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The Evolution of Bio-Mordant Research in Natural Textile Dyeing: A Bibliometric Study

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ABSTRACT - The growing global attention to sustainability has driven the development of environmentally friendly alternatives in textile dyeing processes, one of which is the utilization of bio-mordants as substitutes for metal mordants. Although experimental research on bio-mordants continues to expand, systematic mapping of trends, knowledge structures, and research directions in bio-mordant studies remains limited. Therefore, this study aims to comprehensively analyze the development of bio-mordant research in natural textile dyeing using a bibliometric approach. This study adopts the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, with data sourced from the Scopus database. A literature search using the keywords "bio" and "mordan*" yielded 329 documents, which, after screening and the application of inclusion criteria, resulted in 71 articles selected for further analysis. Bibliometric analysis was conducted using VOSviewer software to map publication trends, geographical distribution, institutional affiliations, author productivity, and keyword co-occurrence. The results indicate that bio-mordant research has experienced significant growth since 2020, reaching its peak in 2023, with publications predominantly originating from countries with strong textile industries. The main keywords identified reflect a close relationship between bio-mordants, natural dyes, color fastness, and sustainability. These findings highlight the theoretical and practical relevance of bio-mordants in supporting the transition toward more sustainable textile dyeing processes and provide opportunities for future research.

Keywords: Bio-mordants, natural dyes, bibliometric analysis, sustainable textiles.

INTRODUCTION

Color is one of the important elements in enhancing the attractiveness and market value of products, particularly in the textile industry (Wiraningtyas et al., 2020). In general, dyes are classified into two main groups, namely natural dyes and synthetic dyes (Pudjianti, 2019, as cited in Khasanah & Widowati, 2022). Over the past two decades, interest in natural dyes has increased again along with the growing consumer awareness of environmentally friendly products and the importance of ecosystem sustainability.

Natural dyes are considered more environmentally friendly because they are derived from renewable natural resources. Over the past two decades, the use of natural dyes has gradually increased, accompanied by growing consumer awareness of environmentally friendly textile products and the importance of environmental conservation. Consequently, natural dyes have begun to be reintroduced in textile dyeing processes (Kusumastuti et al., 2019). Natural dyeing is identified as the use of colorants obtained from natural sources, such as plants (roots, stems, leaves, bark, and flowers) and those derived from animals (lac dyes) (Aliffianti & Kusumastuti, 2020).

The increasing public preference for natural products, concerns over exposure to pollutants that pose potential cancer risks, and the desire to create exclusive products are the main factors driving the resurgence of natural dye usage (Pringgenies, 2013). The production of natural dyes has been practiced for a long time through boiling processes, resulting in dyes in liquid form (Bahri & Jalaluddin, 2017).

Despite their environmental advantages, the industrial-scale application of natural dyes still faces various technical challenges, particularly related to the low color fastness of dyed textile fibers. Poor dye uptake and weak bonding stability cause colors to fade easily after washing or use. To address this issue, a fixation process is required, which aims to strengthen the interaction between the dye, textile fibers, and the fixing agent. Conventionally, fixation is carried out using metal mordants such as alum, ferrous sulfate, and quicklime (Pujilestari et al., 2014). However, the use of metal mordants may pose environmental concerns due to the generation of heavy metal-containing waste.

The concept of bio-mordants emerged in response to environmental concerns associated with the use of metal-based mordants in textile dyeing. Previous studies have highlighted that conventional mordants, although effective in enhancing color fastness, often generate hazardous waste that poses ecological and health risks (Pujilestari dkk., 2014; Kusumastuti dkk., 2019). Consequently, researchers have increasingly explored bio-mordants derived from natural sources as a sustainable alternative.

These conditions have driven the growing body of research on the use of bio-mordants as alternatives to metal-based mordants. Bio-mordants are color-fixing agents derived from biological sources, particularly plants containing tannin compounds. Several studies have demonstrated that *Simplocos* leaves, also known as loba (Laksono, A. I., & Subiyati, S., 2021), as well as angsana wood (*Pterocarpus indicus*), which is rich in tannins, exhibit significant potential as environmentally friendly bio-mordants (Adu et al., 2024). The use of bio-mordants not only has the potential to enhance color fastness but also to reduce negative environmental impacts.

Along with the increasing body of research on the use of bio-mordants in natural textile dyeing, studies aimed at synthesizing and mapping the development of this research field remain relatively limited. Bibliometric studies generally focus on natural dyeing or sustainable textiles in a broad sense, while bio-mordants are discussed only as a subtopic and have not yet been examined as a primary focus. To date, few systematic bibliometric studies have addressed the development of bio-mordants research, including publication trends, keywords, researchers, and the evolution of the field over the past decade. This limitation has resulted in the absence of a clear and comprehensive overview of the research direction of bio-mordants. Bibliometric analysis is a quantitative method used to examine publication trends, knowledge structures, and scientific collaboration patterns based on bibliographic data from reputable databases such as Scopus (Purnomo, Agung. 2019). In contrast to conventional literature reviews, which are inherently subjective, bibliometric analysis enables objective visualization of the interrelationships among research topics and the evolution of a scientific field.

Based on a preliminary review, although extensive experimental research has been conducted on natural dyes and fixation processes, bibliometric studies that specifically map bio-mordants research over the past decade remain relatively limited. Therefore, this study aims to map research trends, identify major thematic clusters, and explore future research opportunities related to the use of bio-mordants in natural textile dyeing using VOSviewer software. The findings of this study are expected to provide theoretical contributions to the advancement of sustainable textile science as well as practical contributions to the textile industry in adopting environmentally friendly fixation technologies.

LITERATURE REVIEW

Natural dyes generally require the use of mordants to achieve effective fixation on textile materials; therefore, the mordanting process is crucial to the success of the dyeing process (Hosen et al., 2021). Bio-mordants are commonly understood as plant-based substances or biomass-derived materials rich in phenolic compounds, particularly tannins, which facilitate the binding of natural dyes to textile fibers. Studies have shown that bio-mordants not only enhance color fastness but also align with the principles of environmentally friendly textile processing (Pringgenies, 2013; Furthermore, the application of bio-mordants supports the transition toward sustainable textile production by reducing reliance on heavy metals and minimizing environmental pollution (El Sayed et al., 2023; Adeel et a l., 2023).

Bio-mordants are natural substances that function to enhance dye uptake in textile fabrics and are used as environmentally friendly alternatives to conventional metal salts in the dyeing process. This study focuses on the application of tannin extracts derived from the bark of the quebracho tree. By optimizing the use of bio-mordants in the dyeing process, it is possible to reduce the emergence of negative environmental impacts (Stanculescu et al., 2017).

Research conducted by Guesmi & Ben Hamadi, 2018, explains that bio-mordants are natural compounds used in the dyeing process by enhancing the adhesion of dyes to textile materials. In their study, the naturally occurring metal content in date seed extracts was utilized as a bio-mordant to replace conventional metal-based mordants. The results

indicated that high-quality dyeing performance was achieved using extracts obtained through the ultrasonic extraction method, in which the highest metal content was detected and functioned effectively as a bio-mordant.

The study conducted by (Adeel et al., 2019), describes bio-mordants as naturally derived plant-based substances used as substitutes for traditional chemical mordants in textile dyeing processes employing natural dyes. The use of bio-mordants has been shown to enhance color fastness and strengthen color yield. This study discusses active compounds such as lawsone from henna, quercetin from acacia, tannins from pomegranate, and curcumin from turmeric, which are capable of forming bonds between dyes and textile fibers, thereby producing satisfactory coloration. The use of date seeds and pomegranate peels as bio-mordants has also been proven to improve color fastness (Ltaief et al., 2023). Furthermore, walnut extract, pine seed shells, and orange peels have been reported to be effective in producing stable colors with high fastness properties through both pre- and post-dyeing processes (Talib et al., 2023). Bio-mordants can also be derived from natural polymeric materials used to enhance the effectiveness of natural dyes on textile fibers. One such natural polymer is chitosan, a biopolymer obtained from shrimp and crab shells, which is applied to improve the color fixation process in textiles (Zhao et al., 2020).

Although interest in bio-mordants has continued to grow, existing studies remain fragmented, with considerable variation in source materials, application methods, and performance evaluation approaches. This fragmentation highlights the need for a systematic mapping of research trends and conceptual developments related to bio-mordants, which can be effectively addressed through a bibliometric approach. To clarify the conceptual understanding of bio-mordants within the context of sustainable textile dyeing, a summary of bio-mordant definitions was compiled based on findings from previous studies. Table 1 presents various definitions of bio-mordants proposed by researchers, emphasizing their role as natural fixation agents derived from biological sources, particularly polyphenolic compounds such as tannins. The presentation of these definitions aims to establish a conceptual foundation that supports the interpretation of bibliometric analysis results and clarifies the position of bio-mordants in the development of environmentally friendly textile dyeing technologies.

TABLE 1. Definition of bio-mordant elements.

No.	Definition of Bio-Mordant Elements	Reference
1	Bio-mordants are defined as color-fixing agents derived from biological sources, particularly plants containing phenolic compounds such as tannins, which function to enhance the bonding between natural dyes and textile fibers without the use of heavy metals.	Pujilestari et al. (2014)
2	Bio-mordants are environmentally friendly alternatives to metal-based mordants that operate through the formation of complex bonds between naturally occurring bioactive compounds and dye molecules on textile fibers.	Kusumastuti et al. (2019)
3	Plant-based bio-mordants utilize tannins, flavonoids, and other polyphenolic compounds to improve color fastness while reducing the environmental impact of textile dyeing processes.	Pringgenies. (2013)
4	Bio-mordants derived from natural biomass sources, such as leaves and wood with high tannin content, act as fixation agents capable of replacing the function of metal mordants in sustainable textile dyeing.	Laksono1 et al., n.d.
5	Bio-mordants are employed in natural dyeing systems to enhance color stability, dye absorption, and compatibility with sustainable textile production concepts.	Adu et al. (2024)
6	In the context of the modern textile industry, bio-mordants are regarded as essential elements in the transition toward safer, more sustainable dyeing processes with minimal hazardous waste generation.	El Sayed et al. (2023); Adeel, Azeem, et al. (2023)
7.	Bio-mordants are defined as plant-based bioactive compounds that play a crucial role in the dyeing of textile materials such as cotton, wool, or silk, producing stable and strong color shades through the formation of hydrogen bonds with fibers and dyes, thereby being considered safer and more environmentally friendly.	Barkaat et al. (2023)
8.	Bio-mordants are defined as functional biological isolates that act as bridging agents between dyes and textile fibers during the dyeing process to produce durable color patterns. In addition to replacing metal mordants, bio-mordants may also provide therapeutic benefits, such as antioxidant and antibacterial properties.	Adeel, Zuber, et al. (2023)

No.	Definition of Bio-Mordant Elements	Reference
9.	Bio-mordants are natural substances that function to enhance dye uptake in fabrics and are used as environmentally friendly alternatives to conventional metal salts in textile dyeing, with the application of tannin extracts derived from quebracho tree bark.	I.R. Stanculescu et al., (2017)
10.	Bio-mordants are natural compounds used in the dyeing process by increasing the adhesion of dyes to textile materials. The naturally occurring metal content in date seed extracts can be utilized as bio-mordants to replace metal-based mordants, with ultrasonic extraction methods yielding the highest metal content and demonstrating effective bio-mordant performance.	Guesmi & Ben Hamadi, (2018)
11.	Bio-mordants are environmentally friendly natural compounds used in dyeing processes to enhance color strength and fabric color fastness. The use of silk fabrics and bio-mordants such as turmeric, henna, and acacia enables effective dye molecule absorption and good color stability; bio-mordants are particularly beneficial for silk dyeing, especially when applied with microwave treatment.	Kiran et al.(2020)
12.	Bio-mordants are defined as natural substances that utilize hydroxyl (–OH) functional groups, primarily derived from phenolic compounds, to form hydrogen bonds with textile fibers, thereby producing a wider range of color shades during the dyeing process.	Habib et al. (2023)
13.	Bio-mordants serve as alternatives to metal-based mordants in dyeing processes. L-cysteine (L-Cys) bio-mordants are considered more environmentally friendly and are beneficial in activating the antibacterial properties of crude prodigiosin pigments on fabrics, particularly nylon.	Mouro et al. (2023)
14.	Bio-mordants are natural binding agents that typically contain tannins and lipid compounds, which assist the fixation process in textile dyeing. Bio-mordants such as sodium alginate and gall oak are part of a sustainable textile dyeing approach, as they are derived from natural sources and have lower environmental impacts compared to synthetic mordants.	Pars & Karadag. (2024)
15.	Bio-mordants can enhance color fastness through reactions between natural dyes and textile fibers, resulting in improved fastness properties when derived from natural sources such as pomegranate, myrobalan, and red sumac.	Batool et al. (2026)

METHOD

This study employs a bibliometric analysis approach to quantitatively evaluate the development of research related to bio-mordants. Bibliographic data were collected from the Scopus database due to its multidisciplinary coverage and reputation as one of the largest scientific databases. The literature selection process was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure transparency, rigor, and reproducibility in the literature search and screening process (Page et al., 2021).

The literature search was conducted using the keywords “bio” and “mordan*” in the article titles, abstracts, and keywords. The initial search yielded 329 documents. Subsequently, the documents were screened based on the presence of the specific keyword “bio-mordant*,” topic relevance, and inclusion criteria comprising: (1) scientific articles published up to 22 January 2026, (2) publications written in English, and (3) a research focus on bio-mordants. Documents in the form of book chapters, review articles, and conference papers were excluded from the analysis.

As illustrated in Figure 1, the screening and eligibility assessment process resulted in 71 articles that met the inclusion criteria and were subsequently analyzed using a bibliometric approach. The analysis was conducted using VOSviewer software to construct and visualize bibliometric maps depicting the intellectual structure, keyword interrelationships, and connections among research entities within the field of bio-mordants (van Eck & Waltman, 2010).

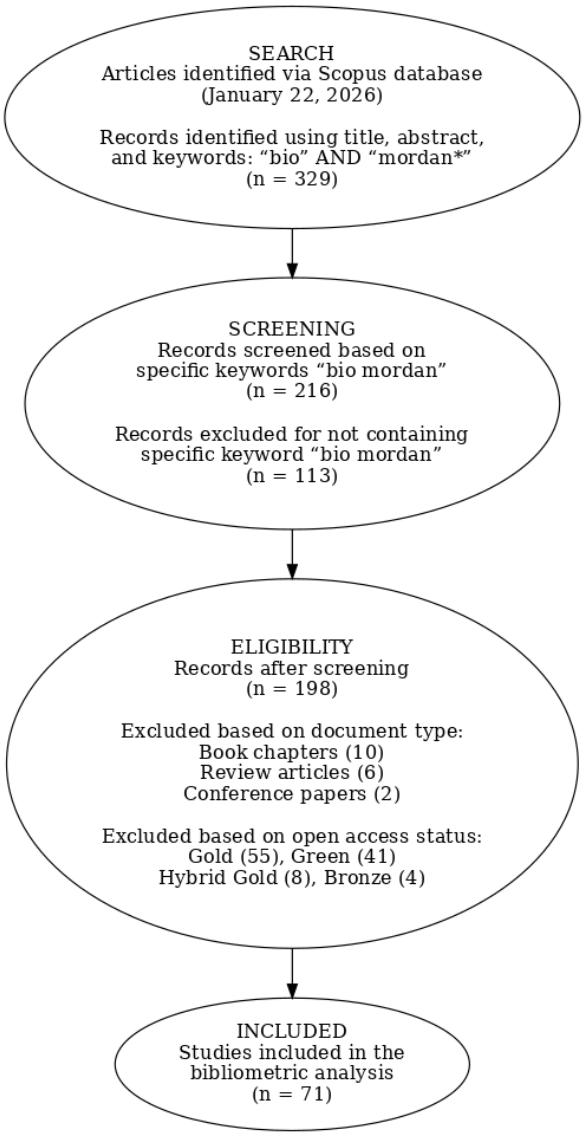

FIGURE 1. PRISMA flow diagram of the literature selection process for bio-mordants research based on the Scopus database.

RESULTS AND DISCUSSION

Based on the Scopus data search conducted on 22 January 2026 using the article title, abstract, and keywords “bio” AND “mordan*” across various disciplines, a total of 329 publications published between 2017 and 2026 were identified (Figure 1). Following the initial identification stage, a document screening process was carried out based on document classification. Articles were excluded according to document type, namely book chapters (10), review articles (6), and conference papers (2). The subsequent screening stage resulted in 71 articles that were further analyzed to address the research questions.

RQ1: To what extent does the exploration of bio-mordants constitute a priority for future research?

The exploration of bio-mordants has shown a progressive development since 2020. An early study conducted by I. Stanculescu et al. (2017), entitled *"Gamma Pre-Irradiation Effects on Natural Dyeing Performances of Proteinic Blended Yarns,"* marked the emergence of bio-mordants as substitutes for metal mordants in textile dyeing. Over time, the evolution of bio-mordants research has attracted increasing attention from new researchers. Although sustainability issues have long been a major focus of scientific inquiry, specific studies addressing the substitution of metal mordants with bio-mordants remain in a developmental stage. This condition indicates that bio-mordants have not yet been fully explored in terms of their source materials, bonding mechanisms, and application methods, thereby demonstrating substantial potential for further investigation in future research.

FIGURE 2 shows that a significant development occurred in 2023, with the number of publications reaching 17 documents. This trend indicates a growing level of attention toward bio-mordants as environmentally friendly fixation solutions. Furthermore, the use of bio-mordants has been reported to contribute significantly to the reduction of pollution from textile industrial waste (El Sayed et al., 2023; Adeel et al., 2023; Talib et al., 2023; Ltaief et al., 2023; Ozdemir & Karadag, 2023; Barkaat et al., 2023; Nasreen et al., 2023; Melaku et al., 2023; Baaka et al., 2023; Lambrecht et al., 2023; Mouro et al., 2023; Shahmoradi Ghaheh et al., 2023; Abou Elmaaty et al., 2023; Manyim et al., 2023; Habib et al., 2023; Adeel, Zuber, et al., 2023; Usman et al., 2023).

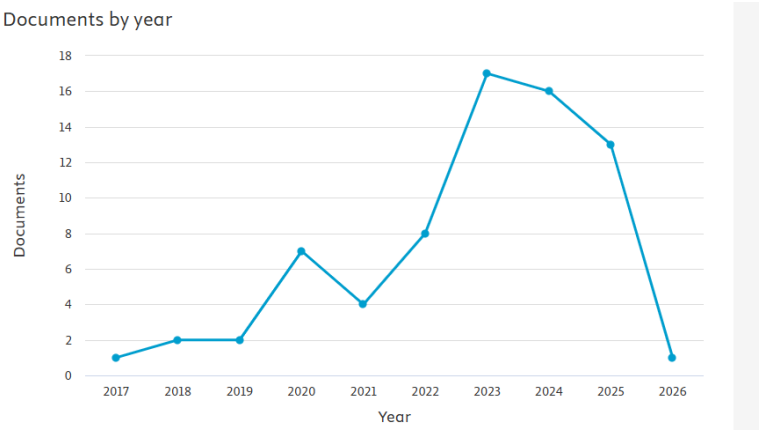

FIGURE 2. Number of bio-mordants. (Source: Scopus database).

Since 2017, research on bio-mordants has demonstrated an increasingly consistent pattern of scholarly attention. A significant surge became evident in 2022 with eight published documents, reaching a peak in 2023 with seventeen documents. This trend indicates a shift in the global research paradigm, in which scholars have increasingly explored diverse bio-mordants sources as strategic elements for advancing sustainability in the textile industry. Bio-mordants exploration has expanded from the identification of plant-based tannins and agricultural waste to microorganisms as alternatives to metal mordants for enhancing the color fastness of natural dyes. This line of research has a high level of urgency for further development, both from scientific and future application perspectives.

RQ2: How are scientific studies on bio-mordants in natural textile dyeing geographically and thematically distributed?

The analysis of the distribution of bio-mordants research across 71 articles was conducted by mapping categories based on country, region, institutional affiliation, journal sources, and authorship. A comprehensive understanding of this scholarly distribution is highly valuable for both textile industry practitioners and academics in future efforts to map the development of safe and environmentally friendly fixation technologies.

FIGURE 3 illustrates that, based on geographical classification, research on bio-mordants is strongly dominated by countries with high demands from the textile industry. Pakistan ranks first with 32 articles, followed by Saudi

Arabia (16 articles), Bangladesh (13 articles), India, Iran, and Türkiye (12 articles each), Egypt (6 articles), Tunisia (5 articles), and Ethiopia and Spain (3 articles each). The dominance of these countries indicates that high textile industry demand, the availability of biological resources, and increasing attention to sustainability issues are key driving factors behind the growth of bio-mordants research in the Asian and Middle Eastern regions.

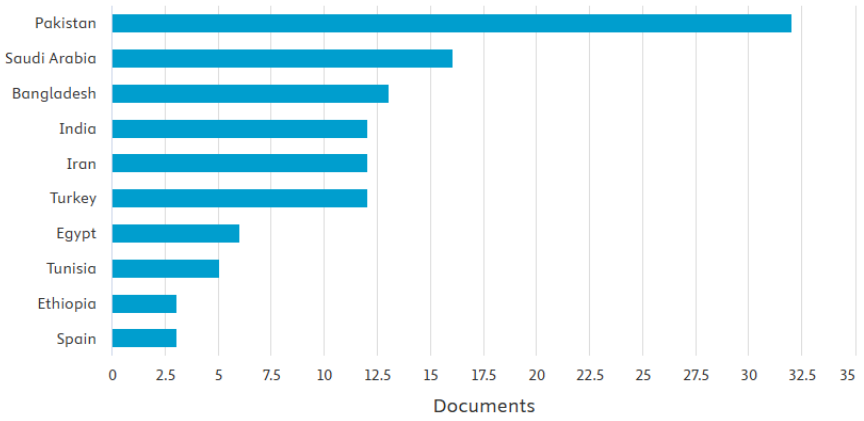

FIGURE 3. Number of articles by country or territory. (Source: Scopus database).

The distribution of scientific research related to bio-mordants by country category shows the dominance of Pakistan with 32 articles, followed by Saudi Arabia with 16 articles. In addition, several other countries have also contributed to this field, including Bangladesh with 13 articles; India, Iran, and Türkiye with 12 articles each; Egypt with 6 articles; Tunisia with 5 articles; and Ethiopia and Spain with 3 articles each.

FIGURE 4 shows that although bio-mordants research is dominated by developing countries with strong textile industry bases in the Asian and Middle Eastern regions, this condition indicates that bio-mordants research is global in nature and involves collaborative efforts through cross-regional knowledge exchange.

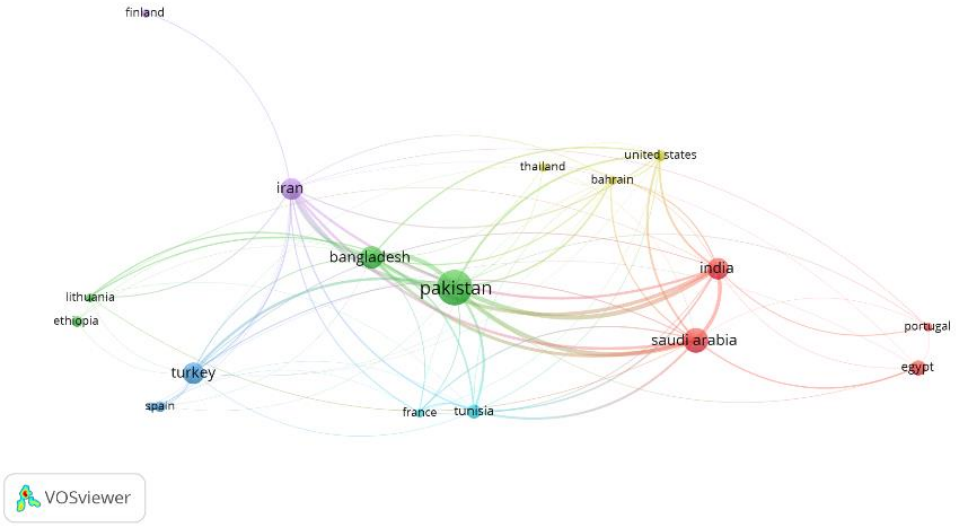

FIGURE 4. Network country visualization. (Source: Output VOSviewer software).

The findings of this study reinforce the notion that the utilization of bio-mordants is not solely of interest to countries with the highest research output, but has also gained global attention in efforts to identify environmentally friendly alternative solutions to replace metal mordants.

Based on the institutional affiliations shown in **FIGURE 5**, Government College University Faisalabad emerges as the most productive institution with 28 articles, followed by the University of Education with 11 articles. Saveetha Medical College and Hospital and Saveetha Institute of Medical and Technical Sciences each contributed 10 articles, while the University of Dhaka and the National Institute of Textile Engineering and Research (NITER) produced 8 articles. Yazd University and King Khalid University each accounted for 7 articles, whereas Marmara Üniversitesi and Riphah International University contributed 6 and 5 articles, respectively.

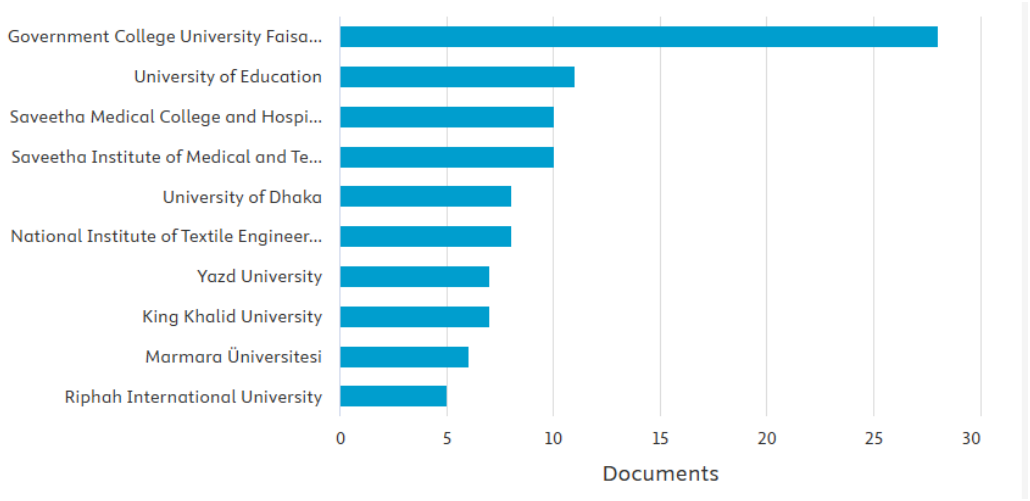

FIGURE 5. Network country visualization. (Source: Scopus database).

The dominance of Government College University Faisalabad in bio-mordants research publications indicates that this institution has emerged as a leading center in the development of environmentally friendly textile technologies and bio-based materials. This is evident from the substantial gap in publication output compared to the University of Education, which ranks second with 11 articles. Further contributions are also evident from medically and technically oriented institutions, such as Saveetha Medical College and Hospital and Saveetha Institute of Medical and Technical Sciences, each producing 10 articles. In addition, research publications are distributed across the University of Dhaka and the National Institute of Textile Engineering and Research (NITER) with 8 articles, followed by Yazd University and King Khalid University with 7 articles, as well as Marmara Üniversitesi and Riphah International University, which contributed 6 and 5 articles, respectively.

Furthermore, **FIGURE 6** shows the allocation of research based on publication sources, indicating that the Journal of Natural Fibers and Sustainability (Switzerland) are the most dominant journals, each publishing six articles. This reflects the strong association of bio-mordants topics with natural fibers and sustainability issues. These are followed by the Journal of Engineered Fibers and Fabrics with five articles, as well as Science Progress and Scientific Reports, each contributing four articles.

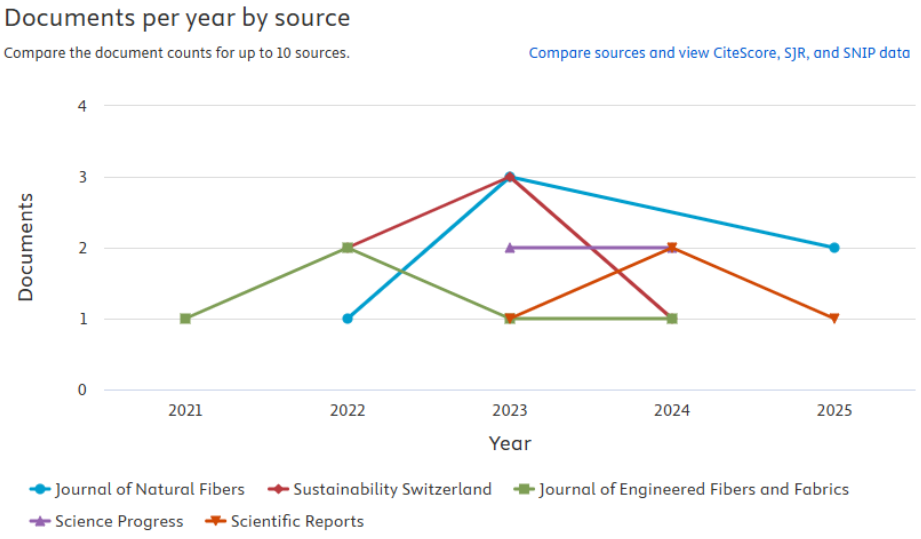

FIGURE 6. Number of articles by sources. (Source: Scopus database).

FIGURE 7 shows that the author productivity analysis indicates the dominance of contributions by several key researchers, with Adeel, S. emerging as the most prolific author with 28 articles, followed by Mia, R. (13 articles), Habib, N. (12 articles), Amin, N. and Hussaan, M. (8 articles each), Batool, F. (7 articles), and Haja, A., Imran, M., and Qayyum, M. A. (6 articles each), all of whom have played significant roles in advancing bio-mordants research. Overall, the distribution of bio-mordants research demonstrates that this topic is rapidly developing in countries with high textile industry demand and adequate natural resource support, while also involving global collaboration, thereby making it academically relevant and strategically important in supporting the transition toward a sustainable textile industry.

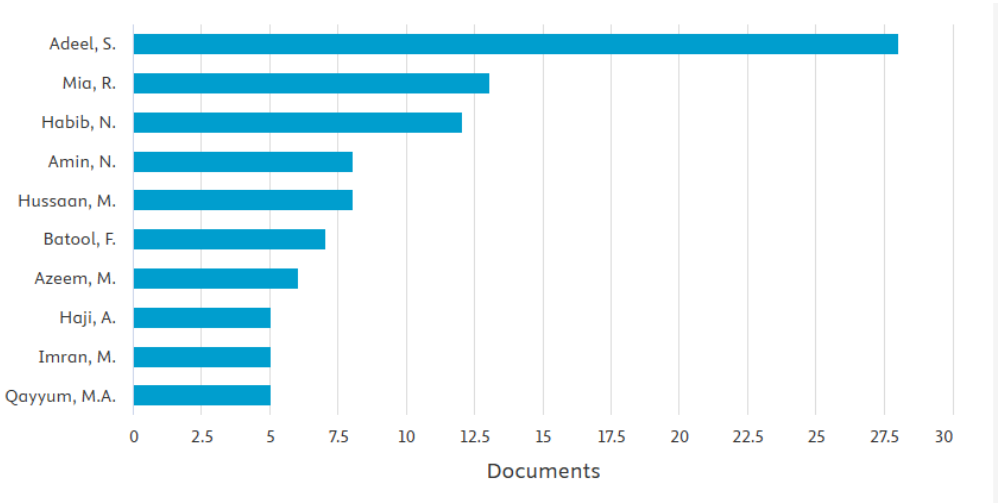

FIGURE 7. Count of publication by author. (Source : Scopus database).

RQ3: What are the theoretical and practical implications of future research perspectives on bio-mordants?

Collectively, the bibliometric findings indicate that bio-mordants research has evolved from exploratory studies into a rapidly expanding research domain closely associated with sustainability-driven textile innovation. The

dominance of specific regions, institutions, and research themes reflects industrial demand and environmental policy pressures, underscoring the strategic position of bio-mordants as a key component in future textile processing research.

From a theoretical perspective, an analysis of 71 articles was conducted using VOSviewer software to visualize the conceptual structure characterized by strong interconnections among material aspects, functional performance, and sustainability, as well as the theoretical and practical implications of bio-mordants research. This bibliometric analysis enriches the textile literature by strengthening the conceptual understanding of color fixation and identifying variables that have the potential to guide future research directions.

Based on **FIGURE 8**, from a practical perspective, the most frequently occurring keywords include dyeing, color, natural dye, bio-mordants, sustainability, cotton, silk, color fastness, textile industry, and eco-friendly. These keywords indicate that bio-mordants research has the potential to enhance color fastness while simultaneously reducing environmental impacts. Accordingly, bio-mordants studies provide a scientific foundation for the textile industry to adopt safer fixation technologies that comply with increasingly stringent environmental regulations.

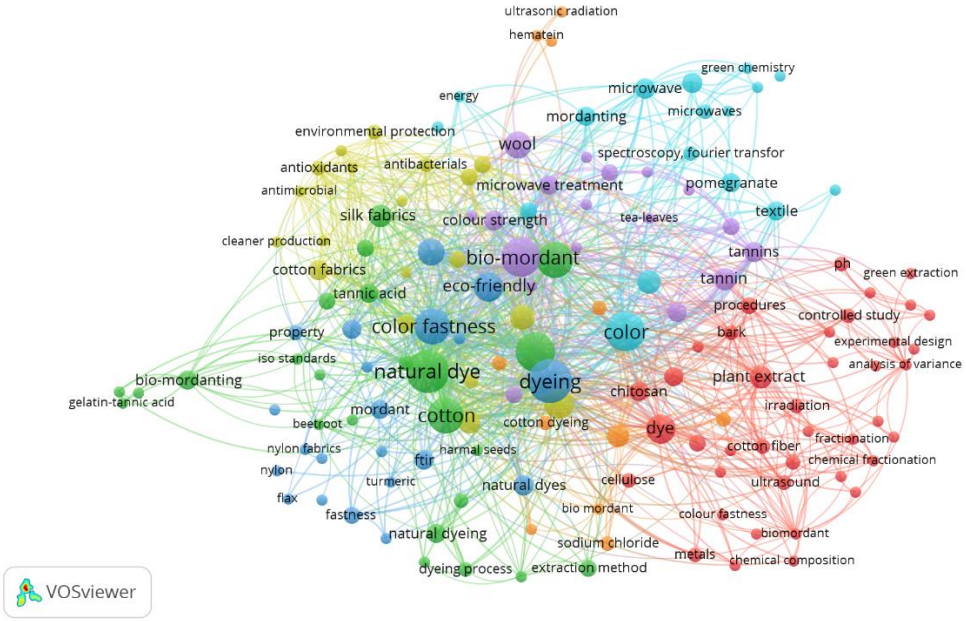

FIGURE 8. Co-occurrence framework and representation of key terms.

(Source: Output VOSviewer software)

TABLE 2. Keyword by author.

Rank	Keyword	Total link strength
1	Dyeing	355
2	Color	308
3	Natural dye	265
4	Bio-mordant	253
5	Sustainability	233
6	Silk	225
7	Cotton	215
8	Color fastness	196
9	Textile industry	174
10	Eco-friendly	139

(Source: Output VOSviewer software)

Based on the findings of previous studies, gaps have been identified in existing research, as most studies have been conducted in countries with high textile demand, one of which is Pakistan, which ranks third globally as a cotton consumer (Ali et al., 2025). In addition, Saudi Arabia represents another country with substantial textile demand due to a surge in the domestic market, resulting in a strong reliance on textile imports (Kamel & Debes, n.d.).

Considering the significant imbalance in the current literature, which is predominantly concentrated in Asian and Middle Eastern countries, the theoretical and practical relevance of future bio-mordants research lies in its capacity to bridge the development of sustainable textile dyeing concepts. The bibliometric findings of this study not only map the knowledge landscape comprehensively but also provide a conceptual foundation and future research directions for the global implementation of bio-mordants.

CONCLUSION

Based on this bibliometric analysis, the development of bio-mordants research in natural textile dyeing from 2017 to 2026 was systematically mapped across 71 Scopus-indexed publications using the PRISMA framework and VOSviewer-based analysis. The results indicate that bio-mordants research has evolved from exploratory studies into an increasingly mature and relevant research domain, in line with growing global attention to sustainability issues and the textile industry's demand for environmentally friendly fixation alternatives. Consequently, this research topic has a high level of urgency for further development in the future. The dominance of publications from countries with strong textile industries further underscores the close relationship between the direction of bio-mordants research and industrial practices as well as environmental policy demands.

In addition, keyword analysis and collaboration networks reveal that bio-mordants research is not limited to material and technical aspects of dyeing, but is also integrated with issues of color fastness, sustainability, and textile industry applications. These findings indicate that bio-mordants play a strategic role both theoretically and practically in supporting the transition toward safer and more sustainable textile dyeing processes. Looking ahead, future research may be directed toward the exploration of new bio-mordants sources, the standardization of application methods, and the strengthening of cross-regional collaborations to expand the industrial-scale implementation of bio-mordants globally. Overall, this study contributes a comprehensive mapping of bio-mordants research developments while offering strategic directions for future research and implementation in the textile industry.

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