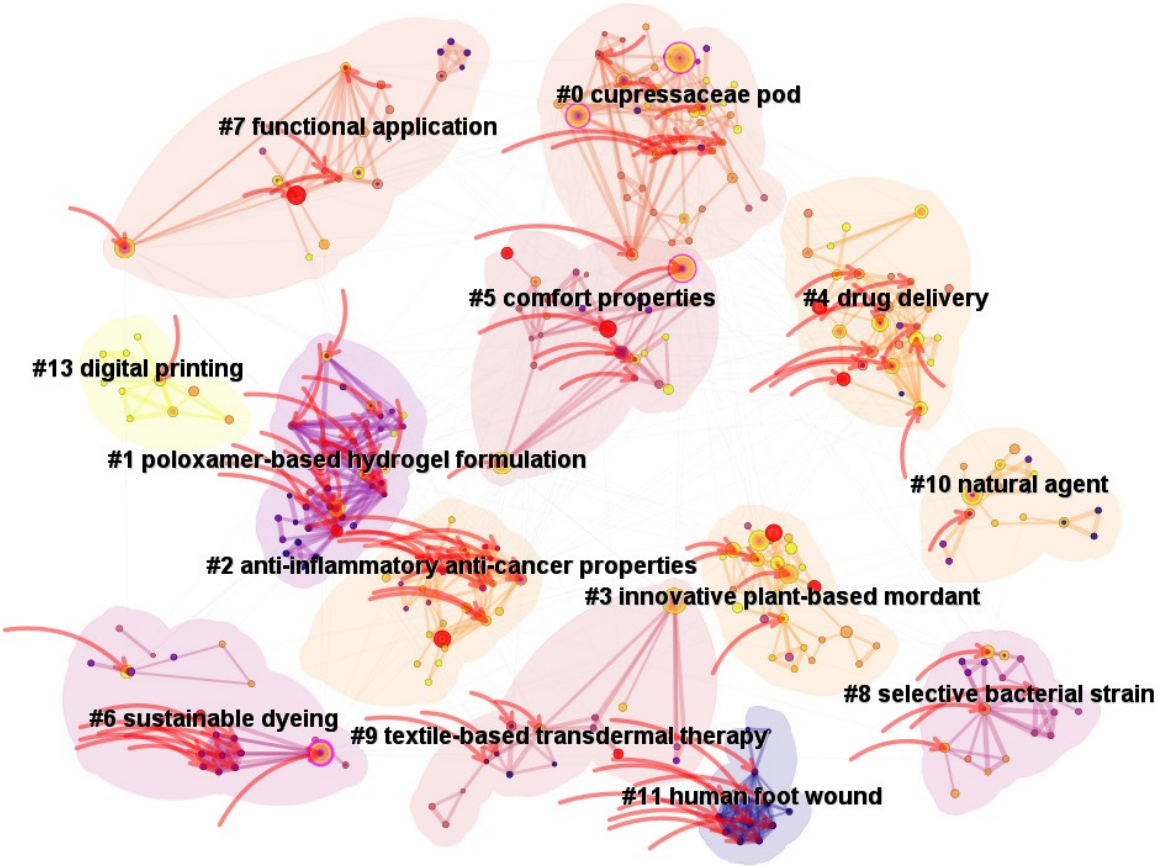

Figure 6. Keywords clustering knowledge map

The results of the keyword cluster analysis revealed the key research directions and thematic connections of herbal-dyed textiles in the past decade. These clusters can be divided into four core modules: (1) raw materials and dyeing technology, (2) sustainability and innovative mordants, (3) functional applications, and (4) medical textiles and bioactive properties.

Theme 1. The raw materials and dyeing technology

The raw materials and dyeing technology module mainly involves the selection of raw materials, the extraction of plant pigments, and the development of new mordants, reflecting the progress of sustainable dyeing technology. #0 Cupressaceae pods indicate the growing interest in using Cupressaceae plants (such as cypress) for Chinese herbal dyeing due to their natural pigments and bioactive compounds. #10 Natural agents explore the natural sources of Chinese herbal dyeing, focusing on plant pigments and their stability. #3 Innovative plant mordants The research focuses on finding environmentally friendly plant mordants as alternatives to traditional metal mordants (such as aluminium salts and iron salts) to improve the fixation rate and colour fastness of dyes.

Theme 2. The sustainability and emerging dyeing

The sustainability and emerging dyeing methods module includes the transformation of herbal dyes to inkjet and other digital printing methods. #6 Sustainable dyeing. The research focuses on reducing water pollution, chemical waste and energy consumption in herbal dyeing to enhance environmental sustainability. #13 Digital printing reflects the trend of environmental protection and technology-driven innovation, promoting the efficient and low-carbon development of herbal dyeing.

Theme 3. Functional application

The functional application module emphasizes that herbal dyeing is not only about colouring but also about enhancing the functionality of textiles, with increasing attention paid to skin-friendly and biocompatible materials. #7 Functional application. The research explores other properties of herbal dyed textiles, such as antibacterial, UV protection and antioxidant effects. #5 Comfort properties focus on the skin-friendliness, breathability and softness of herbal-dyed textiles.

Theme 4. Medical textiles and bioactive properties

This module focuses on the growing medical potential of herbal dyeing, especially in antibacterial, anti-inflammatory, wound healing and drug delivery applications, promoting its application in healthcare textiles. #2 Anti-inflammatory and anti-cancer properties. Some herbal dyes exhibit anti-inflammatory, antioxidant and even anti-cancer properties, expanding their application in medical textiles. #4 Drug delivery is to explore the potential of herbal dyed textiles as controlled-release drug carriers, such as

therapeutic gowns or wound dressings. #9 Textile-based transdermal therapy Studying how herbal dyed textiles can promote the absorption of bioactive compounds through the skin and contribute to the innovation of medical textiles. #11 Human foot wounds Herbal dyed textiles are suggested for wound healing, especially in preventing infection and tissue regeneration. #8 Selective bacterial strains are associated with the effectiveness of herbal dyes against specific pathogens, thus promoting their incorporation into medical textiles. #1 Poloxamer-based hydrogel formulations suggest the study of combining herbal dyed textiles with hydrogels for drug release and moisturizing.

The development of research in this field shows that herbal dyeing is not only an environmentally friendly alternative, but also a high-potential innovation that combines technical, functional and medical values. In the future, it is expected to play an important role in the development of sustainable dyeing, smart medical textiles and functional clothing.

Cited References and Authors Analysis

Figure 6 shows the author's collaboration network in the field of herbal dyed textiles, reflecting the scholars who have published more papers in this research field and their collaborations. From a structural point of view, the figure can be divided into two main collaboration groups, the core author group and the earlier research group.

1. Main research group

(1) The red cluster represents the core author group. The main core authors include Adedayo TE (2021), Jabar JM (2020), and Habib N (2021); the main collaborators include Adeel S (2021), Thakker AM (2021), Sadeghi-Kiakhani M (2021), Phan K (2020), etc. This group is composed of scholars who published papers in 2020-2021, indicating that these authors have been active in the field of herbal-dyed textiles recently. Adedayo TE, Jabar JM and Habib N form a core node, indicating that they may have a high academic influence in this field and collaborate on multiple research projects. These scholars have conducted in-depth research on green dyeing technology, functional textiles and new plant mordants. (2) The green cluster represents an earlier research group, with core authors including Baaka N (2017) and Adeel S (2018); the main collaborators include Hosseinnezhad M (2022) and others. The research of this group started earlier (2017-2018), but there are still scholars (such as Adeel S (2022) and Hosseinnezhad M (2022)) who continue research in this direction. They have made contributions to the basic research of early natural dyes and plant mordants, laying the foundation for subsequent applied research.

Adeel S is an important bridge author. He appears in two different research groups (2018 and 2021/2022), indicating that the author has been active in this field for a long time and plays a key academic bridge role in multiple teams. From early research on natural dyeing mechanisms to more modern sustainable dyeing methods.

From the perspective of network structure, the collaborations in 2020-2022 are more intensive, indicating that the research activity in this field has increased significantly in recent years, and the collaboration between scholars has become closer. This trend may benefit from the increased global attention to sustainable dyeing technology, environmentally friendly textiles, and plant mordants.

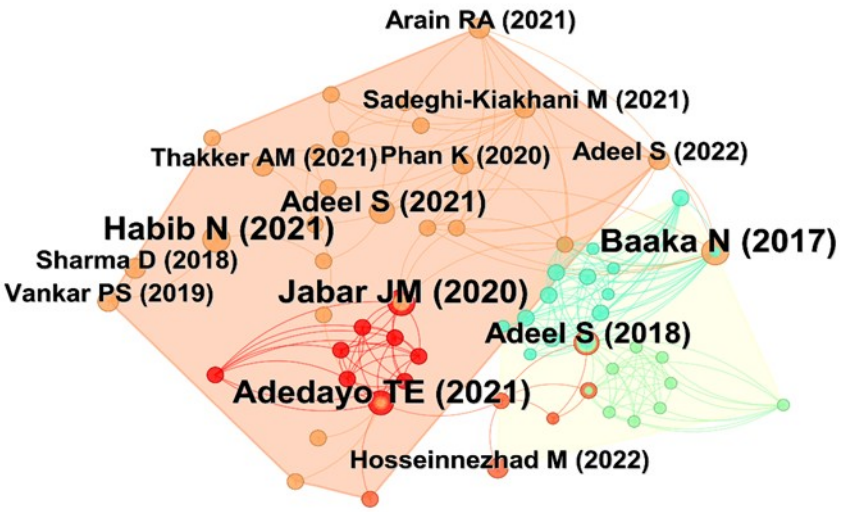

Figure 6. The Most Cited References and Authors in The Herbal Textile Dyeing

Country Analysis

According to the number of research publications on herbal dyeing of textiles in the past decade shown in Figure 7, the ranking of countries is: India, Iran, Pakistan, Turkey, China, United Kingdom, Bangladesh, Nigeria, USA, and Scotland. The author's analysis may be related to the following factors: Historically, South Asia has a deep tradition of herbal dyeing. For example, India has a long history of using natural dyes, and herbal dyeing technology has always played an important role in local textile production. The research on natural dyes in these countries is not only driven by traditional handicrafts but also rich in agricultural resources. The plants required for herbal dyes can be easily obtained locally, reducing experimental and production costs.

Herbal dyeing technology is closely related to the culture and natural environment of the Middle East. In recent years, the Middle East has faced environmental pressure. Herbal dyeing technology has been supported by the government and academia due to its environmental protection and reduction of chemical pollution. Although China has abundant natural dye resources, chemical dyes still dominate the dyeing industry. The application and research of herbal dyeing technology are relatively lagging. Although the attention to environmentally friendly dyeing has increased in recent years, it has not yet been fully popularized.

In China's textile production, herbal dyeing, as a niche environmental protection technology, has a relatively small market demand, resulting in relatively few research results.

Research in Western countries is more inclined to develop new environmentally friendly dyes or other alternative technologies, such as enzyme dyeing, biodegradable dyes, etc., so the research on herbal dyeing has not dominated.

With the increase in global attention to environmental protection, herbal dyeing, as a green and environmentally friendly dyeing method, has been supported by academia and governments in various countries. Natural dyeing technology in developing countries helps promote the development of their own economies and textile industries, while Western countries have relatively few related studies due to differences in technology maturity and market demand.

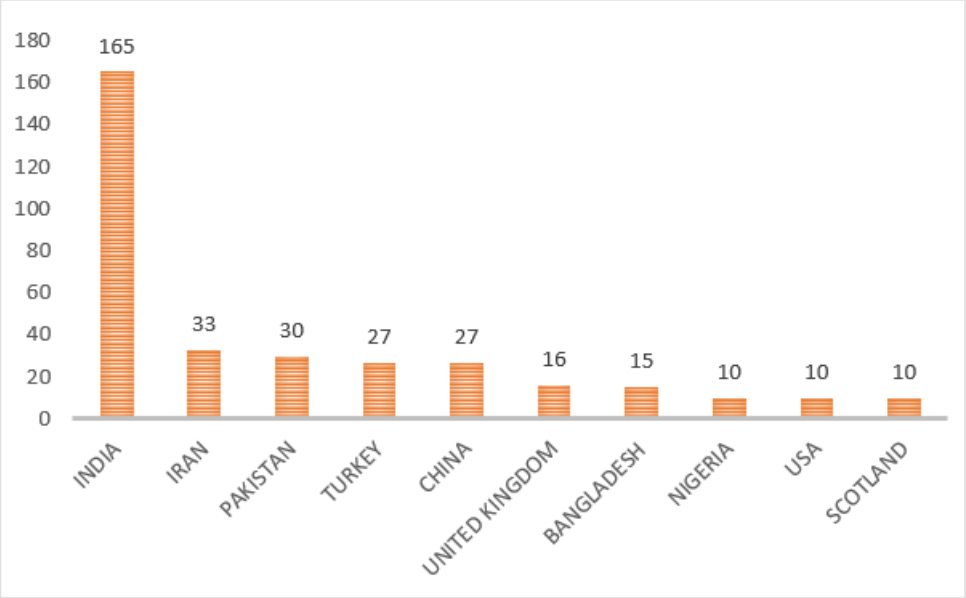

Figure 7. Number of publications for each geographical region in the world

DISCUSSION

The basic research stage focuses on the source of herbs, plant pigment extraction and chemical properties, laying a theoretical foundation for subsequent applied research.

In the process optimization stage, the research direction gradually develops towards improving dyeing technology, developing new mordants, and improving colour fastness. At the same time, modern dyeing processes such as ultrasound and microwave radiation are explored, and functional properties such as antibacterial and antioxidant properties are focused on.

In the functional expansion and sustainable development stage, the research focus shifts from traditional dyeing technology to green dyeing technology, medical textiles and interdisciplinary integration, involving bioactive functions such as anti-inflammatory, antibacterial, wound healing, and

drug delivery, promoting the application of herbal dyed textiles in high-performance and medical fields.

The analysis of the research cooperation network shows that Adeel S, as a key author across time, connects the early basic research group with the recent applied research group, and plays an important role in the transformation from basic theory to sustainable dyeing methods. In recent years, the research cooperation in this field has become increasingly close, especially between 2020 and 2022, when the research activity has increased significantly. Scholars such as Adedayo TE, Jabar JM, and Habib N have played a core role in recent research and formed a dense cooperation group.

Based on the analysis of this study, the researchers believe that the future research directions of herbal dyed textiles are mainly the following: 1) Development of new plant mordants, research on more environmentally friendly and efficient plant mordants to reduce the impact of traditional metal mordants on the environment. 2) Sustainable dyeing process, optimize the application of modern technologies such as ultrasound, microwave radiation and digital printing in herbal dyeing, and improve dyeing efficiency and durability. 3) Expansion of functional textiles, further study the antibacterial, antioxidant, and UV protection properties of herbal dyed textiles, and expand their application in medical, health care and high-end functional textiles. 4) Deepen interdisciplinary cooperation, strengthen cross-disciplinary research in green chemistry, materials science, biomedicine and other disciplines, and promote the industrialization and market application of herbal dyeing technology.

CONCLUSION

Research in the field of herbal dyeing textiles has expanded from plant pigment extraction to green dyeing processes and functional applications. In recent years, environmentally friendly technologies such as ultrasound and microwave radiation have been used to improve dyeing efficiency, and antibacterial, UV protection, and anti-inflammatory functions have become research focuses. However, this field still faces challenges in transforming laboratory research into industrialization [60], including improving dyeing stability, reducing production costs, and establishing industry standards. Although technologies such as bio-mordants and digital printing help reduce pollution, their stability, cost, and life cycle assessment still need to be optimized. Future research should combine synthetic biology and nanotechnology to improve the applicability of plant mordants and accelerate the promotion and application of new technologies. Herbal dyeing shows great potential in medical and functional textiles (such as antibacterial textiles and drug-releasing fabrics). However, insufficient functional verification and low market acceptance have become major obstacles to commercialization. It is recommended to strengthen interdisciplinary cooperation in medicine and biomaterials science,

establish unified testing standards, and enhance market recognition. The author's cooperation network shows that cooperation will be closer in 2020-2022, but research islands still exist. It is recommended to promote cross-border cooperation, open data sharing, and international academic exchanges to accelerate technological innovation. Future research should focus on technological innovation, interdisciplinary integration, industrial promotion and policy support to promote the development of highly stable bio-mordants, intelligent dyeing processes and standardized certification systems. Through multi-party cooperation, herbal-dyed textiles are expected to become an important innovation direction for the sustainable textile industry.

Conflicts of Interest

The authors declare no conflict of interest.

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