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A Systematic Literature Review on the Investigation and Application of Vegetable Fibers in Textiles/Apparel and Future Research Agenda

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ABSTRACT

Vegetable fibers have attracted increasing attention from researchers and manufacturers in the textile and apparel industry for their renewable, biodegradable, and eco-friendly features. However, due to the scattered nature and rapid development, a review that adopts a holistic perspective and analyzes the knowledge evolution structure of the vegetable fiber domain could hardly be found. This paper systematically reviewed the research progress and frontiers of the vegetable fiber domain over the past 25 years, with bibliometric analysis and knowledge mapping (by VOSviewer) of the 179 relevant articles retrieved from the Web of Science. A rapid increase in publications and citations was observed in the recent 5 years. India, China, and Turkey, with competitive textile industries and diverse agricultural sectors, have been active in vegetable fiber research. According to the clustering result of co-citation analysis, fiber-reinforced composites, vegetable fibers with sound/thermal insulation, and natural colorants were the main research topics with the most cited articles. “Knitting,” “insulation,” “Indian pineapple leaf,” and “color strength” were identified as the emerging research hotspots based on the keyword co-occurrence network. Future studies are expected to improve efficiency and automation, meanwhile decreasing the cost and environmental impact throughout the whole process chain of vegetable fibers.

摘要

植物纤维因其可再生、可生物降解和环保的特性，越来越受到纺织服装行业研究人员和制造商的关注. 然而，由于其分散性和快速发展，很难找到一种采用整体视角分析植物纤维领域知识演化结构的综述. 本文系统地回顾了过去25年来植物纤维领域的研究进展和前沿，对从Web of Science检索到的179篇相关文章进行了文献计量分析和知识图谱绘制（由VOSviewer完成）. 近五年来，出版物和引用量迅速增加. 印度、中国和土耳其拥有具有竞争力的纺织业和多样化的农业部门，一直积极从事植物纤维研究. 根据共引分析的聚类结果，纤维增强复合材料、具有隔音/隔热性能的植物纤维和天然色素是被引用最多的主要研究课题. 基于关键词共现网络，“针织”、“绝缘”、“印度菠萝叶”和“颜色强度”被确定为新兴的研究热点. 未来的研究有望提高效率和自动化程度，同时降低植物纤维整个工艺链的成本和环境影响.关键词

KEYWORDS

Vegetable fibers; cellulosic fibers; natural fibers; bibliometric; knowledge mapping; sustainability

关键词

植物纤维; 纤维素纤维; 天然纤维; 文献计量学; 知识图谱; 持续性

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Introduction

Natural cellulosic fibers have been utilized by humans since ancient times as food resources, body coverage, hunting and defending tools, and food storage vessels. Nowadays, natural fibers still have wide applications in textile and apparel, pulp and paper, packaging, building and furniture, cosmetics, medicine, and food products (Kicińska-Jakubowska, Bogacz, and Zimniewska 2012; Reddy and Yang 2005). Compared with synthetic fibers, natural fibers are low-cost and eco-friendly, as the main source of their production is solar energy, consuming little chemicals or fossil fuels. They are also biodegradable and recyclable during the post-use phase.

With the increasing environmental awareness among consumers, a trend toward "green products" has thrived in recent years. This also holds true for the textile and apparel industry. Apart from fibrous plants that are typically cultivated and harvested for textile materials, such as cotton, flax, and sisal, cellulosic fibers extracted from vegetables, including banana, pineapple leaf, coconut, okra, etc., have also been applied to textile products. Though vegetable fibers have been used interchangeably with cellulosic fibers (or plant fibers, vegetal fibers, biofibers) in some previous studies, it is specifically meant to refer to those non-traditional cellulosic fibers derived from vegetables in this study. As most of the vegetables that have been involved were originally grown as a food resource, with their non-edible portions contributing to textiles as byproducts, such applications further enhance sustainability and reduce carbon footprints by "turning waste into wealth."

Besides the economic and environmental benefits gained from vegetable fibers, some unique properties have been found due to their structures and compositions, such as the deodorization property of coffee extracts, thermal insulation and sound-absorbing properties of kapok fiber. Those additional functions extended the potential application of vegetable fibers and raised interest in both the commercial market and the academic field. However, due to the scattered nature of the relevant studies and its fast development just in recent years, there have not been many reviews on vegetable fiber research. Kicińska-Jakubowska, Bogacz, and Zimniewska (2012) summarized and listed the characteristics of different natural fibers from the aspect of fiber length and diameter, longitudinal and cross-section shape, together with their potential applications. Güven et al. (2016) focused on the research progress of natural fiber – reinforced polymeric composites, one of the main industrial applications of natural fibers. Both Geremew et al. (2021) and Chokshi et al. (2022) discussed the chemical and mechanical properties of natural fibers based on testing results from present studies.

Those reviews provided specific information about the properties of each type of vegetable fiber, whereas few of them adopted a holistic view of the whole domain. In addition to the knowledge itself, how it has been changing over time and space also matters. With the increasing research interest and fast development of vegetable fiber, analysis of the up-to-date progress in this field is of great necessity. It may help researchers identify research gaps and hotspots based on visualized mapping of the present research state, as well as inspire new applications of vegetable fibers among designers and manufacturers, who seek "greener" products to meet the market trends. This review was conducted based on a bibliometric analysis of present vegetable fiber research, utilizing VOSviewer, the knowledge-mapping and visualization tool, to scientifically and intuitively depict the development path and trending areas in this domain. It is expected that this systematic review could offer insight into the evolution of vegetable fiber research and guide researchers toward promising future hotspots.

Methodology

Literature retrieval and database establishment

The selection of academic database and the design of retrieval strategy would largely influence the quality of a dataset (Chen and Song 2017). To cover as much representative research on vegetable fibers as possible, a combined search based on keywords regarding various vegetable fibers was adopted. The main types of plant fibers are demonstrated in Figure 1. According to Güven et al.'s (2016) study, plant fibers could be classified into five categories, bast, leaf, fruit, seed, and stalk

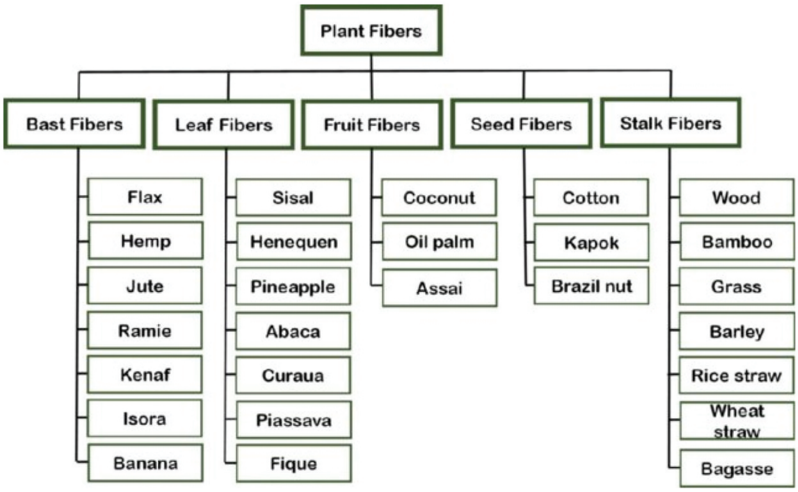


Figure 1. Classification of plant fibers (Güven et al. 2016).

fibers, each representing the specific portion that was utilized for fiber retrieval. Considering that cash crops such as cotton and flax have long been cultivated as the raw material for the textile industry, keywords “cotton,” “flax,” and “sisal” would be excluded from the search string, so as to shift the focus to the emerging new types of cellulosic fibers, which were originally used in other domains rather than textile and apparel industry.

Moreover, it was found that a great number of articles were relevant to the retrieval and application of vegetable oil instead of fiber. To clarify the research scope, research that included “vegetable oil” in its title was also removed. The query after adjustments was shown as below. The first part indicated the research with topics relevant to vegetable fibers or a specific type of them, while the second part limited the research to the textile or apparel domain:

TS=(vegetable fiber OR abaca OR brazil nut OR barley OR rice straw OR wheat straw OR bagasse OR Palm OR coconut OR banana OR pineapple leaf OR lotus OR kapok OR broomcorn OR okra OR olive OR coffee) AND TS=(textile OR fashion OR fabric OR apparel OR clothing OR yarn) NOT TI=(vegetable oil)

The search was performed in the Web of Science Core Collection (with “conference Proceeding Index for Science (CPCI-S)” and “Conference Proceedings Citation Index – Social Science & Humanities (CPCI-SSH)” removed). The time span was defined as “1998–2023 (updated to September 18, 2023)” to contain all the relevant publications during the past 25 years. “Material Science Textiles” was selected among the Web of Science categories to reclarify the research field. After a manual screening of the 225 articles, 179 of them were remained and downloaded in the form of full content and cited references for further analysis. The functions “Create Citation Report” and “Analyze Results” on Web of Science were used for basic analysis of the publication year, research area, and affiliations.

Visualization and interpretation

VOSviewer (version 1.6.19) was used in this study to perform the visualization of literature relevant to vegetable fibers. The software has been widely applied in bibliometric studies for its capability of data mining and constructing visualized networks. Co-occurrence and co-citation analysis would be conducted to detect and monitor the dynamic frontiers of the vegetable fiber domain. Co-occurrence analysis of keywords could reveal the research focuses and emerging new topics. Co-citation network, which shows publications that are frequently cited together, would be used to establish the main research branches and the significant outcomes from each branch with the detection of the most cited articles.

For most of the networks, three types of visualization results were generated by the software. Network visualization shows different clusters of items (keywords, authors, articles, etc.) in varied colors. The sizes of the nodes and labels are proportional to their weight, an attribute that indicates the importance of the item, while the distance between nodes represents their relatedness. The larger the size of the node, the higher weight it obtains; the closer the two nodes are, the stronger their relatedness. With a similar network, overlay visualization demonstrates the items in a different color system, which is in accordance with the score attributes. The score, not specifically defined in this study, refers to the time at which a node appears. The colors of nodes transform from blue to yellow, indicating their time of appearance changing from the earliest to the latest. Finally, density visualization is used to make a combined evaluation of the nodes from aspects of both the number and the weight of neighboring nodes. The color of items with higher density (neighboring nodes in larger quantities and with higher weight) should be closer to yellow than to green (Van Eck and Waltman 2018). The three types of visualization formats will be selectively adopted in this review considering the focus of analysis.

Results and discussions

Database analysis based on the Web of Science

Temporal distribution of vegetable fiber research

The yearly publications and citations in the research field of vegetable fibers during the past 25 years are depicted in Figure 2. The development process could be summarized into three stages. At the first stage from 1998 to 2008, little attention was paid to this domain, with only five relevant articles published in total during the decade. However, an emerging research focus of the vegetable fiber domain – natural dyeing – has already appeared in three out of the five articles (Gatewood et al. 1998; Hwang, Lee, and Kim 2008; Mathur and Gupta 2003). Hwang et al.'s research on the properties (color strength, color fastness, and deodorizing performance) of natural colorant extracts from gardenia,

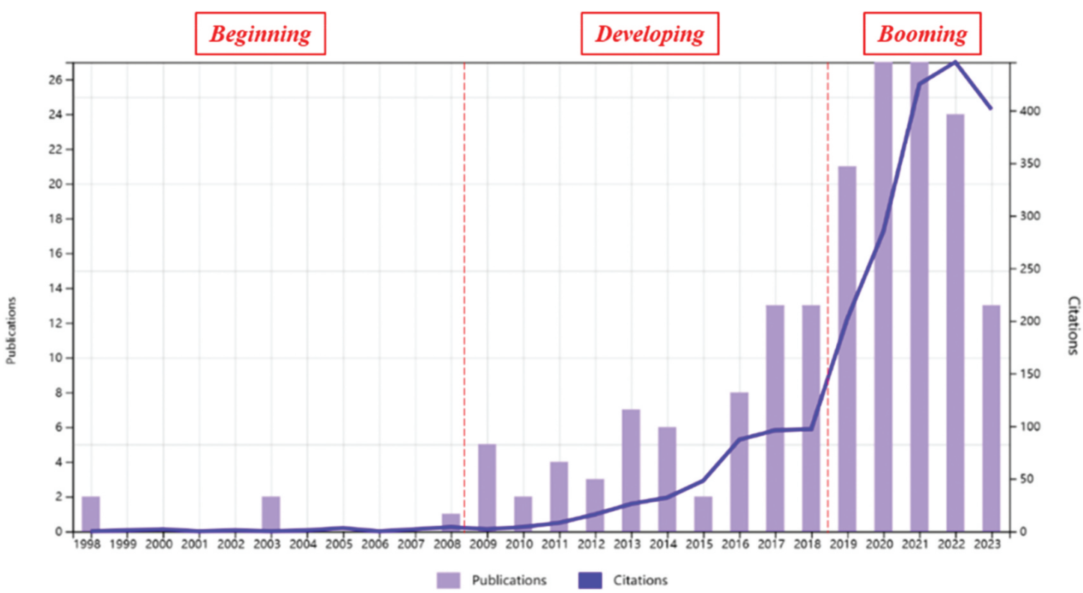


Figure 2. Total publications and citations per year from 1998 to 2023 retrieved from the web of science.

coffee sludge, Cassia tora. L., and pomegranate, which was published on Fibers and Polymers in 2008, has been cited 54 times till now and was one of the most cited articles in the whole field.

In the following ten years from 2009 to 2018, a gradual increase could be observed in the number of both publications and citations. An average of 6 articles regarding vegetable fibers were published each year. With a glance at their contents, it is gratifying to find that these studies have covered an extremely wide range of vegetable fiber species. Fibers were extracted for use in textiles from dawaf palm tree (doum) (Amer et al. 2009; Sghaier, Zbidi, and Zidi 2009), banana (Basak et al. 2016; Mukhopadhyay, Fangueiro, and Shivankar 2009; Venkateshwaran and ElayaPerumal 2012), Agave americana L (El Oudiani et al. 2009), okra (Khan et al. 2009), kapok (Ding et al. 2014; Liu and Wang 2011; Liu, Yan, and Zhang 2016), pineapple leaf (Hazarika et al. 2018; Jose, Salim, and Ammayappan 2016; Sureshkumar et al. 2012), turmeric (Ghoreishian et al. 2013), coconut (Dong and Lijing 2013; Mishra, Basu, and Samanta 2017), sugarcane (Asagekar and Joshi 2014), lotus (Cheng et al. 2017; Oh and Na 2014), and coffee (Hong 2018; Koh and Hong 2017). Besides the fundamental structural and mechanical properties, some additional properties unique to those vegetable fibers were also investigated, such as sound-absorbing (Liu, Yan, and Zhang 2016), thermal insulation (Huang et al. 2013), fire-retardant (Basak et al. 2016), deodorizing (Ghoreishian et al. 2013), and anti-microbial (Oh and Na 2014) properties.

In the past 5 years, the number of research related to vegetable fibers has increased rapidly, with more than 20 articles published each year. The times of citations also increased and peaked in 2022, right after the publication number reached the highest record of 27 articles per year in 2020 and 2021. From the perspective of research topics, extensive research was conducted on fiber extracted from bananas, kapok, pineapple, and coconut. In addition to the fundamental properties of vegetable fibers (Hassan et al. 2022; Mizera et al. 2021), the technologies involved in the processing stages (extraction, pretreatment, fabrication, evaluation) were investigated for higher production rates and upgraded properties with fiber modifications (Chattopadhyay et al. 2020; Jalil et al. 2021; Thilagavathi et al. 2020; Soraisham et al. 2022). Attempts were continuously made to introduce new types of vegetable fibers to the textile industry as potential sources, including hibiscus sabdariffa (Kalita et al. 2019), musa acuminata leaf (Mothilal et al. 2020), areca sheath (Das, Chaudhuri, and Singha 2021; Jothibasu et al. 2020), corn leaf fiber (Singh et al. 2022), and water hyacinth (Motaleb, Abakevičienė, and Milašius 2023).

Though a slight decrease in publications occurred in 2022, it is more likely to be a fluctuation than a downward trend considering the ongoing heated discussion on biodegradable and renewable materials. With a limited number of present studies and a comparatively abundant knowledge basis (citations), much of the research field still awaits to be explored.

Spatial distribution of vegetable fiber research

To gain knowledge of the spatial distribution of vegetable fiber research, the main contributing countries/regions are mapped in Figure 3. It could be easily recognized that India, demonstrated with the darkest filling color, contributed the largest amount of research to this domain. Among the 75 publications, more than 30 of them were relevant to banana fiber. Various parts of the banana plant, including the pseudo-stem, leaf, leaf sheath, and the bracts of banana inflorescence (Durai et al. 2023; Manickam and Kandhavadivu 2022; Sakthivel et al. 2021; Soraisham et al. 2022), have been utilized as raw materials for the textile and pulp-paper industry (Basak et al. 2016). The emergence of such research focus might be closely related to the global and Indian agricultural composition. Globally, banana is the fruit with the second-largest production after citrus. India, in turn, is by far the largest producer of bananas, contributing 26.8% of world production in 2017 (Evans, Ballen, and Siddiq 2020). Such dominance has driven the research and application of banana fiber, which would help maximize economic benefits with byproducts made from non-fruit parts.

China was the contributing country that ranked second. Twelve out of the 24 publishments were relevant to Kapok, which demonstrated good oil absorption (Ke et al. 2022), thermal insulation (Jabbar et al. 2022), and sound absorption (Liu, Yan, and Zhang 2016; Liu et al. 2022) due to its

Countries/Regions	Record Count	% of 179 Records
India	75	41.90%
China	24	13.41%
Turkey	14	7.82%
Bangladesh	8	4.47%
Pakistan	8	4.47%
South Korea	8	4.47%
Malaysia	6	3.35%
Egypt	5	2.79%
Japan	5	2.79%
Tunisia	5	2.79%
Algeria	4	2.23%
Indonesia	4	2.23%
Usa	4	2.23%
Czech Republic	3	1.68%
Ethiopia	3	1.68%
France	3	1.68%
Iran	3	1.68%
Saudi Arabia	3	1.68%
Sri Lanka	3	1.68%

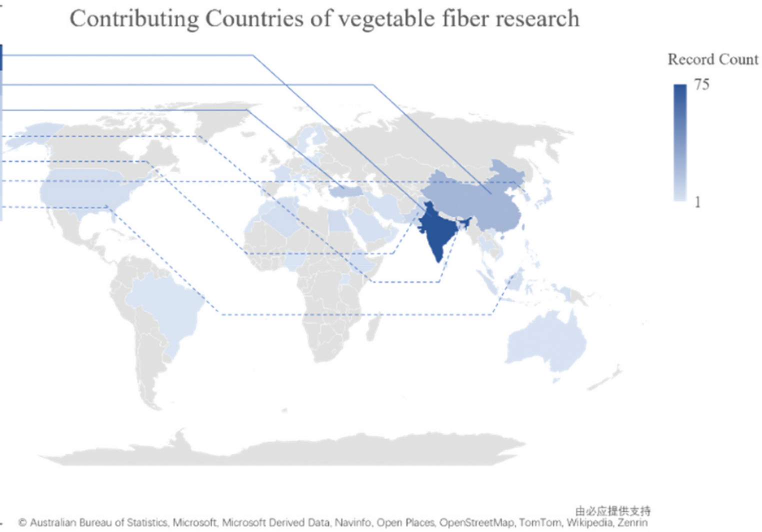


Figure 3. The main contributing countries/regions of vegetable fiber research.

hollow structure and small fiber diameter. The impact of spinning, dyeing, mercerization, and other processing methods (Ding et al. 2014; Liu and Wang 2011; Yan, Xu, and Wang 2013) on the kapok yarn/fabric properties was also studied. South Korea ranked fourth along with Bangladesh and Pakistan. A number of their publications focused on the antioxidant, antimicrobial, and dyeing properties of coffee extracts (Hong 2018; Hwang, Lee, and Kim 2008; Koh and Hong 2017, 2019), which could be easily associated with the popularity and large consumption of coffee in Korea (Choi 2022).

The other main contributing countries, including Turkey, Bangladesh, Pakistan, and Malaysia, though no specific trend was found in their research focus, a common ground could be found between them – they all have diverse agricultural sectors and a globally competitive textile industry. Turkey and Pakistan excel as major textile exporters, while Bangladesh and Malaysia are renowned for their textile and apparel manufacturing. Notably, all these nations have economies rooted in agriculture. Such background might boost the interdisciplinary research between the two domains and promote early investigation of vegetable fibers.

Top 10 journals of vegetable fiber research

To facilitate the retrieval and submission of vegetable fiber research, the journals with the largest number of publications in this field are demonstrated below (Figure 4). Journal of Natural Fibers has published 57 relevant articles, accounting for more than 30% of the retrieved articles. Fibers and Polymers, Indian Journal of Textile Research, Textile Research Journal, Journal of Industrial Textiles, and Journal of the Textile Institute, with publication numbers 17 (9.5%), 16 (8.9%), 16 (8.9%), 14 (7.8%), and 10 (5.6%), respectively, were also the core journals in this field. Cellulose, Research Journal of Textile and Apparel, Industria Textila, and Coloration Technology held some other studies relevant to vegetable fibers, with a focus on the utilization of fiber cellulose, application in apparel, industrial textiles, and fabric dyeing.

Co-citation analysis for main research topics in the vegetable fiber domain

Co-citation analysis was conducted to identify similar topics in research. When two articles were cited together by other articles, the two are said to be co-cited. The more frequently the articles were co-cited, the higher the similarity in their topics. It was regarded that a research field could be

Figure 4. Top 10 journals of vegetable fiber research according to the web of science.

conceptualized as the time mapping from the research frontiers to the knowledge base (Chen et al., 2015). Therefore, the research topics identified in the cited literature could largely reflect the long-existed focuses of the domain during the selected period. The cited references of the 179 articles were used to develop the co-citation map, with the six main clusters shown in Figure 5. Each cluster was then analyzed to dive deeper into every branch of vegetable fiber research. As demonstrated in Figure 6~Fig. 10, the references highlighted were those with the highest citation counts. See Table A1 in the Appendix for the top 10 most cited publications. Some of the inter-cluster connections are shown next to the specific nodes.

The largest cluster, containing 52 articles, focused on fiber-reinforced composites (see Figure 6). According to Saheb and Jog's (1999) and Mohanty, Misra, and Hinrichsen (2000) reviews, natural fibers such as jute, sisal, flax, hemp, and ramie have already been used to develop fiber-reinforced composites by that time for their low cost, high density and specific properties. With the improvement of fiber extraction and modification technology, such as steam explosion process (SEP) technique and alkalization (Mwaikambo and Ansell 2002), fibers extracted from cornhusk (Reddy and Yang 2005), banana pseudostem or peduncle (Ortega et al. 2016; Preethi and Balakrishna Murthy 2013), which were used to be agricultural residues, could also be applied to fiber reinforced composites. Such innovations could help save natural resources required for the cultivation of fibrous crops, meanwhile

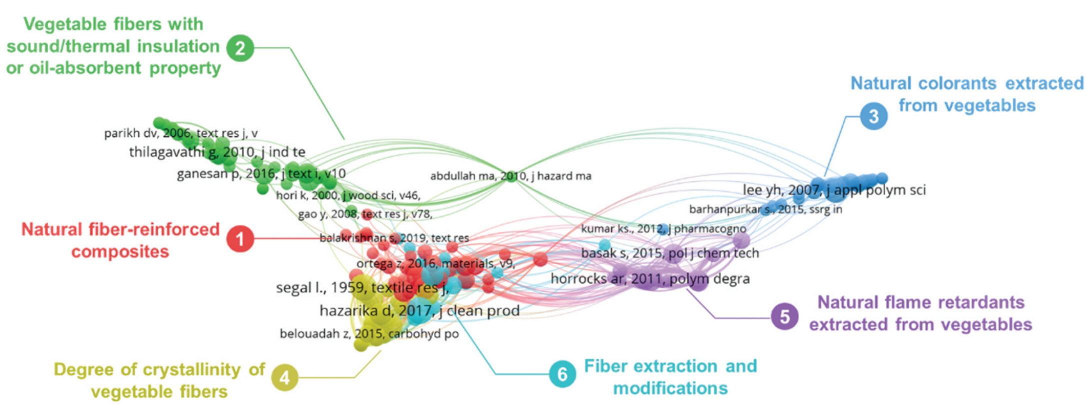


Figure 5. Co-citation map of vegetable fiber research.

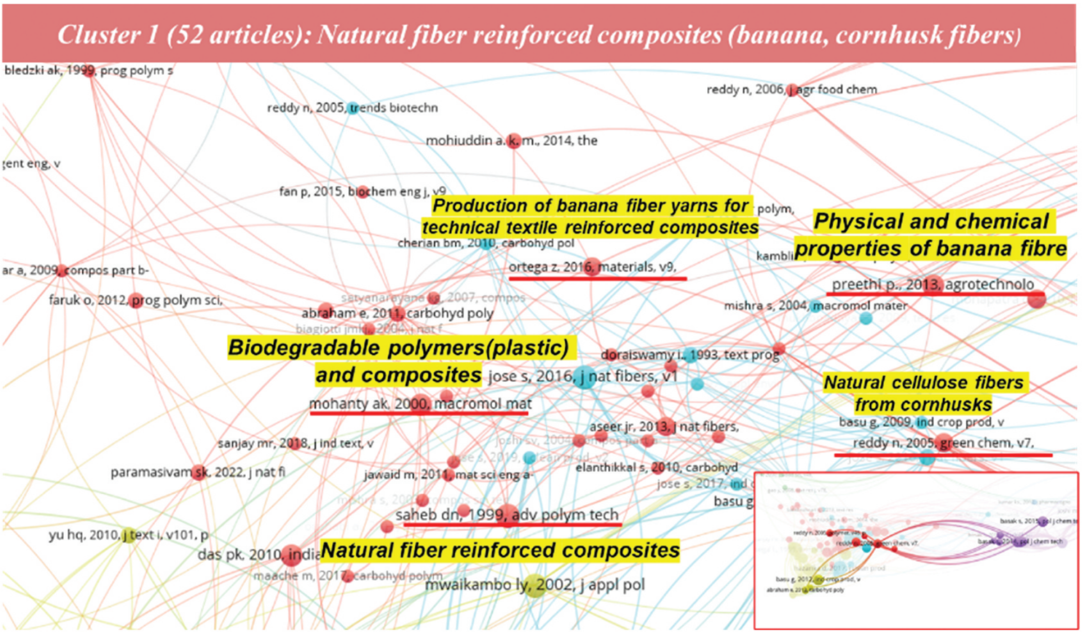


Figure 6. Cluster 1: natural fiber-reinforced composites (banana, cornhusk fibers).

reducing the environmental impact during the degradation phase with the use of biodegradable components.

The second largest cluster mainly contained literature on oil absorbent and sound absorbent properties of some vegetable fibers (shown in Figure 7). Kapok fibers, which have been frequently

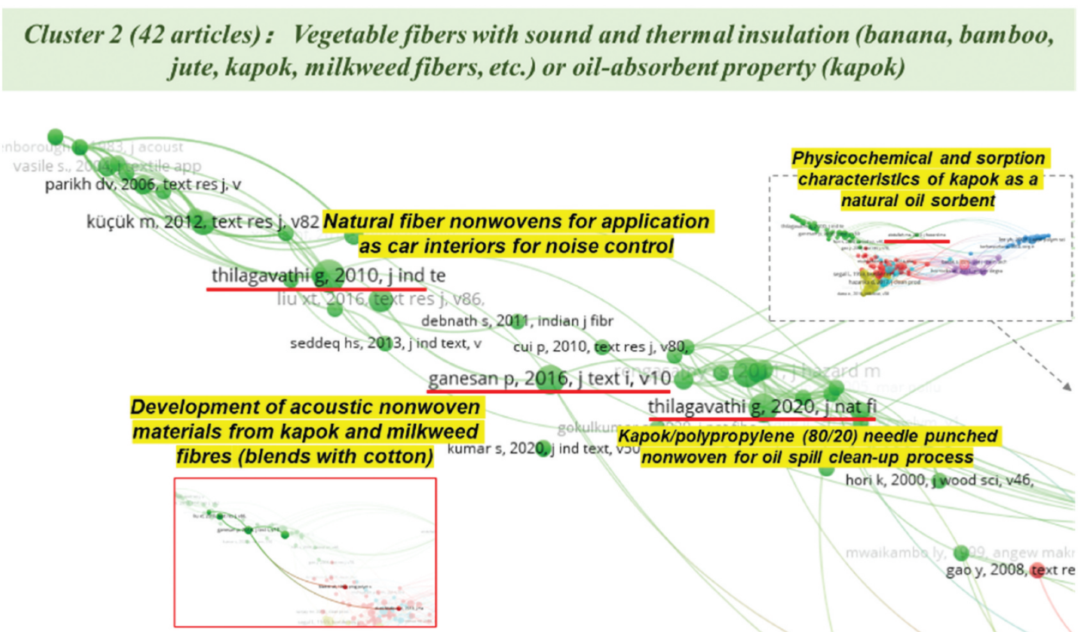


Figure 7. Cluster 2: vegetable fibers with sound and thermal insulation (banana, bamboo, jute, kapok, milkweed fibers, etc.) or oil-absorbent property (kapok).

involved in these articles (Renuka, Rengasamy, and Das 2016; Sinha, Kanagasabapathi, and Maity 2020), were proven to have good absorption capacity for oil due to their hollow structure and hydrophobic-oleophilic property. Chemical treatments could even enhance their oil absorption and retention (Ke et al. 2022; Truong, Le, and Bui 2022). Moreover, experimental tests verified their structural stability and reusability with up to 15 cycles of reuse (Abdullah, Rahmah, and Man 2010), and their eco-friendly nature with only a small amount of ash residue as the final product after burnt (Thilagavathi, Karan, and Thenmozhi 2018).

The large surface area of fibers could also provide benefits in acoustical and thermal insulation, which has been identified in kapok and other vegetable fibers including banana, bamboo, jute, and milkweed fibers (Ganesan and Karthik 2016; Thilagavathi et al. 2010). The needle punching technique was commonly used to fabricate nonwoven sound absorbers and thermal wadding, with the aforementioned vegetable fibers or their blends with synthetic fibers (Jabbar et al. 2022; Velayutham et al. 2022).

Cluster 3 focused on the dyeing, colorfastness, and other special properties of the vegetable extracts (shown in Figure 8). Compared with chemical colorants that are massively used in fabric dyeing, natural dyes are much more eco-friendly. Moreover, additional antimicrobial and deodorization properties were found in extracts from curcumin (Han and Yang 2005) and coffee sludge (Lee 2007). Attempts have been made by researchers to source colorants from gardenia, Cassia tora. L., pomegranate, curcumin, and coffee sludge for natural fabrics such as cotton, silk, and wool (Hwang, Lee, and Kim 2008). To improve the color strength, colorfastness to light, and perspiration, which were the common defects of natural dyes, the impact of concentration, mordants, and mordanting techniques were investigated. In recent research, new types of natural colorants have been derived from pumpkin peel (Che, Teng, and Ji 2023), coconut coir (Kawlekar et al. 2022; Kiran et al. 2020), date palm leaves (Hossain et al. 2022), and olive leaves (Özomay, Güngör, and Özomay 2022). Their applications have also been extended to fully utilize the advantages of natural dyes, for example, extracts from coffee sludge could be applied to face masks to enhance the protective function with their antibacterial nature (Kalebek 2022).

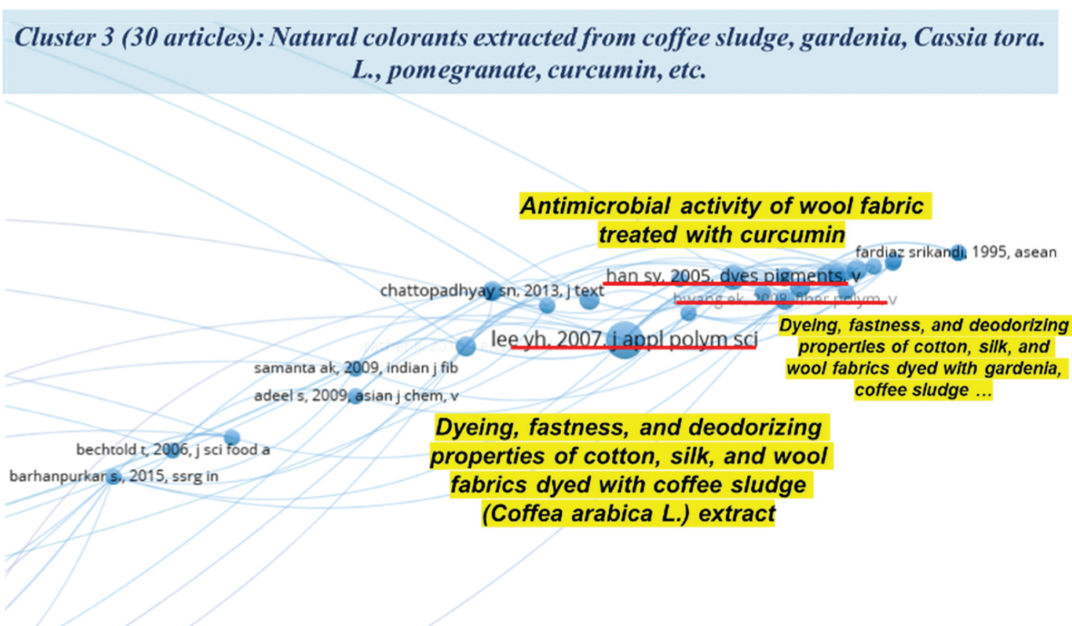


Figure 8. Cluster 3: natural colorant extracted from vegetable fibers.

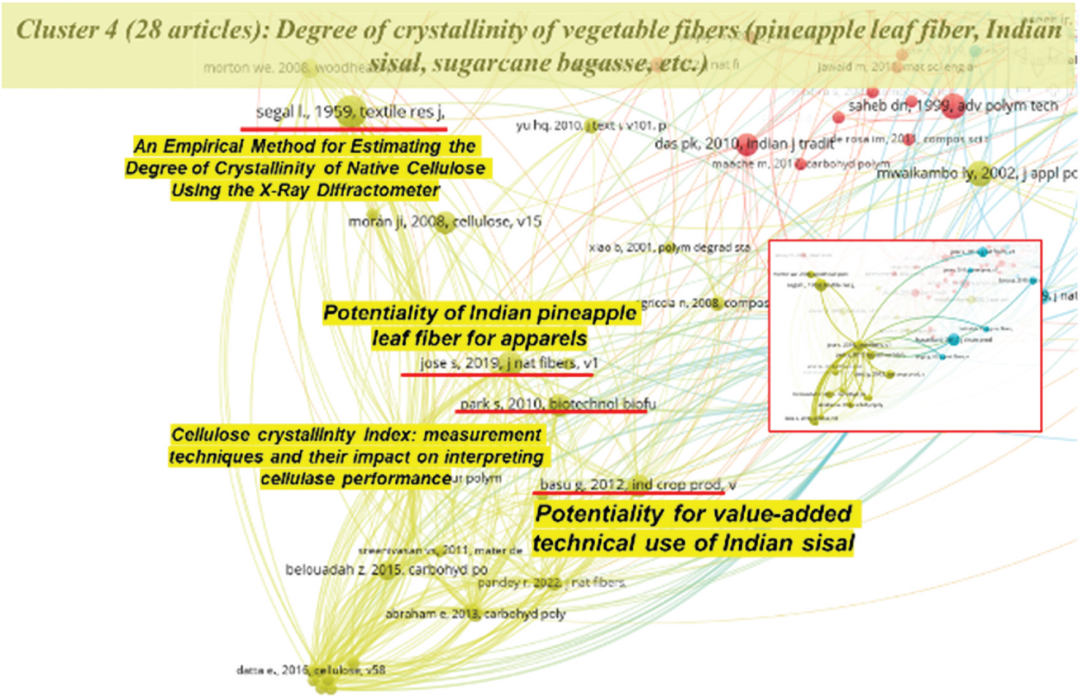


Figure 9. Cluster 4: degree of crystallinity of vegetable fibers.

A strong connection was shown between Cluster 4 and Cluster 6, according to the linked network shown in Figures 9 and 10. For Cluster 4 (see Figure 9), the degree of crystallinity was frequently referred to in the most cited articles, as well as recent studies on vegetable fibers (Martina et al. 2022; Motaleb, Abakevičienė, and Milašius 2023; Park et al. 2010; Segal et al. 1959). The crystallinity of cellulosic fibers was a prominent indicator of their physicomechanical properties such as strength, stiffness, tensile, and durability. Therefore, it has been commonly used to evaluate the quality and processability of vegetable fibers, especially pineapple leaf fibers and Indian sisal fibers aimed for load-bearing applications (ropes, binders, twines) (Basu et al. 2012; Jose et al. 2018). Different measurement methods of crystallinity index, utilizing X-ray diffraction or nuclear magnetic resonance, have previously been compared for their varied result in Park et al.'s research (2010).

For Cluster 6 (see Figure 10), the processing methods of vegetable fibers, including fiber extraction, subsequent treatment, and modification were investigated for more effective utilization in textiles/apparel (Jose, Salim, and Ammayappan 2016). Since fiber crystallinity was also one of the target indices to be improved, this overlapping in research content probably has led to the correlation between Cluster 4 and Cluster 6. Among the frequently cited articles in Cluster 6, Basu et al. (2015) increased the softness, cellulose content, and crystallinity index of coconut fibers with an accelerated chemical retting process. Hazarika et al. (2017) further improved the esthetic look and moisture absorption of pineapple leaf fibers with a degumming and bleaching process. While both studies relied on chemical treatment to modify vegetable fibers, the environmental impact and other side effects should not be excluded from the cost of such methods.

Cluster 5, with several links with Cluster 1 and Cluster 6 (see Figure 11), also involved the use of bananas and coconut, but the focus was shifted to the flame retardancy and thermal stability of their extract. Flame retardant treatment of textiles has been a challenge for long. According to Horrocks's review (Horrocks 2011), the halogen-based flame retardant would cause persistent and bio-accumulative environmental risks to humans due to the toxic components, while the phosphorous-based flame retardant would lead to a significant decrease in the tensile strength and softness of

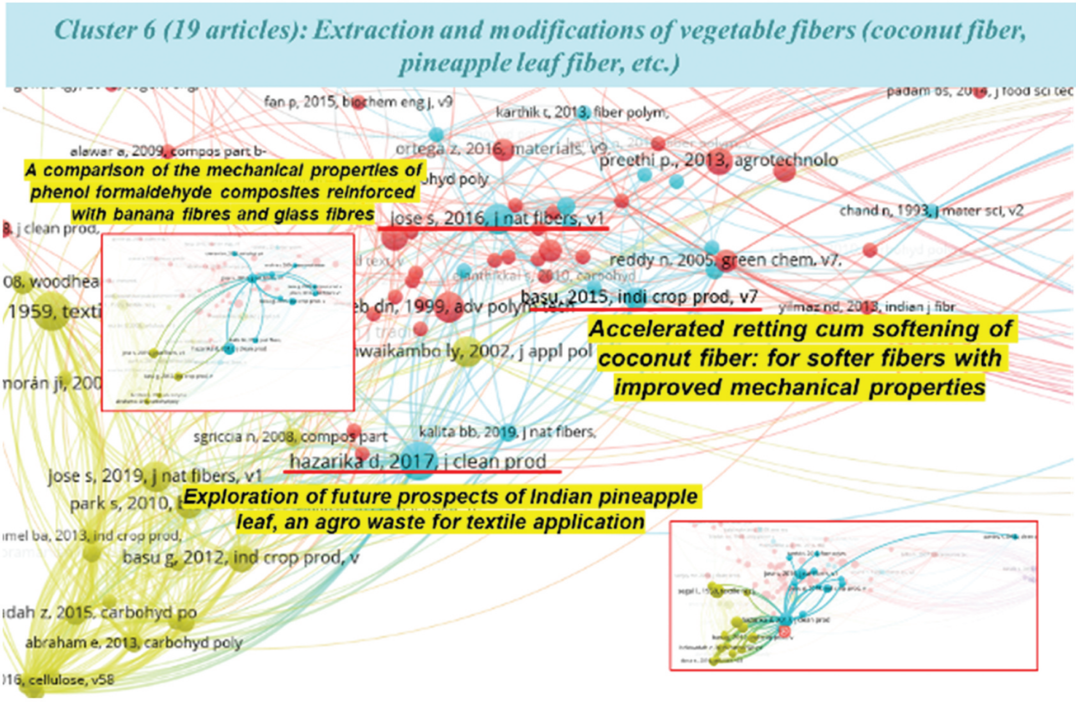


Figure 10. Cluster 6: extraction and modifications of vegetable fibers.

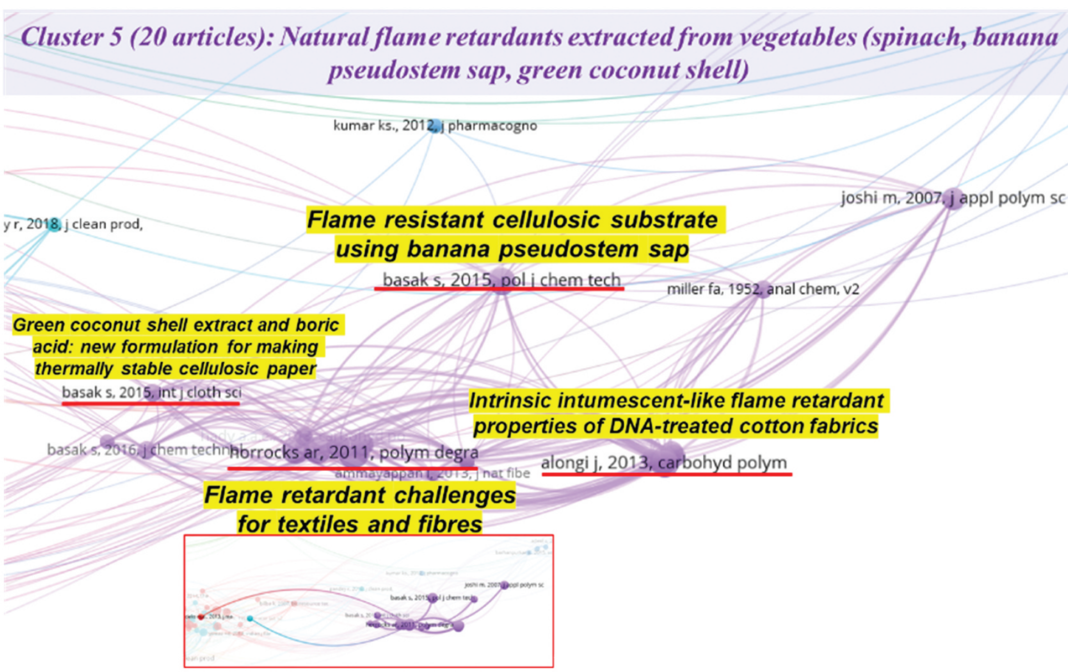


Figure 11. Cluster 5: natural flame retardants extracted from vegetables.

textiles. Therefore, researchers have been working on natural products as a new substitute for synthetic flame retardants. Alongi et al. (2013) first proposed using DNA (deoxyribonucleic acid) from fish species as a natural fire retardant. In the field of plants, extracts from spinach (Basak, Samanta, and Chattopadhyay 2015), banana pseudostem (Basak, Samanta, Saxena, et al. 2015), and green coconut shell (Basak, Samanta, Chattopadhyay, et al. 2015), containing phosphorous, silicate, other minerals or metals, turned out to be effective as flame retardant, with almost no or only slight impact on the fabric touch and tear strength. Such discoveries provided solutions to the flame-retardant treatments of varied home furnishings, meanwhile reaching the full potential of agricultural wastes.

The main connections between different clusters were outlined with red borders in Figures 6–11, shown as the linkages between nodes of varied colors. Two reasons were identified for such connections. The first was the multifunction of vegetable fibers. For example, Clusters 1, 2, and 5, with a focus on fiber-reinforced composites, sound and thermal insulators, and natural flame retardants respectively, all involved the utilization of bananas, either the fibers or sap from banana pseudostem and peduncle. This indicated the trend of fully exploring the potential properties of vegetable extractions. To increase the production rate and resource utilization rate, cooperation and integration between the supply chain of different vegetable-sourced products might be expected in the future. The second reason for the overlapping among clusters was the involvement of similar properties, such as "crystallinity" in Clusters 4 and 6. Cluster 4 focused on the degree of crystallinity of vegetable fibers and the way of evaluation, while Cluster 6 discussed more about the modification methods for improving the crystallinity. Different from synthetic fibers, the properties of vegetable fibers greatly rely on the extraction and treatment processes. Appropriate method selection and technology advancement were expected to enhance fiber performance with minimized environmental impact.

Co-occurrence analysis for research hotspots and frontiers

Based on the co-citation analysis of the knowledge basis, the co-occurrence analysis wasconducted on the keywords of 179 articles to identify the research hotspots and frontiers. Three types of visualization networks were constructed, shown in Figures 12 and 13.

In the network visualization (Figure 12), "cotton," "cellulose," and "extraction," with the occurrence frequency of 20, 19, and 18, respectively, were the keywords that were most commonly used, followed by "composites," "natural fiber," "mechanical-properties," "kapok," "natural" and "dye." Though "cotton" has been excluded when retrieving the articles, it still frequently appeared in

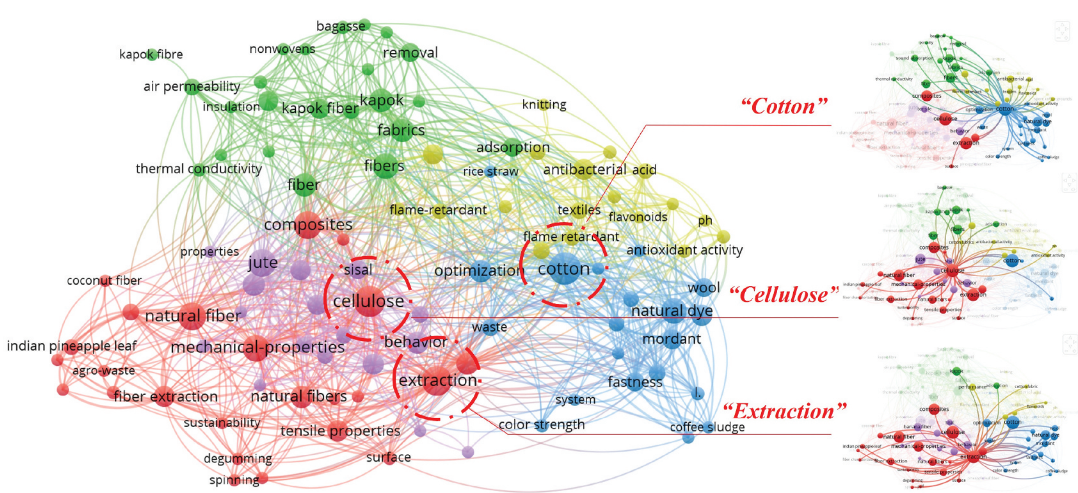
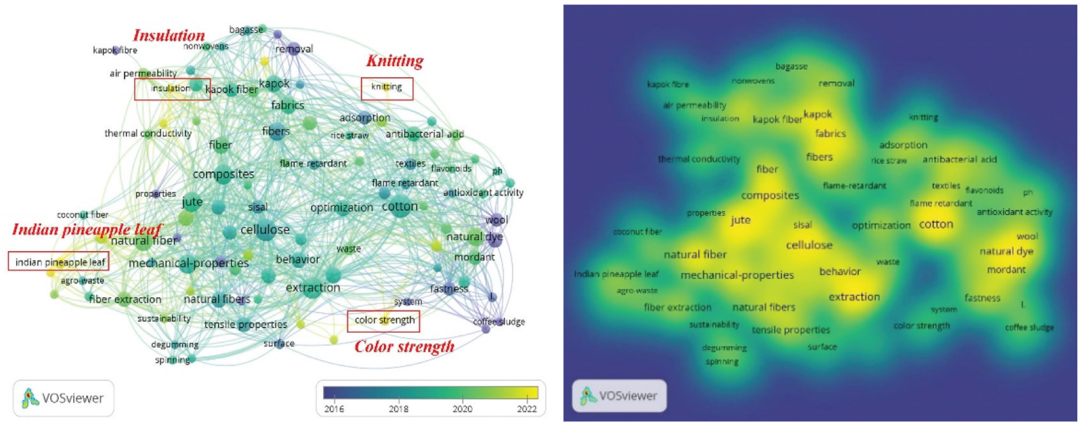


Figure 12. Network visualization of keyword co-occurrence map.



a b

Figure 13. a. Overlay visualization of keyword co-occurrence network; b. density visualization of keyword co-occurrence network.

vegetable fiber research, as it has been commonly blended with vegetable fibers to improve the fabric hand or used to test the dyeing effect of vegetable extracts. "cellulose" is the main content of vegetables to be utilized in textiles/apparel. Their outstanding mechanical properties have been manifested in some applications of vegetable fibers, such as fiber-reinforced composites and load-bearing materials made from pineapple leaf fibers. Efforts have been made to increase the cellulose content with innovations in the fiber extraction and modification processes, which were also referred to in the research relevant to "extraction." Efficient extraction methods with less impact on the fiber quality (fiber length, mechanical strength, etc.) are still awaiting to be developed, especially for vegetable fibers that are produced in high capacity worldwide, such as banana fibers and pineapple leaf fibers.

The other keywords could mostly correspond to the research clusters identified in the co-citation network. For example, "kapok" fibers, with great potential as a sound absorber, have been extensively investigated by studies shown in Cluster 2 (Figure 7). The keyword "dye" should be frequently mentioned in Cluster 3 research (Figure 8), with the research focus of utilizing extracts from coffee sludge, curcumin, gardenia, and other vegetables as natural colorants.

To obtain the time distribution of the keywords, the overlay visualization was adopted (Figure 13a). "Knitting," "insulation," "Indian pineapple leaf," and "color strength" were identified as the emerging research hotspots, all of which have an average publication year of 2022. Their connections with other keywords are demonstrated in Figure 14. "Knitting" has been commonly used for the fabrication of vegetable-fiber-based textiles, which enables the fabric to be softer and more flexible compared to weaving (Karasawa et al. 2022). Moreover, it was found that the variation of knitted structures might significantly affect the specific performance of vegetable-fiber-based textiles (Jin et al. 2021; Peterson et al. 2021; Zhang et al. 2023), which deserves to be investigated in future parameter studies.

"Insulation" has been extensively referred to as acoustical and thermal insulation in Cluster 2 of the co-citation map (Figure 7); however, the green area shown in the density visualization map (Figure 13b) indicated that there is still much space for future studies. In the latest studies, needle-punched nonwovens were developed with fibers extracted from palm, coffee husk, bagasse, etc. (Krithika et al. 2022; Periyasamy et al. 2023; Sajid et al. 2021). Such processing methods have fewer restrictions on the fiber length, while still maintaining the large surface area of fibers unaffected. Blends with rubber crumbs, PET (polyethylene terephthalate), PLA (polylactic acid), and other materials were fabricated for better mechanical properties of nonwovens (Agirgan, Agirgan, and Taskin 2022; Thenmozhi and Thilagavathi 2023). Further research may be conducted on the comprehensive impact of factors such as blending ratio, punch density, layering, thickness, and other nonwoven fabric characteristics to optimize the overall performance. Evaluation of other fabric

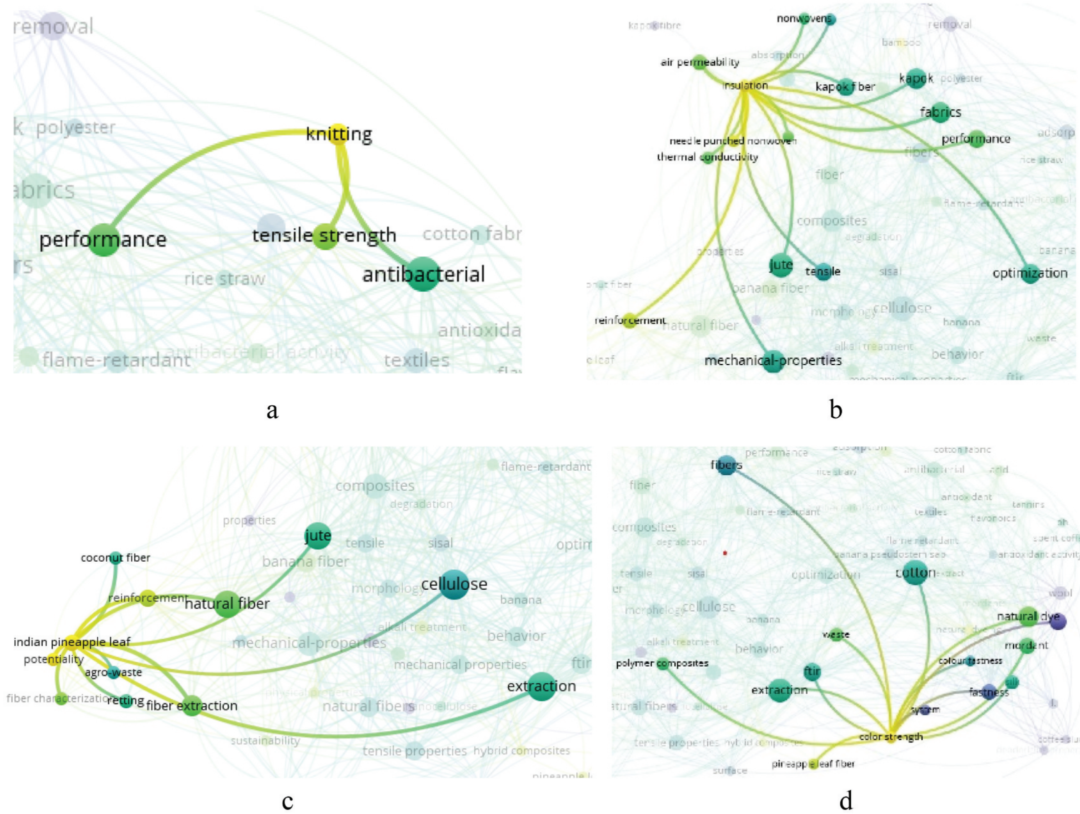


Figure 14. Research frontiers in vegetable fiber field: a. "knitting;" b. "insulation;" c. "Indian pineapple leaf;" d. "color strength".

properties, such as thermal stability, fire retardancy, endurance, and abrasion resistance, should also be included accordingly to meet the requirements of specific application scenarios.

"Indian pineapple leaf" has been widely applied to fiber-reinforced composites, sound absorbers, and other industrial products (Ng et al. 2023; Thilagavathi et al. 2020). However, its current application to apparel is quite limited due to its rigidity, with several attempts at socks or insoles. Improvements are expected in the modification and fabrication methods of PALF (pineapple leaf fiber) for better fabric hand and esthetic appearance (P. Hazarika et al. 2018; Jose et al. 2018). The pre- and post-process of the PALF fabrication should also be noted: Most of the research on PALF has not touched on the harvesting of pineapple leaves, which mainly relies on manpower. Harvesting methods with higher automation and efficiency will help reduce the overall cost of PALF products. Though PALF has been regarded to be eco-friendly with the utilization of agro-wastes, the extraction and modification processes (decortication, water retting, degumming, bleaching) may still involve extensive use of chemicals and water, which are worth noticing in future studies.

"Color strength" refers to two research directions. One is the properties of natural dyes derived from vegetable fibers, the other is the dyeing property of vegetable-fiber-based textiles. For the former direction, natural dyes derived from lotus seedpod, date fruit leaf, coconut coir, and marigold flower have been used to dye cotton, silk, and other natural textiles with advantages such as good color strength, ultraviolet protection, and anti-microbial properties (Fang et al. 2023; Hossain et al. 2022). Bio-mordants derived from plants (acacia, turmeric, banana peel) can further facilitate the natural dyeing process (Kiran et al. 2020; Diarsa and Gupte 2022; Phromphen 2023). For the latter direction, the color strength and retention property have shown to be a challenge for vegetable-fiber-based textiles, due to their fiber structures and compositions. PH, enzyme, and metal mordant treatment have been used for removing impurities and facilitating dyeing (Masudur Rahman et al. 2023), while the environmental impact of such processes remains to be discussed.

Based on the keywords that occurred recently, it can be speculated that the focus of vegetable fiber research has gradually shifted to applications and end uses. Physical and chemical methods have been used to overcome the common drawbacks of vegetable fibers, such as difficulties in extraction and dyeing processes, and to explore potential applications. In addition to the products that have been well established in the market, new inventions such as vegan leather appeared recently. Though its relevant research is still in limited amount, a surge in popularity has been shown with the latest launch of bio-based leather products by fashion and textile brands such as Stella Macartney, Dupont, Biofluff, etc. (Leiber 2023; McCartney, n.d.; Templeton, Carrera, and Richford 2024). Such products could serve as an alternative for real animal fur with similar fabric hand and appearance, though the accessibility and sustainability of the treatment processes remained to be discussed. With the advancement of fiber/textile modification technology and the integration of knowledge across multiple disciplines, vegetable fibers are expected to be utilized with higher creativity and added value.

Conclusions

The paper has reviewed the research progress and frontiers of vegetable fibers during the past 25 years, utilizing VOSviewer for knowledge mapping and clustering. The number of publications and citations has experienced an abrupt increase in the last 5 years, indicating emerging research interest and attention shifted to this field. New types of vegetable fibers with diverse properties have been continuously explored and introduced for wider applications. India, China, and Turkey were the countries that were most active in vegetable fiber research. Almost all the major contributing countries had a competitive textile industry and diverse agricultural sectors, which might boost interdisciplinary research on vegetable fibers. Journal of Natural Fibers was the leading journal in the vegetable fiber field. Other core journals included Fibers and Polymers, Indian Journal of Fiber Textile Research, and Textile Research Journal.

According to the co-citation analysis, six research topics were identified in vegetable fiber research, including fiber-reinforced composites, vegetable fibers with sound/thermal insulation or oil-absorbent properties, natural colorants, the crystallinity of vegetable fibers, natural flame retardants, extraction and modifications of vegetable fibers. The progress of each was summarized by analyzing the most cited articles. "Knitting," "insulation," "Indian pineapple leaf," and "color strength" were identified as the emerging research hotspots based on the keyword co-occurrence network. It was suggested that besides the modifications of fibers, innovations in knitted structure should be noticed as a possible way of improving vegetable-fiber-based textile properties. For application in acoustical and thermal insulation, other fabric properties, such as thermal stability, fire retardancy, endurance, and abrasion resistance, should also be considered. For both the application of PALF and natural colorants, the chemicals and water used in the extraction and modification processes should not be neglected. Future studies are expected to improve efficiency and automation, meanwhile decreasing the cost and environmental impact throughout the whole process chain of vegetable fibers.

Highlights of the paper

- Visualization tool VOSviewer and bibliometric analysis were utilized to systematically investigate the time distribution of the research, leading countries and journals, research hotspots and frontiers of the vegetable fiber domain in the past 25 years.
- The publications and citations of vegetable fiber research increased rapidly throughout the past 5 years and peaked during 2020–2023. India, China, and Turkey have contributed more than 60% of articles in the vegetable fiber domain. Journal of Natural Fibers was the leading journal in this field, accounting for more than 30% of the publications.

- Fiber-reinforced composites, sound and thermal insulators, and natural colorants were the most frequently studied applications of vegetable fibers. With the development of fiber extraction and modification technology, vegetable fibers that used to be agricultural residues (cornhusk, banana pseudostem, pumpkin peel, etc.) were explored as new resources.
- To widen the application of vegetable fibers in textile and apparel, the efficiency and automation of the extraction process should be improved. Fabrication methods that rely on structural modification rather than chemical treatment may be investigated to make the process chain more sustainable.

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Appendix

Table A1. Top 10 publications with highest weight (citations).

Title	Author	Publication year	Weight (citations)	Cluster
Development of apparels from silk waste and pineapple leaf fiber	Hazarika et al.	2018	9	6
An empirical method for estimating the degree of crystallinity of native cellulose using the X-ray diffractometer	Segal et al.	1959	9	4
Dyeing, fastness, and deodorizing properties of cotton, silk, and wool fabrics dyed with coffee sludge (Coffea arabica L.) extract	Lee	2007	8	3
Flame retardant challenges for textiles and fibers: New chemistry versus innovatory solutions	Horrocks	2011	7	5
An overview on production, properties, and value addition of pineapple leaf fibers (PALF)	Jose et al.	2016	7	6
Potentiality of Indian pineapple leaf fiber for apparels	Jose et al.	2018	7	4
Chemical modification of hemp, sisal, jute, and kapok fibers by alkalization	Mwaikambo and Ansell	2002	7	4
Natural fiber polymer composites: a review	Saheb and Jog	1999	7	1
Development of natural fiber nonwovens for application as car interiors for noise control	Thilagavathi et al.	2010	7	2
Intrinsic intumescent-like flame retardant properties of DNA-treated cotton fabrics	Alongi et al.	2013	6	5