Plant-Derived Sustainable Technologies: Integrating Scientometric Analysis of Green Nanoparticle Synthesis with Advances in Natural Dye Extraction

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Abstract

Although there has been rapid development in sustainable technologies based on plants as environmentally friendly alternatives for the synthesis of green nanoparticles and natural dyes, it is necessary to explore combining global scientometric analysis with the latest technological advances in extractions. This work provides an integrative review that includes scientometric analysis of literature about the synthesis of nanoparticles using plants as well as the sources of natural dyes, methods of their extraction, methods of characterization of the dyes, and sustainable applications. Scientometric analysis of 1,762 publications during 2015–2025 from 520 different sources has been performed to evaluate scientific growth, collaborations, keyword dynamics, and new topics related to the synthesis of nanoparticles using plants. The analysis has shown that the average annual growth rate was 18.81%, and that there was a transition from synthesis and characterization to application-oriented research in the field of photocatalysis and environmental protection. Based on the results of the analysis, a review of the main sources of plants for natural dyes, traditional and modern extraction methods, such as ultrasonic, microwave, and Soxhlet extractions, as well as their features and sustainability, has been provided. The recent achievements in the characterization of the dyes using UV–Vis spectroscopy, FTIR, HPLC, LC–MS, XRD, and SEM–EDX have been presented. In summary, this review paper attempts to combine scientometric knowledge with the progress made in the development of technology in the extraction of natural dyes, and outlines the trends in present-day research as well as existing knowledge gaps.

Keywords: Plant extracts, Natural dyes, Ultrasound-assisted extraction, Microwave-assisted extraction, Metal nanoparticles, Sustainable extraction.

1. Introduction

The rising environmental concerns due to the increasing use of synthetic dyes, processing of harmful chemicals, and the use of high-energy-consuming processes for synthesizing raw materials have led to the rapid development of environmentally friendly technologies based on the principles of green chemistry [1], [2]. The dyeing process in industries and the synthesis of nanoparticles also contribute to water pollution and the generation of harmful effluents and carbon emissions. To address this issue, plant-based materials serve as a common foundation for two emerging sustainable technologies: (a) biosynthesis of nanoparticles using plants, and (b) the extraction of natural dyes. Both technologies utilize bioactive compounds found in plants, environmentally friendly

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methodologies, and renewable plant biomass; however, these fields are usually discussed separately [3], [4]. The use of plants for the synthesis of nanoparticles utilizes various phytochemicals like flavonoids, phenolics, terpenoids, alkaloids, and tannins as reducing agents [3], [5]. Simultaneously, the use of plant-based dyes derived from renewable sources like barks, leaves, flowers, seeds, roots, and agro-waste products also provides a cost-effective and environmentally friendly option for replacing synthetic dyes [6]. This also aligns well with the global sustainability agenda [4], [7]. Over the last decade, the pace of research in this field has grown tremendously due to the increasing demand for environmentally friendly products in textile coloration, wastewater treatment, antimicrobial agents, and photovoltaic devices [8], [9]. Advances in characterization studies have also been made possible by the use of UV-Visible spectroscopy, Fourier Transform Infrared spectroscopy (FTIR), X-ray Diffraction (XRD), High-Performance Liquid Chromatography (HPLC), Liquid Chromatography-Mass Spectrometry (LC-MS), and Scanning Electron Microscopy (SEM) for validation and performance correlation studies. Alongside this, the use of advanced extraction techniques such as Ultrasound-Assisted Extraction (UAE), Microwave-Assisted Extraction (MAE), and optimized Soxhlet extraction has also improved efficiency, selectivity, and sustainability [10], [11].

Although there is a growing number of publications on the production of green nanoparticles using plants and sustainable natural dye extraction, previous review papers did not cover these issues as a whole. Either reviews are about the bibliometric development of the field of green nanotechnology, or reviews provide information about extraction and characterization of natural dyes. At the same time, the connection of such information with the overall development of research is not provided. Therefore, there is still no comprehensive review covering the scientometric analysis of global trends in the field and sustainable technologies involving natural dye extraction, characterization, and usage.

Therefore, this review integrates scientometric analysis of plant-mediated nanoparticle synthesis with a comprehensive review of natural dye extraction technologies to provide a unified perspective on plant-based sustainable materials.

In line with the above considerations, this review aims to: conduct scientometric analysis of global publication trend, collaboration networks and thematic development in the field of green nanoparticle synthesis from plants; review plant resources, traditional and modern technologies for the extraction of sustainable natural dyes; analyze recent developments in the field of dye characterization and its link to dye quality and textile sustainability; and highlight challenges, gaps, and opportunities in the field of sustainable plant-based materials.

To accomplish these goals, the following research questions will be answered in this review:

- RQ1. What publication patterns, collaborations, and research topics are prevalent within the field of the evolution of plant-mediated green nanoparticle synthesis?
- RQ2. What plant species and extraction methods have shown their effectiveness in producing natural dyes sustainably?
- RQ3. What role do modern characterization approaches play in the knowledge about dye chemistry, dyeing of textiles, and eco-applications?
- RQ4. In what directions should researchers work in order to develop sustainable plant-based technologies faster?

These research questions give the readers a clear path in this review and match the structure of the paper perfectly.

2. Relationship between Plant-Mediated Green Nanoparticle Synthesis and Natural Dye Extraction

Whereas plant-mediated synthesis of nanoparticles and natural dyes have conventionally been studied separately, they both utilize biomass from plants and various phytochemicals including flavonoids, tannins, phenolics, anthocyanins, alkaloids, and terpenoids. The phytochemicals act as reducing and stabilizing agents in the process of nanoparticle synthesis as well as natural colorants in the process of dye extraction. Hence, both processes involve green chemistry practices, valorisation of biomass, reduction of solvents, and sustainable processing. Additionally, plant-based nanoparticles have been used for the purposes of dye degradation, functionalizing textiles, antimicrobial coatings, and wastewater treatments. This makes connections between nanotechnology and sustainable dyes. As a result, the combination of scientometrics related to plant-mediated synthesis of nanoparticles with natural dyes is helpful.

3. Bibliometric Analysis

Due to the fact that the area of green nanoparticle synthesis via plants is the largest field where studies involving the use of biomolecules obtained from plants for sustainable materials synthesis are being carried out, the scientometric study is dedicated to this field in order to find global trends in research, collaborations, and technology development.

3.1. Data source and methodology

A bibliometric study was undertaken to examine global research trends in the green synthesis of nanoparticles using plant extracts and their applications. Bibliometric analysis was performed using the Bibliometrix R package (version 4.5.1) through the Biblioshiny web interface. Network visualization and calculation of graph metrics were performed using the functions implemented in Bibliometrix.

The search was limited to papers published in English from 2015 to 2025 in peer-reviewed journals. As a result of applying the filters to the search, 1,762 papers from 520 journals authored by 6,934 authors were found (Figure 1). Duplicate entries were automatically identified and filtered out by the Scopus database before exporting. Further inspection of the dataset was carried out manually in Bibliometrix (Biblioshiny), where inconsistencies in author keywords and terminology were addressed. Similar keywords (e.g., singular-plural, misspellings, abbreviations, and capitalizations) were merged based on the custom-built thesaurus to facilitate co-word analysis.

Network and visualizations were produced using the Bibliometrix R package (via the Biblioshiny interface). Co-word, collaboration, and co-citation networks have been built to analyze intellectual and collaborative networks. The significance of nodes in the network was analyzed using indicators such as betweenness centrality, closeness centrality, and PageRank calculated directly in Bibliometrix. Betweenness centrality reveals intermediary nodes connecting different research clusters, closeness centrality indicates relative accessibility of nodes within a network, and PageRank reveals influential nodes linked to other influential nodes.

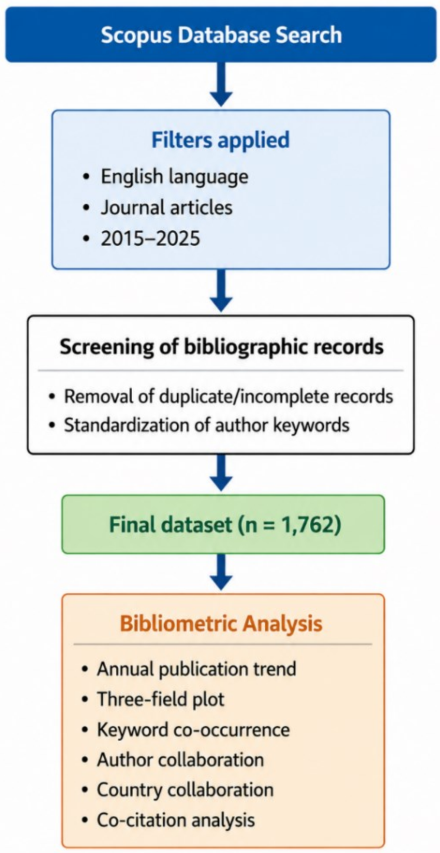

Figure 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) workflow diagram of the bibliometric data collection and selection process.

Since the literature search was carried out on 7 January 2026, publication data in 2025 include only those entries indexed in Scopus at the date of the literature search. Therefore, publication counts in 2025 should be treated provisionally and cannot be directly compared with calendar years. The bibliometric study consisted of publications from 2015 to 2025, with a total of 1,762 documents from 520 sources. The study had a total of 6,934 authors, with a growth rate of 18.81%. This indicates a rapidly increasing research trend in this domain. The study had a total of 97,832 references, with an average of 34.15 citations per document and a document average age of 4.23 years. The international co-authorship contribution to publications was 32.29%, with an average co-author count of 5.45.

The bibliometric mapping and network analysis were undertaken to study trends in publications, keyword co-occurrence networks, international co-authorship networks, and author co-citation networks. Network centrality measures such as betweenness, closeness, and PageRank were used to identify key nodes in the network.

3.2. Publication trends

The scientific production trend throughout the years shows a steady increase from 2015 onwards, with a steep rise in scientific production from 2018 onwards (Figure 2).

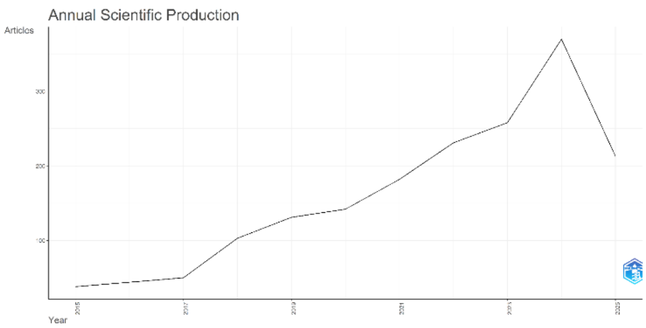

Figure 2. Annual scientific production on green synthesis of nanoparticles from 2015 to 2025, showing the yearly number of publications indexed in the Scopus database.

The highest number of publications was achieved in 2024, followed by a slight decrease in 2025, possibly due to incomplete records from the latest year. The steady rise in scientific production from 2018 to 2024 indicates an increase in research activities in response to environmental issues, green chemistry, and the need to develop eco-friendly methods for nanomaterials. The high annual growth rate indicates that green chemistry using plant extracts is a rising research frontier.

3.3. Word cloud analysis

The word cloud analysis gives a visual representation of the conceptual density and thematic priorities of the research domain of plant-mediated green synthesis of nanoparticles, as shown in Figure 3 and Figure 4.

The prominence of words such as “green synthesis,” “plant extract,” “metal nanoparticles,” “Fourier transform Infrared spectroscopy,” “X-ray diffraction,” “scanning electron microscopy,” “photocatalysis,” and “degradation” indicates a well-defined and technically well-structured research environment that integrates aspects of green chemistry, nanoparticle characterization, and application in environmental remediation.

The prominence of “green synthesis,” which appears as the largest and most central word in the word cloud, indicates that environmentally friendly synthesis methods are the foundation of the research domain in green synthesis of nanoparticles. Its central location in the keyword network confirms that green and sustainable methods are the primary drivers of the research in this domain.

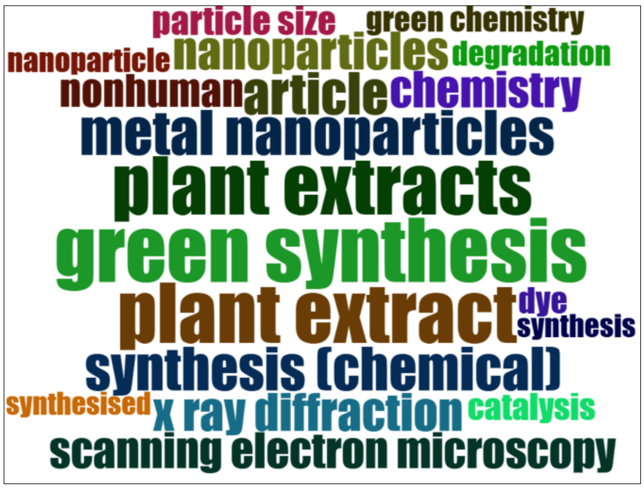

Figure 3. Word Cloud Analysis illustrating the most frequently occurring author keywords in publications retrieved from the Scopus database (2015–2025). The size of each keyword is proportional to its frequency of occurrence in the retrieved literature.

Figure 4. Treemap visualization of the most frequently occurring merged author keywords in the bibliometric dataset (2015–2025). The area of each rectangle is proportional to the frequency of keyword occurrence, highlighting the dominant research themes in green synthesis of nanoparticles.

The term green synthesis is associated with the term "plant extract/plant extracts," which appears as one of the most important nodes in the network in terms of PageRank and betweenness centrality measures, indicating that the term plays a bridging role in connecting other concepts.

The term "metal nanoparticles" indicates the materials focus of the research domain, and the literature predominantly reports on the synthesis of silver, gold, zinc oxide, and other metal or metal oxide nanoparticles using plant-mediated green synthesis methods. The co-occurrence of this term with green synthesis indicates that the research in this domain primarily focuses on green synthesis methods and not merely nanoparticles. The co-occurrence of the two words, "nanoparticles" and "nanoparticle," indicates methodological variation in the literature but confirms the central role of nanoparticles in the research domain in green synthesis of nanoparticles.

Equally noteworthy is the high occurrence rate of advanced characterization techniques like "Fourier transform infrared spectroscopy (FTIR)", "X-ray diffraction (XRD)", and "scanning electron microscopy (SEM)". The importance of FTIR arises from the fact that the identification of the specific groups responsible for the reduction and stabilization of nanoparticles is crucial. The regular use of FTIR, XRD, SEM, and other similar methods proves that the characterization of the physical and chemical nature of the nanoparticles is an inherent part of plant-based green nanoparticle research.

Apart from synthesis and characterization studies, the occurrence rate of "photocatalysis" and "degradation" reflects the most significant function of plant-mediated nanoparticles. This reflects that the primary function of nanoparticles derived from plants is environmental remediation. The occurrence of "photocatalysis" under the umbrella of "green synthesis" reflects the fact that the field of research has evolved from merely synthesizing nanoparticles to performance-based research.

The occurrence of "green chemistry", "catalysis", "antibacterial activity", "adsorption", "biosynthesis", etc., although to a smaller extent than "photocatalysis", reflects the fact that the scope of application is widening from merely dye degradation to other areas. This reflects the fact that although photocatalysis is the most significant function of plant-mediated nanoparticles, there are studies focused on the antimicrobial properties and antioxidant properties of nanoparticles derived from plants.

3.3.1. Keyword co-occurrence and trend topics

The keyword co-occurrence network also identifies the presence of two major and interconnected thematic groups that shape the intellectual theme of the research domain (Figure 5). Node size is proportional to keyword occurrence frequency, link thickness indicates the strength of co-occurrence between keywords, and node colors represent different thematic clusters identified by the clustering algorithm.

The first group is mainly focused on the themes of green synthesis, characterization methods, and environmental degradation. This group comprises highly interconnected keywords like green synthesis, plant extracts, metal nanoparticles, Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), photocatalytic activity, dye degradation, silver nanoparticles, and adsorption. Centrality measures have also shown that plant extracts (Betweenness = 0.093; PageRank = 0.035), metal nanoparticles (Betweenness = 0.087; PageRank = 0.031), and green synthesis (Betweenness = 0.071; PageRank = 0.029) are the key connecting entities within the cluster of keywords related to the theme of green synthesis and characterization methods for photocatalytic activity and dye degradation (Table 1). The high betweenness of these keywords implies that these keywords are the integrating entities within the theme of green synthesis because they connect the methods of material synthesis with the methods of material characterization and performance evaluation. This suggests that plant extract-based green synthesis is not an isolated research theme but an integrating theme within the research domain of photocatalytic activity and dye degradation. The strong association of characterization methods like FTIR and SEM with degradation-related keywords also suggests that the structural confirmation of the material is often correlated with the photocatalytic activity of the material.

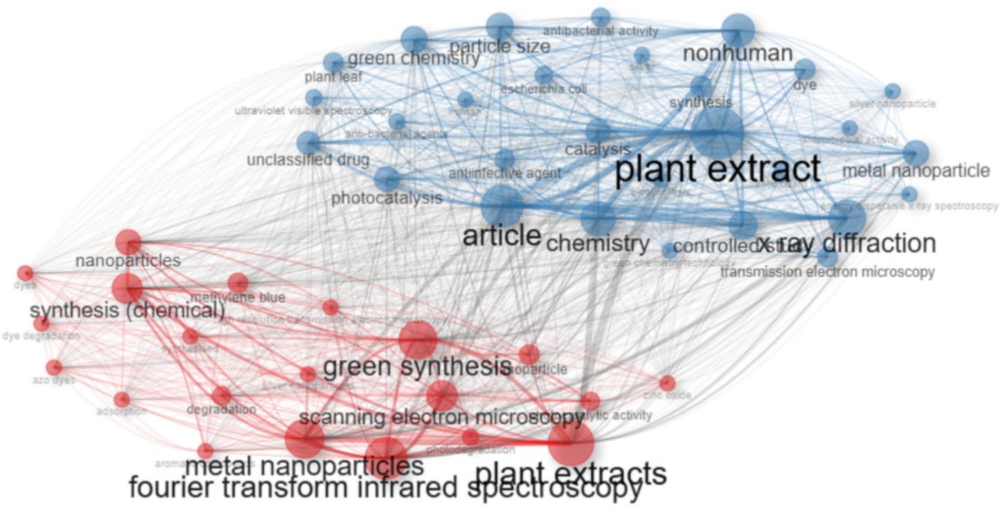

Figure 5. Keyword co-occurrence network of merged author keywords generated using Bibliometrix (Biblioshiny) from 1,762 Scopus-indexed publications (2015–2025).

Table 1. Network centrality analysis of key research nodes, showing cluster classification and corresponding Betweenness, Closeness, and PageRank values.

Node	Cluster	Betweenness	Closeness	PageRank
Green Synthesis	1	0.071	0.02	0.029
Plant Extracts	1	0.093	0.02	0.035
Fourier Transform Infrared Spectroscopy	1	0.051	0.02	0.034
Metal Nanoparticles	1	0.087	0.02	0.031
Synthesis (Chemical)	1	0.041	0.02	0.025
Nanoparticles	1	0.015	0.02	0.022
Scanning Electron Microscopy	1	0.027	0.02	0.026
Photocatalytic Activity	1	0.015	0.02	0.017
Methylene Blue	1	0.02	0.02	0.019
Degradation	1	0.011	0.02	0.018
Nanoparticle	1	0.008	0.02	0.019
Synthesised	1	0.009	0.02	0.014
Photodegradation	1	0.011	0.02	0.016
Silver Nanoparticles	1	0	0.02	0.015
Aromatic Compounds	1	0.016	0.02	0.015
Dyes	1	0.008	0.02	0.013
Azo Dyes	1	0.007	0.02	0.014
High Resolution Transmission Electron Microscopy	1	0.01	0.02	0.013
Dye Degradation	1	0.006	0.02	0.01
Adsorption	1	0.001	0.02	0.011
Zinc Oxide	1	0	0.02	0.011
Plant Extract	2	0.083	0.02	0.041
Article	2	0.034	0.02	0.034
X Ray Diffraction	2	0.044	0.02	0.031
Chemistry	2	0.032	0.02	0.029
Nonhuman	2	0.022	0.02	0.028
Photocatalysis	2	0.017	0.02	0.022
Particle Size	2	0.019	0.02	0.024
Controlled Study	2	0.018	0.02	0.025
Catalysis	2	0.024	0.02	0.022
Dye	2	0.008	0.02	0.019
Green Chemistry	2	0.022	0.02	0.023
Metal Nanoparticle	2	0.026	0.02	0.023
Unclassified Drug	2	0.011	0.02	0.021
Synthesis	2	0.01	0.02	0.02
Antibacterial Activity	2	0.014	0.02	0.018
Plant Leaf	2	0.01	0.02	0.019
Transmission Electron Microscopy	2	0.011	0.02	0.019
Escherichia Coli	2	0.013	0.02	0.018
Antiinfective Agent	2	0.017	0.02	0.019
Ultraviolet Visible Spectroscopy	2	0.009	0.02	0.017
Silver	2	0.009	0.02	0.015
Energy Dispersive X Ray Spectroscopy	2	0.005	0.02	0.016

Table 1. Continued on next page.

Table 1 (continued): Network centrality analysis of key research nodes, showing cluster classification and corresponding Betweenness, Closeness, and PageRank values.

Node	Cluster	Betweenness	Closeness	PageRank
Anti-Bacterial Agents	2	0.012	0.02	0.017
Antioxidant	2	0.004	0.02	0.012
Biosynthesis	2	0.004	0.02	0.011
Green Chemistry Technology	2	0.008	0.02	0.015
Antimicrobial Activity	2	0.005	0.02	0.012
Human	2	0.003	0.02	0.012
Silver Nanoparticle	2	0.002	0.02	0.014

Network analysis was done using the mapping program for bibliometrics. The significance of the nodes was assessed using three common network metrics that include betweenness centrality, closeness centrality, and PageRank. The network analysis was done with the help of the Bibliometrix software (Biblioshiny interface) in *R*. The software calculates common graph theory-based centrality measures for analyzing the structural significance of nodes in the bibliometric network. The betweenness centrality score is calculated on the basis of the number of times a node serves as a bridge on the shortest paths between other nodes in the network.

The closeness centrality is defined as the inverse of the sum of the shortest paths from the given node to all other reachable nodes, measuring the centrality of the node within the network. PageRank centrality is an iterative algorithm for calculating the score on the basis of the number and the quality of connections of a node.

The betweenness centrality determines the frequency at which a node falls along the shortest path of other nodes in the network and thus shows the bridging nature of a particular node within various clusters. Closeness centrality evaluates the average minimum path distance from a node to all other nodes in the network. PageRank assesses the relative importance of a node depending on the number and quality of connections. All the network indices are unitless network indices computed by the bibliometric program. They need to be assessed in a comparative manner within the network under investigation.

The similarity of the closeness centrality measures provided in Table 1 is due to the fact that the network of co-occurrences is very connected. This leads to similar shortest path lengths between the nodes and hence similar values of the closeness centrality measure.

Interpretation of all these metrics as a whole allows for an even better understanding of the relationship between bibliometric indicators. PageRank metric is useful in identifying the key leaders in research, such as specific research institutes, nations, or research topics that play an important role in the scientific field. Betweenness centrality metric identifies those nodes that act as bridge nodes to connect different research themes or collaboration groups. The closeness centrality metric shows those nodes that are central to the network and can interact quickly with other elements in the network.

The second cluster of themes is related to the broader framework of the chemical synthesis of catalysts and biological activity. This cluster comprises words like X-ray diffraction, chemistry, photocatalysis, catalysis, antibacterial activity, plant leaf, transmission electron microscopy (TEM), biosynthesis, and green chemistry. Under this cluster of themes, the theme of plant extract has the highest PageRank of 0.041. This further substantiates the significance of the theme of plant extracts in the broader domain of both physicochemical and biological themes. The presence of themes like antibacterial activity, anti-infective agents, and biosynthesis along with advanced structural characterization tools like XRD and TEM suggests the integration of the field of plant nanoparticles with the broader theme of environmental remediation.

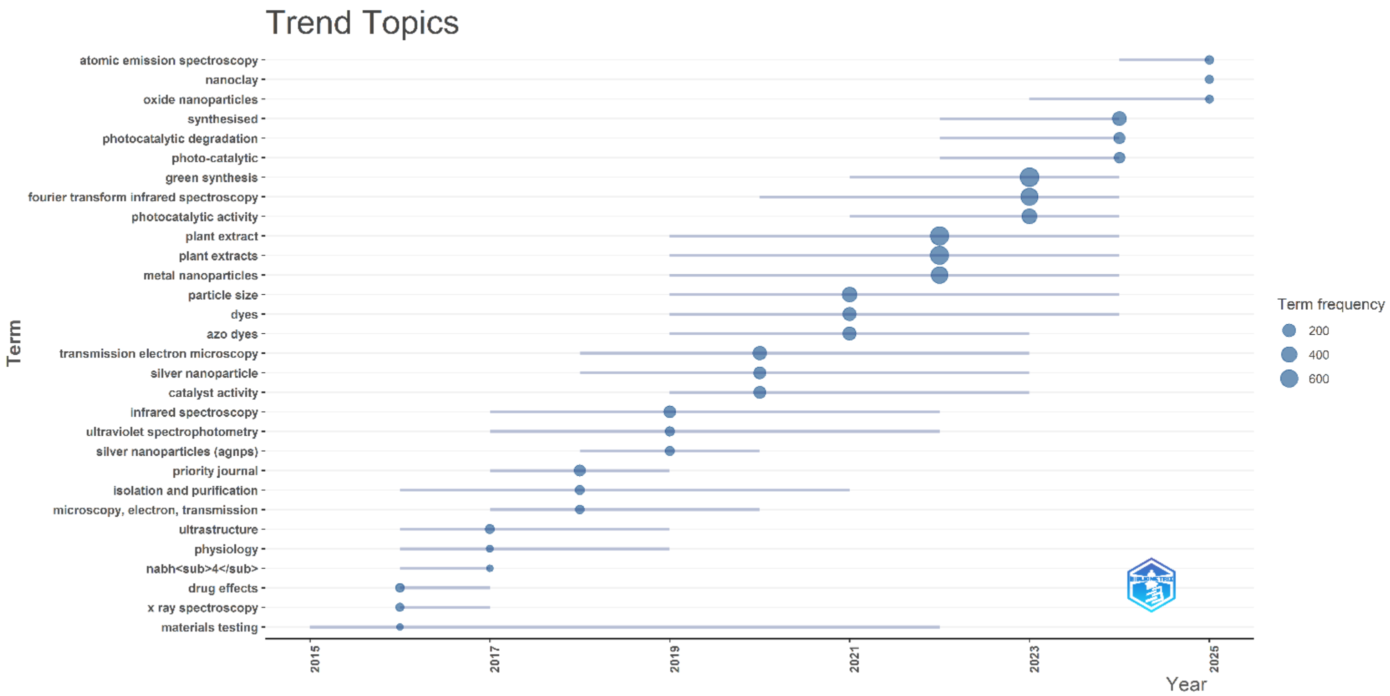

Figure 6. Trend topics analysis of author keywords in publications on the green synthesis of nanoparticles (2015–2025).

The integration of themes like catalysis and biological activity is an indication of the multidisciplinary expansion of the field of plant nanoparticles. This is because the field of plant nanoparticles is now being considered for its potential to exhibit multiple functions rather than just structural activity. Trend topic analysis of the themes is provided in Figure 6. The horizontal lines indicate the time span during which each keyword appeared in the literature, while the circles represent the year of highest prominence. Bubble size is proportional to the frequency of keyword occurrence, highlighting the temporal evolution of major research themes.

This analysis suggests the dynamic change in the research themes of the field of plant nanoparticles. It is observed that during the initial period of 2015-2017, the research themes were focused on the optimization and validation of the synthesis of plant nanoparticles through analytical tools like UV-Visible spectroscopy, XRD, and infrared spectroscopy. However, during the more recent period of 2020-2025, there has been a marked shift towards research themes like photocatalytic degradation of organic pollutants, oxide nanoparticles, antibacterial activity, antimicrobial activity, and the development of nano clay-based nanocomposites.

3.4. Three-field plot analysis of corresponding author countries, authors, and keywords

The three-field plot (AU_CO (author countries) – AU – KW_Merged (merged author keywords)) shows the relationship between the countries of the corresponding authors, the individual authors, and the dominant keywords in the area of green nanoparticle synthesis by plant mediation (Figure 7). In the left column (AU_CO), it is clear that India is the most prominent country among the corresponding authors, as the thickness of the connection flows is much higher compared to other countries like Malaysia, Saudi Arabia, Pakistan, Korea, Mexico, China, Iran, Iraq, Indonesia, and South Africa. In the central column (AU), the top prolific authors are represented, including Kumar S, Chen Z, Pugazhendhi A, Sabouri Z, Ahmad A, Kumar P, Sharma A, Selvaraj R, Varadavenkatesan T, Vinayagam R, Darroudi M, Iqbal M, and Kaviyarasu K. The high number of interlinking bands between these authors and the keyword column shows the high interconnectedness between the individual researchers and the individual keywords.

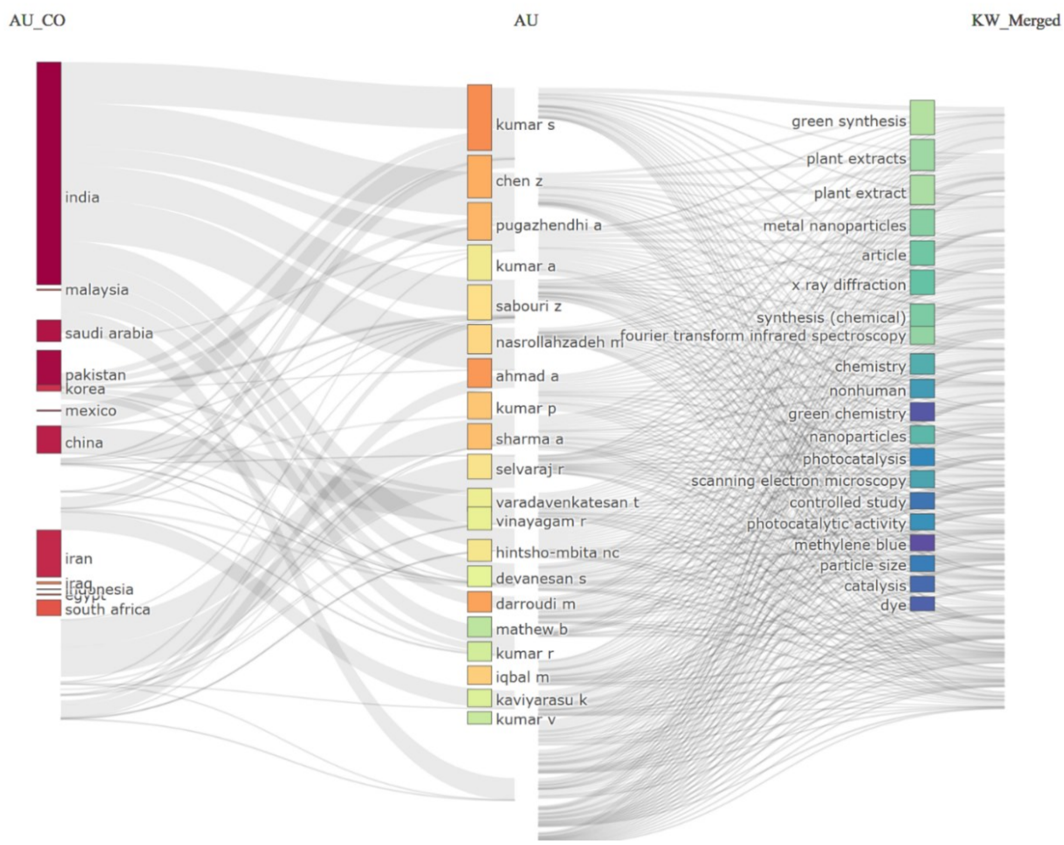

Figure 7. Three-field plot illustrating the relationships among corresponding author countries (AU_CO), authors (AU), and merged author keywords (KW_Merged). The width of each connection represents the strength of the association between the linked entities.

The keywords in the right column (KW_Merged) include the most frequently appearing words like green synthesis, plant extracts, plant extract, metal nanoparticles, X-ray diffraction, Fourier transform infrared spectroscopy, synthesis (chemical), chemistry, green chemistry, nanoparticles, photocatalysis, scanning electron microscopy, photocatalytic activity, methylene blue, particle size, catalysis, and dye. The high intensity of the connection between the Indian authors and keywords like green synthesis, plant extracts, metal nanoparticles, FTIR, XRD, and other advanced analytical tools shows the prominent role played by India in the area. Moreover, the presence of other countries in the same area shows the overall trend toward standardized research practices.

The bar chart of countries for the corresponding author further reinforces India's leadership in this area of research. India has the maximum number of publications, a significant proportion of which are classified as Single Country Publications, indicating high levels of domestic research output. Nevertheless, the presence of Multiple Country Publications indicates the growth in international collaborations in this area of research. India is followed by other notable countries such as Pakistan, Iran, and China, though with significantly lower levels of publication output. Other countries, such as Korea, Saudi Arabia, Ethiopia, South Africa, Egypt, Turkey, Malaysia, Brazil, Mexico, Indonesia, Iraq, Algeria, Bangladesh, Australia, Nigeria, and Germany, contribute a smaller but significant proportion of the publication output, indicating the growth in internationalization of research in green nanoparticle synthesis.

The presence of Single Country Publications (SCP) and Multiple Country Publications (MCP) indicates that India's research output is dominated by strong domestic research networks, while other countries indicate a high level of collaborative and balanced research output (Figure 8).

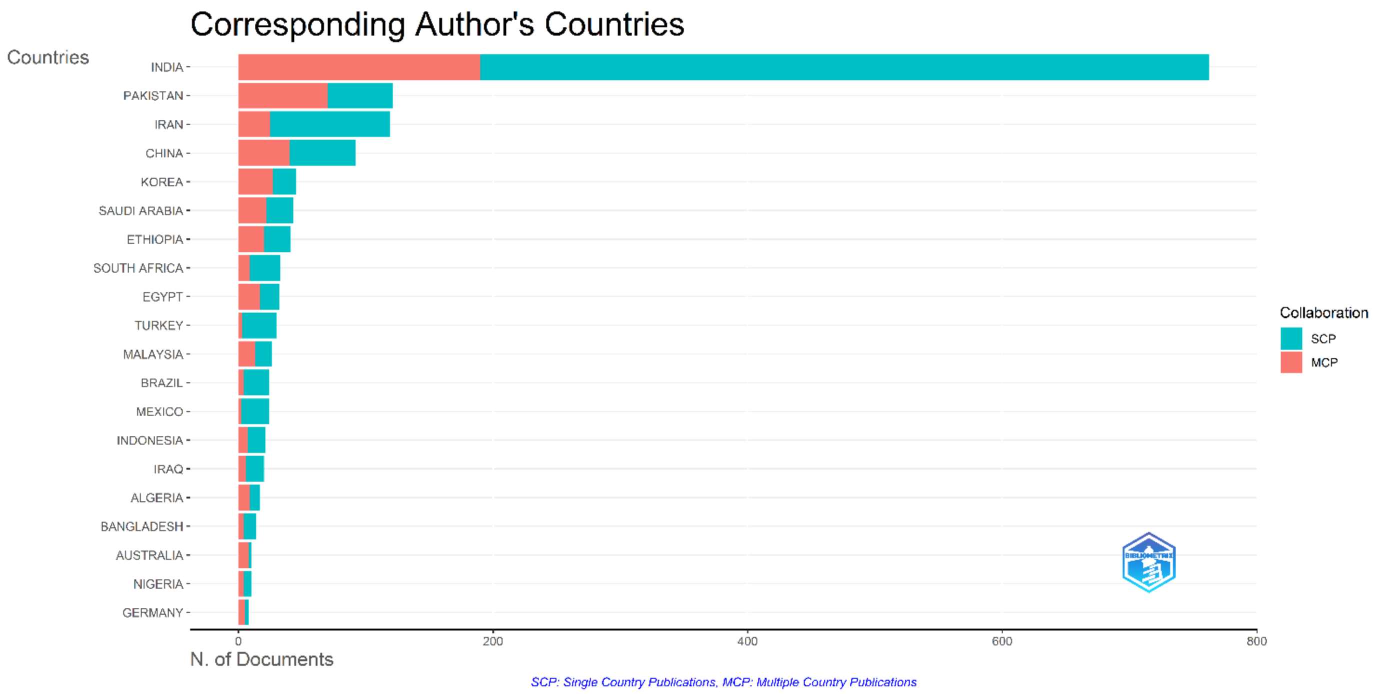

Figure 8. Corresponding author's country analysis showing the geographical distribution of research output. Bars are partitioned into SCP (Single Country Publications) and MCP (Multiple Country Publications).

These visualizations clearly indicate that the research output in the area of green nanoparticle synthesis mediated by plants is dominated by India, while the global collaborative framework for this area of research, centred around sustainable nanotechnology, advanced materials, and environmental remediation, is increasingly diverse.

3.4.1. Collaboration networks

The author collaboration network shows the presence of several influential and well-defined clusters of researchers, which points to the collaborative and interdisciplinary nature of the research in the green synthesis of nanoparticles via plant mediation (Figure 9). The indices used in the evaluation are calculated through graph-theoretical network analysis on the co-authorship, co-occurrence, and collaboration networks. Betweenness Centrality is an index that calculates the centrality of a node as it acts as the middleman in shortest paths between other nodes, thereby measuring the importance of such a node as a bridge in the network. Closeness Centrality is an index that calculates the closeness of a node to all other reachable nodes by calculating the inverse of the shortest path distance. PageRank is a dimensionless index based on an iterative algorithm for ranking the importance of a node if the node connects to other important nodes. Network importance was evaluated using three graph-theoretical metrics:

- **Betweenness centrality**

$$BC(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}} \quad (1)$$

where $\sigma_{st}$is the number of shortest paths between nodes $s$and t, and $\sigma_{st}(v)$is the number of those paths passing through node v. Larger values indicate stronger bridging roles.

- **Closeness centrality**

$$CC(v) = \frac{n-1}{\sum d(v,u)} \quad (2)$$

where $d(v,u)$denotes the shortest-path distance between two nodes. Higher values indicate that a node is more centrally located within the network.

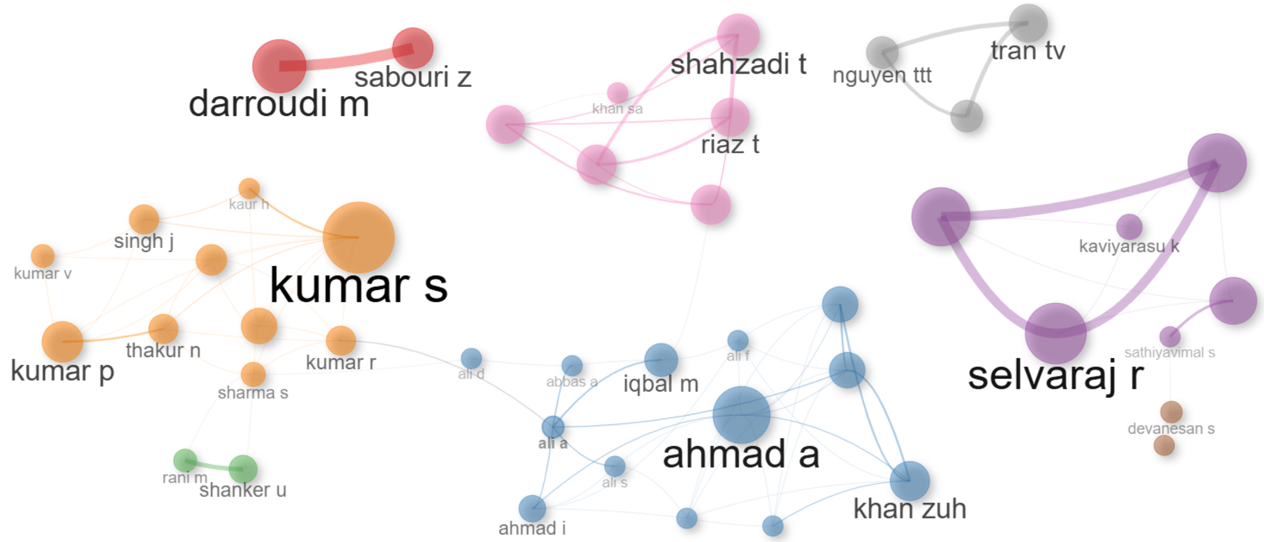

Figure 9. Author collaboration network generated using Bibliometrix (Biblioshiny) from 1,762 Scopus-indexed publications (2015–2025).

- **PageRank**

PageRank is an iterative importance score that assigns greater weight to nodes connected to other highly connected nodes.

It evaluates the relative importance of a node by considering both the number and the quality of its connections. Unlike degree centrality, PageRank assigns greater importance to nodes connected to other highly influential nodes. The PageRank score of node i is calculated iteratively as

$$PR(i) = \frac{1-d}{N} + d \sum_{j \in M(i)} \frac{PR(j)}{L(j)} \tag{3}$$

where:

- $PR(i)$is the PageRank score of node i;
- $d$is the damping factor, typically 0.85;
- $N$is the total number of nodes in the network;
- $M(i)$denotes the set of nodes linked to node i;
- $PR(j)$is the PageRank score of node j; and
- $L(j)$is the number of outgoing links from node j.

In this study, Bibliometrix reports raw betweenness values, which are dimensionless but not normalized. The reported closeness values are calculated by Bibliometrix and are dimensionless (Table 2).

Table 2. Author collaboration showing cluster classification and corresponding Betweenness, Closeness, and PageRank values.

Node	Cluster	Betweenness	Closeness	PageRank
Darroudi M	1	0	1	0.023
Sabouri Z	1	0	1	0.023
Ahmad A	2	8.503	0.01	0.033
Iqbal M	2	156.641	0.013	0.019
Ahmad I	2	17.387	0.012	0.019
Ali S	2	7.569	0.012	0.01
Abbas A	2	26.323	0.012	0.015
Ali A	2	223.24	0.015	0.022
Khan Au	2	60.017	0.012	0.032
Khan Zuh	2	3.813	0.01	0.037

Table 2. Continued on next page.

Table 2 (continued): Author collaboration showing cluster classification and corresponding Betweenness, Closeness, and PageRank values.

Node	Cluster	Betweenness	Closeness	PageRank
Tahir K	2	2.536	0.01	0.032
Ali D	2	13.505	0.011	0.008
Ali F	2	39.868	0.011	0.018
Imran M	2	0	0.009	0.017
Khan A	2	1.921	0.01	0.017
Shanker U	3	0	0.009	0.024
Rani M	3	0	0.009	0.024
Pugazhendhi A	4	12	0.091	0.023
Selvaraj R	4	1.333	0.077	0.034
Varadavenkatesan T	4	1.333	0.077	0.034
Vinayagam R	4	1.333	0.077	0.034
Kaviyarasu K	4	0	0.059	0.009
Sathiyavimal S	4	10	0.077	0.018
Kumar S	5	55.843	0.011	0.043
Sharma A	5	5.557	0.011	0.019
Kumar P	5	3.449	0.009	0.027
Kumar A	5	24.051	0.011	0.019
Kumar R	5	185.813	0.014	0.021
Kumar V	5	0.286	0.009	0.011
Singh J	5	3.13	0.009	0.021
Sharma S	5	66.259	0.011	0.019
Thakur N	5	17.956	0.011	0.029
Kaur H	5	0.333	0.009	0.022
Devanesan S	6	6	0.059	0.016
Losetty V	6	0	0.043	0.012
Iqbal S	7	125	0.011	0.024
Khan Sa	7	0	0.007	0.006
Shahid S	7	29	0.008	0.029
Shahzadi T	7	0	0.008	0.029
Zaib M	7	0	0.008	0.027
Riaz T	7	0	0.008	0.028
Tran Tv	8	0	0.5	0.024
Nguyen Dtc	8	0	0.5	0.022
Nguyen Ttt	8	0	0.5	0.022

The values reported by Bibliometrix are dimensionless relative importance scores obtained through iterative computation of the PageRank algorithm. Their magnitude depends on the structure and size of the analyzed network; therefore, they are interpreted only as relative measures of node influence within the same network.

Among the contemporary researchers, Kumar S (PageRank = 0.043), Khan Zuh (PageRank = 0.037), and Ahmad A (PageRank = 0.033) are found to be the most influential researchers based on their PageRank scores. In addition to the presence of influential researchers, the bridging capacity of the researchers is revealed by the betweenness centrality scores. Among the researchers, Ali A (Betweenness = 223.24), Kumar R (Betweenness = 185.81), and Iqbal M (Betweenness

= 156.64) are found to have exceptionally high betweenness scores, which indicates their bridging capacity between the otherwise isolated clusters of researchers. In other words, these researchers act as the leaders in the multinational and multi-institutional research teams. In addition to the presence of influential researchers, the collaboration map shows the presence of a dominant South Asian group consisting of researchers from India, Pakistan, and Iran, along with a strong East Asian group consisting of researchers from China, Korea, and Japan. In addition to these clusters, the presence of emerging Southeast Asian collaboration points to the growing regional research activity in this area. Moreover, the average co-authoring rate of 5.45 authors per document points to the team-based nature of this research field, which reflects the multidisciplinary nature of the researchers involved in the synthesis, characterization, and application studies in green nanotechnology.

The collaboration network is made up of several components that are not well-connected to each other. Closeness centrality is calculated by Bibliometrix in relation to the structure of the network independently. As a result, nodes that are well-connected in small networks get scores close to 1, while those nodes that are in large or not well-connected networks have much lower scores.

3.4.2. Country collaboration maps

The strength of collaboration among the countries was determined by applying the international collaboration network developed via the Bibliometrix R package (version 4.5.1). The international collaboration network was created based on the country affiliations of the authors. The edge weight between two countries is the strength of the connection in the collaboration network matrix of the countries. These edge weights are taken from the collaboration network of the Bibliometrix output and not normalized further. Thus, the edge weights can be considered as the collaboration strengths in the network and not as any normalized index. From the country-level analysis, India is the most productive country in the domain of plant-mediated green synthesis of nanoparticles, followed by Pakistan, Iran, China, and Korea. From the collaboration network map, strong transnational collaborations are evident among countries such as India and Japan, Iran and New Zealand, China and Korea, India and Australia, and Malaysia and Indonesia (Figure 10).

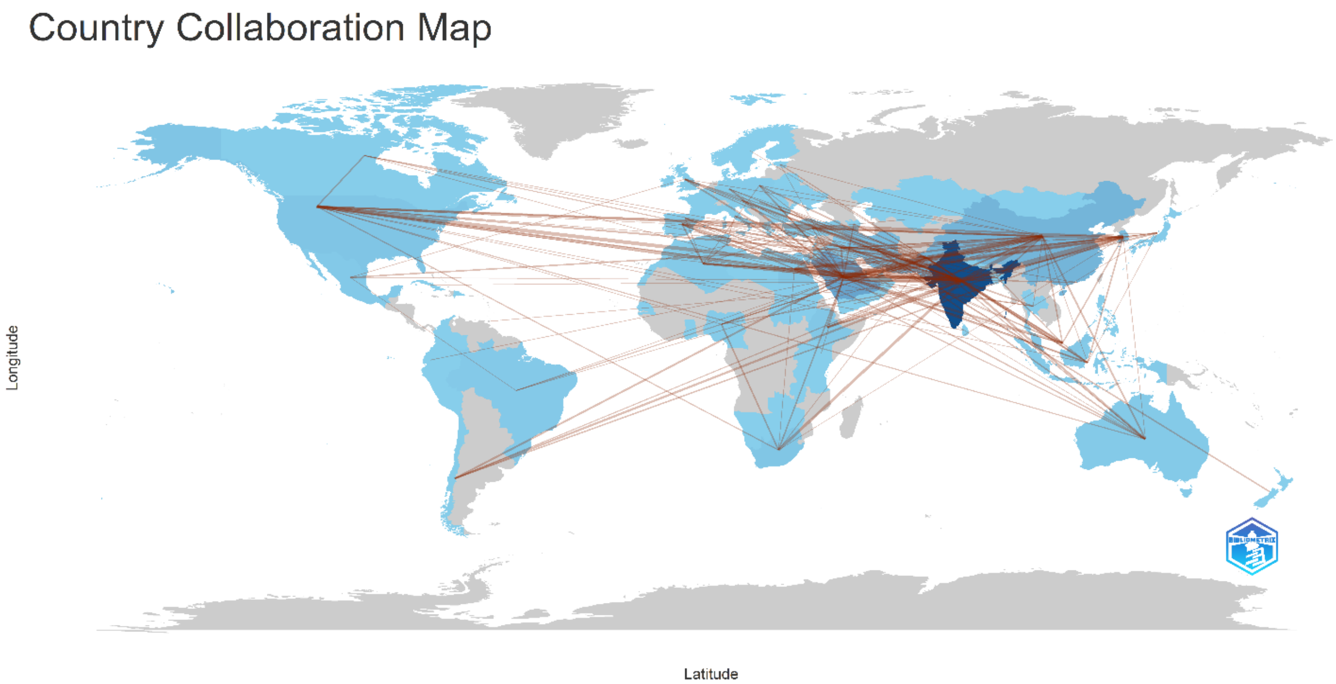

Figure 10. Global country collaboration map illustrating international co-authorship in publications.

This shows the presence of regional research collaborations, especially between countries in the Asian region with strong scientific engagement from countries like Japan and Australia. The high number of collaborations involving countries like Japan and Australia also suggests the presence of these countries as international research hubs for other countries in the Asian region (Table 3). Moreover, the presence of single-country publications (SCP) in India suggests strong research potential in the country. Also, the gradual increase in the number of multiple-country publications (MCP) suggests a gradual increase in internationalization.

The analysis of countries' collaboration was conducted using the Bibliometrix R package (version 4.5.1) through the Biblioshiny web interface. A collaboration matrix has been constructed based on the affiliation of authors' countries. The figures presented represent the collaboration weights obtained from Bibliometrix. The weights can be non-integers because they reflect the collaborative strength, not publication counts.

3.5. Author co-citation and bibliographic coupling

The co-citation network analysis also highlights the key contributors to plant-mediated green nanoparticle synthesis research, who have played a major role in the intellectual development of this research domain (Figure 11). Among these key contributors, Vidhu V.K. shows a high value of betweenness centrality (553) and a high PageRank value (0.065), indicating a key position in linking diverse research streams within this domain (Table 4). Another key contributor to this domain, Iravani S., also shows a high value of influence in this domain, with a high betweenness centrality value (452.08) and a high PageRank value (0.044), indicating extensive co-citation within diverse research clusters within this domain. Another key contributor to this domain, Joseph S., also shows a high value of betweenness centrality (418), indicating a key position in linking diverse research streams within this domain. Another key contributor to this domain, Bishnoi S., also shows a high value of betweenness centrality (310.4), indicating a key position in linking diverse research streams within this domain. Another key contributor to this domain, Siripireddy B., also shows a high value of betweenness centrality (250.276), indicating a key position in linking diverse research streams within this domain.

The bibliographic coupling analysis also indicates thematic clustering in plant-mediated green nanoparticle synthesis methodologies, silver nanoparticle biosynthesis, mechanistic studies on phytochemical reduction, and application-oriented studies on photocatalytic degradation and antimicrobial activity. This indicates a high degree of intellectual integration in this domain, focusing on linking diverse research streams within this domain to plant-mediated green nanoparticle synthesis methodologies. The co-citation network analysis clearly indicates that this domain is intellectually anchored by a set of key contributors, who have played a major role in linking diverse research streams within this domain.

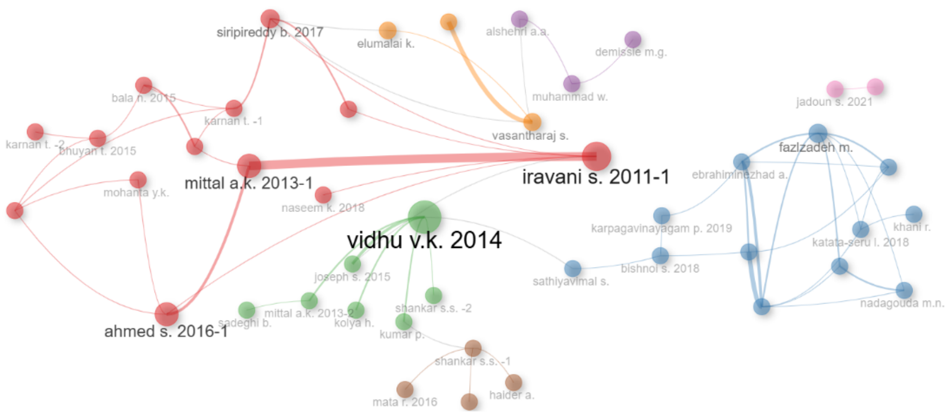

Figure 11. Author co-citation network generated using Bibliometrix (Biblioshiny) from the retrieved Scopus dataset (2015–2025).

Table 3. Country collaboration network showing pairwise collaboration strength.

From	To	Collaboration edge value
IRAN	NEW ZEALAND	171.48
BANGLADESH	JAPAN	138.03
CHINA	JAPAN	138.03
EGYPT	JAPAN	138.03
INDIA	JAPAN	138.03
INDONESIA	JAPAN	138.03
ITALY	JAPAN	138.03
KOREA	JAPAN	138.03
MALAYSIA	JAPAN	138.03
PAKISTAN	JAPAN	138.03
SAUDI ARABIA	JAPAN	138.03
USA	JAPAN	138.03
BANGLADESH	AUSTRALIA	134.49
CHINA	AUSTRALIA	134.49
EGYPT	AUSTRALIA	134.49
INDIA	AUSTRALIA	134.49
IRAN	AUSTRALIA	134.49
IRAQ	AUSTRALIA	134.49
JAPAN	AUSTRALIA	134.49
KOREA	AUSTRALIA	134.49
MALAYSIA	AUSTRALIA	134.49
PAKISTAN	AUSTRALIA	134.49
SAUDI ARABIA	AUSTRALIA	134.49
TURKEY	AUSTRALIA	134.49
USA	AUSTRALIA	134.49
CHINA	KOREA	127.84
INDIA	KOREA	127.84
IRAN	KOREA	127.84
PAKISTAN	KOREA	127.84
SAUDI ARABIA	KOREA	127.84
CHINA	INDONESIA	117.24
EGYPT	INDONESIA	117.24
INDIA	INDONESIA	117.24
KOREA	INDONESIA	117.24
MALAYSIA	INDONESIA	117.24
PAKISTAN	INDONESIA	117.24
SAUDI ARABIA	INDONESIA	117.24
TURKEY	INDONESIA	117.24
INDIA	HONG KONG	114.11
PAKISTAN	HONG KONG	114.11
QATAR	HONG KONG	114.11
SAUDI ARABIA	HONG KONG	114.11
UNITED KINGDOM	HONG KONG	114.11
CHINA	MALAYSIA	109.69
INDIA	MALAYSIA	109.69
IRAN	MALAYSIA	109.69
KOREA	MALAYSIA	109.69
PAKISTAN	MALAYSIA	109.69

Table 4. Author co-citation analysis depicting cluster, betweenness, closeness and PageRank.

Node	Cluster	Betweenness	Closeness	PageRank
Iravani S. 2011-1	1	452.08	0.002	0.044
Ahmed S. 2016-1	1	108.281	0.001	0.029
Mittal A.K. 2013-1	1	47.32	0.001	0.035
Karnan T. -1	1	51.009	0.001	0.028
Siripireddy B. 2017	1	250.276	0.002	0.028
Bhuyan T. 2015	1	41.2	0.001	0.023
Mohanta Y.K.	1	0	0.001	0.014
Naseem K. 2018	1	0	0.001	0.008
Bala N. 2015	1	11.675	0.001	0.023
Sangeetha G. 2011	1	22.902	0.001	0.022
Ezealisiji K.M.	1	72.258	0.001	0.026
Jamkhande P.G. 2019	1	0	0.001	0.016
Karnan T. -2	1	0	0.001	0.01
Fazlzadeh M.	2	7.74	0.001	0.036
Sathiyavimal S.	2	330	0.002	0.011
Bishnoi S. 2018	2	310.4	0.001	0.021
Karpagavinayagam P. 2019	2	18.133	0.001	0.013
Ebrahiminezhad A.	2	21.491	0.001	0.033
Khani R.	2	0	0.001	0.008
Kuang Y. 2013	2	132.638	0.001	0.04
Wang T. 2014	2	238.189	0.001	0.029
Xiao Z.	2	25.279	0.001	0.022
Katata-Seru L. 2018	2	40.129	0.001	0.022
Nadagouda M.N.	2	0	0.001	0.017
Njagi E.C. 2011	2	0	0.001	0.019
Vidhu V.K. 2014	3	553	0.002	0.065
Kumar P.	3	148	0.001	0.016
Shankar S.S. -2	3	0	0.001	0.011
Kolya H.	3	0	0.001	0.014
Mittal A.K. 2013-2	3	40	0.001	0.024
Joseph S. 2015	3	418	0.002	0.019
Sadeghi B.	3	0	0.001	0.012
Alshehri A.A.	4	78	0.001	0.017
Muhammad W.	4	40	0.001	0.029
Demissie M.G.	4	0	0.001	0.016
Elumalai K.	5	0	0.001	0.012
Vasantharaj S.	5	151	0.001	0.034
Rajendrachari S.	5	0	0.001	0.022
Shankar S.S. -1	6	117	0.001	0.043
Mata R. 2016	6	0	0.001	0.015
Nabila M.I.	6	0	0.001	0.015
Haider A.	6	0	0.001	0.015
Jadoun S. 2021	7	0	0.2	0.023
Karthik K.V. 2022	7	0	0.2	0.023

Scientometrics analysis reveals that green technologies from plants are an emerging research domain characterized by rapid growth in research concerning green synthesis, characterization, and application in the environment. Based on the above global research trends, the subsequent sections will deal with natural dye sources, extraction, characterization, and textile applications.

3.6. Interpretation of bibliometric trends, research gaps, and future directions

As shown in the bibliometric analysis, there has been a great increase in the number of publications between 2015 and 2025 as a result of the growing interest around the world in sustainable materials, green chemistry, and environmentally benign nanotechnology. Some of the important research themes, such as green synthesis, plant extracts, metal nanoparticles, and natural dyes, have been mostly driven by growing concern about the adverse impact of environmental pollution and human health associated with chemical synthesis and synthetic dyes. Policies related to sustainable manufacturing and green chemistry have encouraged research in the area of plant-mediated synthesis of nanoparticles and natural dye extraction.

It is evident from the thematic development that there has been a clear change in research themes over time. Initially, the research was focused on synthesis methods and the structural characterization of the nanoparticles using techniques such as FTIR, XRD, and SEM. With the establishment of these synthesis procedures, there has been a gradual shift in research towards applications such as photocatalytic degradation of contaminants, antimicrobial materials, wastewater treatment, biomedicine, and multifunctional textiles. It can be seen that some of the newer research themes include ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE).

There are some differences in the level of maturity in some of the research themes indicated in the bibliometric networks. Research topics such as green synthesis, plant extracts, nanoparticle characterization, photocatalysis, and metal nanoparticles indicate well-established areas of research, while many other emerging topics still need to be researched. These include the commercialization of industrial-scale production of plant-mediated nanoparticles, standardization of the extraction procedure of natural dyes, artificial intelligence and machine learning-assisted process optimization, life cycle assessment of green synthesis processes, techno-economic feasibility studies, and regulatory issues associated with the commercialization of the technology. In addition to this, international collaboration has increased, but more interdisciplinary collaboration among the material scientists, chemical engineers, environmental scientists, and industry professionals needs to be done in order to promote technology transfer.

Some of the research gaps are also revealed through the analysis. Most of the literature is mainly focused on laboratory-scale research without much consideration for scalability, reproducibility, long-term stability, and commercialization of the process. Fewer comparative studies exist to identify the best biological resource under standard experimental conditions. Also, fewer research studies incorporate the use of natural dye extraction in combination with the plant-mediated synthesis of nanoparticles.

Future research should, therefore, be focused on developing scalable protocols, process optimization of the advanced techniques such as UAE and MAE, computational tools for process optimization using artificial intelligence and machine learning, techno-economic and life cycle assessments, and international and interdisciplinary collaborations.

4. Plant Sources for Natural Dyes

One of the studies aimed to investigate the process of water-based extraction of catechu from the heartwood of *Acacia catechu* and its application on scoured and bleached cotton fabric. The authors compared the results of pre-mordanting, meta-mordanting, and post-mordanting techniques, and the results revealed that the deepest shades of brown colour were achieved through the application of the post-mordanting technique using alum and copper salts. Spectrophotometric analysis revealed that the K/S values of the post-mordanting samples were higher than those of the other techniques. The fastness properties revealed good washing and rubbing resistance, making catechu an effective and eco-friendly bark-based natural dye [12].

Researchers have extracted natural indigo from the leaves of *Indigofera tinctoria*. The extracted indigo was then subjected to sulfonation to increase its solubility in water. The cotton fabric that was dyed with the chemically modified indigo showed better colour intensity and fastness properties than cotton fabric that was dyed with the natural indigo. The study showed that the chemically modified indigo from the leaves is a sustainable natural dye with good colour uptake properties [13]

The annatto seeds were extracted using a Soxhlet apparatus with ethanol as a solvent to produce bixin-based dyes. The dyeing process on cotton fabric tested different types and concentrations of mordants. The study found that bright orange shades were achieved, with a slight change in hue to red-orange after mordanting. The authors emphasized how dye concentration and mordant types could be optimized to achieve maximum depth and wash fastness, showing annatto dye's eco-friendly properties as a natural seed-based dye [14].

The extraction of madder root was carried out in order to obtain the anthraquinone dyes, which include alizarin and purpurin. Traditional and microwave-assisted extraction techniques were used, and the latter method was found to be effective in saving time and energy while maintaining the quality of the dye. Cotton fabrics dyed using madder, which was then mordanted using alum and biological mordants like tannin, produced a strong red color with good fastness properties. It has been emphasized in the study that the use of root-based dyes like madder is important in the field of sustainable dyeing due to the rich shades produced and their historical significance [15].

The turmeric rhizomes were extracted for the pigments using both aqueous and solvent-based extraction methods. Cotton fabrics dyed with turmeric exhibited vibrant yellow hues. When alum mordant was used for pre-treatment, the cotton fabrics exhibited good wash and light fastness properties. Furthermore, the cotton fabrics dyed with turmeric exhibited antimicrobial properties [16].

Pomegranate peel extract, high in tannins, was extracted using a combination of boiling and mild acid solutions. The dyeing tests showed that chitosan-treated samples absorbed more dye, producing deeper shades of beige-brown. The fastness properties were good, particularly when alum was used as a mordant. The authors found pomegranate peel to be a promising natural dye source from a waste material, with inherent mordant properties [17].

The marigold petals were subjected to hot water extraction for the release of carotenoid and flavonoid pigments. Various mordants were used, and iron resulted in an olive and gold color, while alum resulted in a bright yellow color. K/S value and fastness properties were significantly improved with the use of a suitable mordant. From the study, it was concluded that marigold flowers are readily available and can be used as a dye for cotton, offering versatility in color variation with the use of a suitable mordant [18].

The onion skins underwent hot aqueous extraction at an acidic pH to obtain the flavonoid dyes, primarily quercetin. The cotton fabric, when dyed with the onion skin extract, was found to have shades of gold and brown. The mordants, alum and copper, helped to intensify the shades and produce subtle changes in the hue. The study concluded that the process of onion skin dyeing was a viable option to dispose of kitchen waste, resulting in attractive shades on the fabric [19].

One of the recent studies investigated the application of rose and marigold flowers' extracts in dyeing 100% cotton fabrics using aqueous, alkaline, and acidic methods. Cotton fabrics were mordanted using alum and vinegar, and the results showed that the best results were obtained using the acidic method. The results also showed good wash and light fastness properties for the dyed fabrics. This study confirms the possibility of using natural dyes like rose petals for dyeing cotton fabrics [20].

A study was conducted to investigate the dyeing of cotton fabrics using Terminalia Chebula extract using in situ azoic dyeing methods. Terminalia Chebula extract was found to impart olive to greyish-brown shades to the fabrics, and the fastness properties were improved by using biomordants. In addition, antimicrobial and UV resistance properties were also found to be improved in the dyed fabrics, thus proving the efficiency of Terminalia Chebula as a multi-purpose natural dye for cotton fabrics [21]

Lawsonia inermis, commonly known as Henna, leaves' extract was used for dyeing cotton fabrics, and the effects of different dye formulations and mordants were examined. It was found that the dye has a reddish-brown color and good wash and rubbing fastness. Alum and copper salts as mordants helped in achieving good depth of shades. Henna is an environmentally friendly dye for cotton fabrics [22], [23].

This study focused on dyeing and finishing of cotton fabrics using eucalyptus leaf extracts. The dyeing process was optimized with natural and synthetic mordants, resulting in yellow to beige hues. The fabrics also exhibited enhanced mosquito repellence and good fastness properties. The study demonstrated eucalyptus extract as both a dye and functional finishing agent for cotton [24].

The diversity of plant sources has stimulated the development of efficient extraction technologies, which are discussed in the following section.

5. Extraction Techniques

The field of extraction technology has experienced tremendous development in the past decades, from conventional to innovative techniques, emphasizing the concepts of efficiency, sustainability, and selectivity in the extraction process [10], [11]. The conventional techniques, such as maceration, percolation, and hydrodistillation, have shown limitations in terms of long extraction time, high consumption of organic solvents, and the potential for the degradation of thermolabile compounds, among others. This has led to the development and application of advanced extraction techniques that can overcome the limitations of conventional techniques while adhering to the concepts of green chemistry and sustainability in the extraction process. The development and evolution of extraction technology have been largely driven by the need to obtain bioactive compounds from natural sources, especially for application in the pharmaceutical, food, cosmetic, and biofuel industries, among others. This has led to the development and optimization of various advanced extraction techniques, including ultrasound-assisted extraction, microwave-assisted extraction, Soxhlet extraction, enzyme-assisted extraction, and supercritical fluid extraction, among others. Each of the advanced techniques has its own merits and limitations, making them more applicable in specific situations compared to others. The innovative extraction techniques can be considered the application of the concept of process intensification, emphasizing the concepts of efficiency, sustainability, and the reduction of negative impacts on the environment in the extraction process. The basic concepts behind the application of the advanced extraction techniques include the reduction of extraction time, the reduction of the amount of energy required, the reduction of the amount of organic solvent required, and the increase in extraction efficiency and quality, among others. The advanced extraction techniques can also be combined synergistically to form hybrid techniques, allowing the application of the merits of each technique while overcoming the limitations of each technique.

5.1. Ultrasound-Assisted Extraction (UAE)

The mechanical effects of ultrasound create micro-channels and cracks in biological materials, thereby facilitating solvent penetration into the cell. Ultrasound also increases micro-mixing in the solid-liquid interface, thereby minimizing the boundary layer and increasing rates of diffusion. This mechanism increases extraction efficiency compared to conventional methods (Table 5).

The process of UAE uses high-frequency sound waves, in the frequency range of 20 kHz to 100 kHz, to enhance the process of extraction through a phenomenon called acoustic cavitation. Ultrasound passes through a solvent, creating a series of compressions and decompressions in the solvent, resulting in the formation of microscopic bubbles. The bubbles then grow in a series of cycles and eventually collapse, creating extreme temperatures up to 5000 K and pressures up to 1000 atm.

Table 5. Optimal Conditions for Ultrasound-Assisted Extraction of Selected Compounds.

S. No.	Plant Material	Target Compound (Dye)	Optimal Conditions (UAE)	Yield / Performance	Reference
1	*Xylocarpus moluccensis* (heartwood & bark waste)	Anthraquinone-based red dye	Ultrasonic bath; 80 min; ~49 °C; medium sonic volume; 0.1 M NaOH	Higher dye yield and color strength than boiling method	[25]
2	*Cassia alata* flower petals	Anthraquinonoid yellow dye	Ultrasonic water bath (40 kHz, 500 W); 50 °C; 45 min; methanol	Maximum color intensity; good fastness on cotton, silk & leather; antibacterial activity	[26]
3	*Swietenia mahagoni* flowers	Polyphenolic natural dye	Ultrasonic bath (40 kHz); 30 min; 50 °C; sample–solvent ratio 1:20 (ethanol)	Maximum dye yield ≈ 0.855%; satisfactory silk dyeing and fastness	[27]
4	Hawthorn fruits (*Crataegus* spp.)	Flavonoids (quercetin, rutin, kaempferol)	UAE with ethanol–water; pH 5; 60 °C; 40 min (RSM optimized)	20–70% higher extraction efficiency vs conventional; good fastness on polyamide	[28]
5	*Eucalyptus globulus* leaves	Tannins & polyphenolic dyes	Ultrasonic bath (20–40 kHz); 60 °C; 30 min; ethanol–water	Enhanced colour strength values, good fastness & antibacterial activity on tencel fabric	[29]

The UAE process has shown promising results in the efficient extraction of bioactive compounds such as phenolics, flavonoids, oils, aromas, and pigments from plant materials. UAE has shown efficient extraction of phenolic compounds from nettle plant material compared to conventional methods. The optimum conditions were achieved in 30 minutes, a solid-solvent ratio of 1:30, and 80% power intensity.

Despite its advantages, UAE has certain limitations. The UAE process is highly dependent on the physical properties of plant materials such as particle size, shape, and composition. The solvent used in UAE also affects the process because solvent viscosity and surface tension influence cavitation. The UAE process also has a drawback in that high-intensity ultrasound causes degradation of compounds through free radicals during cavitation, particularly in aqueous or oxygen-containing systems.

Another drawback is noise pollution and erosion of equipment during industrial-scale UAE. The problem can be addressed through proper safety measures. Also, drawback is high energy consumption in large-scale UAE systems, thereby affecting their economic viability.

One of the earlier studies carried out using the UAE technique involved the extraction of anthraquinone-based dyes from Xylocarpus moluccensis, employing an ultrasonic cleaner bath. In the study, the authors compared the UAE technique with the traditional boiling method of extraction and found a greater yield of the dye under optimized UAE conditions, namely 80 min, ~49 °C, and a sonic volume of medium. This was attributed to the cell wall disruption caused by the formation of cavitation bubbles, which enhanced the mass transfer of the colorant into the alkaline solvent. Not only was the yield of the dye greater, but the color obtained was of a deeper shade, which proved the advantages of the UAE technique over the traditional boiling method [25]

More recent studies have extended the use of UAE in the exploration of flower-based dye sources. For example, Muruganandham et al. described an eco-friendly method for the extraction of yellow dye from Cassia alata flower petals using ultrasonic bath and ultrasonic probe techniques [26]. The study showed that the UAE method using an ultrasonic water bath at 50 °C for 45 min produced the highest colour intensity with reduced solvent and energy use. The extracted dye was characterized by UV-Visible and FTIR spectroscopy to identify the presence of anthraquinonoid derivatives. The study also showed that the extracted dye had good colour strength and wash fastness properties on cotton, silk, and leather without the use of any mordant. Moreover, the extracted dye showed antibacterial properties, thus proving the potential of UAE in the production of natural dyes with additional properties [26].

Optimization-based studies have also contributed to the scientific understanding of UAE. Islam et al. studied the process of dye extraction from Swietenia mahagoni flowers using the Box-Behnken response surface methodology. In this study, the effects of sonication time, temperature, and the ratio of the sample to the solvent were statistically modeled. Optimum conditions for the process were found to be a sonication time of 30 min, a temperature of 50 °C, and a solvent ratio of 1:20 g/mL. Under these optimum conditions, the maximum dye yield was found to be ~0.855%, and the fastness properties of the extracted dye were satisfactory on silk fabrics. This study thus demonstrated the importance of using UAE in conjunction with statistical tools for process optimization [27].

In another extensive research article, the authors used the UAE method for the extraction of flavonoid-based dyes from hawthorn fruits. The UAE method was found to increase the efficiency of the extraction process by 20 to 70%, depending upon the solvent system used. It was observed that the best solvent system for the process was the combination of ethanol and water. The optimal conditions for the process were determined to be pH 5, 60°C, and 40 min. The dyes obtained were used for the coloration of polyamide fabric. The dyes showed good color strength and fastness properties, along with good antimicrobial and antioxidant activities. This research article demonstrated the potential of the UAE method for the coloration of textiles [28].

Recent research has focused on the relevance and scalability of the process. Rehman et al. described a study on the ultrasonic-assisted extraction of tannin-based dyes from Eucalyptus globulus leaves, followed by dyeing of Tencel fabric. Optimized extraction and dyeing were carried out at relatively low temperatures (≈60°C) and times (≈30 min). Ultrasonic dyeing resulted in higher K/S and better fastness compared to conventional dyeing methods. Additionally, the study proved that ultrasonic dyeing imparts better antibacterial properties, especially when proper mordants are used, further supporting the application of UAE in dyeing and its importance in sustainable dyeing processes [29].

On the whole, the analyzed research works prove that the classical extraction methods, especially the Soxhlet extraction method, are effective in extracting natural dyes due to the ease of their use and well-known modes of operation. But long extraction periods, high usage of solvents and energy make such methods not ecologically and economically efficient enough. Even though Soxhlet extraction usually gives good results in terms of extraction yield, the long extraction time can be a cause of thermal decomposition of heat-sensitive plant chemicals with a negative effect on the color properties.

The efficiency of extraction processes must be validated through advanced characterization techniques, discussed in the next section.

5.2. Microwave-Assisted Extraction (MAE)

With respect to the extraction of plant materials, microwave energy can produce tremendous pressure within the cells, causing the cell walls to rupture and resulting in the extraction of bioactive compounds [30]. This approach can be especially useful in the extraction of bioactive compounds that are sequestered within glandular trichomes, vacuoles, and other structures that may not be easily accessible using conventional techniques (Table 6). MAE has a number of advantages compared to other conventional techniques for the extraction of bioactive compounds. For instance, the process reduces the time required for the extraction process from hours to minutes, and the amount of solvent required can be reduced up to 90%. Moreover, the process increases the efficiency of the extraction process and the selectivity of the compounds, and the shorter time required prevents the degradation of the bioactive compounds. Furthermore, the MAE process can be used to process more than one sample at a time, especially in analytical chemistry.

However, the drawbacks associated with the process include the need to use solvents that have high dielectric constants in order to effectively absorb microwave energy, and the potential for hot spots to form in the samples, leading to the degradation of the bioactive compounds. The filtration step is still required after extraction, adding to processing time.

Table 6. Optimal Conditions for Microwave-Assisted Extraction of Selected Compounds.

S. No.	Plant Material	Target Compound / Dye	Optimal Conditions (Extraction & Dyeing)	Yield / Performance Outcome	Reference
1	Red sandalwood powder (*Pterocarpus santalinus*)	Santalin (red natural dye)	Aqueous & acidic media (2% v/v HCl); 4 g powder/100 mL; boiling; microwave (MW) irradiation 1–5 min; dyeing at 80 °C for 65 min; extract:fabric = 1:30	Enhanced color extraction and improved dye uptake on silk under MW treatment	[30]
2	Spent tea leaves (*Camellia sinensis*)	Tannin-based brown dye	Aqueous & acidic media; M:L = 1:30; boiling 40 min; MW irradiation 1–6 min (800 W, 2450 MHz); dyeing at 80 °C for 50 min; extract:fabric = 1:35	Higher color yield and deeper shades on wool using MW-irradiated extracts	[31]
3	Plant-based dye sources (various botanical materials)	Polyphenolic / flavonoid dyes	Aqueous, acidic & basic media; M:L = 1:25; boiling 45 min; MW irradiation up to 10 min (2-min intervals); dyeing at 80 °C for 45 min; extract:fabric = 1:25	MW-irradiated extracts produced superior color strength on silk fabrics	[32]
4	Stem bark (unspecified species)	Natural tannin / phenolic dye	Water extraction; 3 g powder/400 mL; boiling at 90 °C for 1 h; filtration; conventional dyeing	Adequate dye yield for cotton coloration using conventional extraction	[33]
5	Harmal seeds (*Peganum harmala*)	Alkaloid-based yellow–red dye (harmine, harmaline)	Acidified methanolic extract; MW irradiation ≈4–5 min; dyeing at 85 °C for 45 min; optimized salt & mordant conditions	Significantly higher K/S values; improved fastness with bio-mordants	[34]
6	Waste black tea leaves (*Camellia sinensis*)	Tannin (brown dye)	Aqueous medium; MW irradiation ≈5 min; optimized extract pH & volume; dyeing of silk at 55–80 °C for 45 min	Deeper shades, good to excellent fastness; effective agro-waste valorization	[31]
7	Cotton fabric dyed with Reactive Yellow C4GL	Synthetic reactive dye (for stripping)	Microwave absorber-assisted alkali hydrolysis & reduction; urea as absorber; MW treatment ~120 s	>90% stripping efficiency with minimal fabric damage and good re-dyeability	[35]

To successfully isolate the natural color from red sandalwood powder (RSWP), two extraction media, i.e., aqueous (neutral) and acidic, were used. For an acidic medium, 2 mL of conc. HCl was added to 98 mL of water (2% v/v). Then, neutral and acidic media were employed to extract the dyes from the plant by boiling 4 g of finely meshed plant powder with 100 mL of water. After dye extraction in the given media, the crude material was filtered by conventional filtering to obtain the pure extract. The silk fabric and the extract were treated with microwave radiation for 1 to 5 min using a high-power microwave irradiator. After this, the treated and untreated extracts were used to dye treated and untreated silk fabric at 80 °C for 65 min, keeping an extract-to-fabric ratio of 1:30 [30].

To improve the extraction of natural colorant, spent tea leaves powder was boiled with aqueous and acidic media for 40 min keeping with spent tea leaves material to liquor ratio 1:30. After attaining extract, both wool and extract of various mediums were exposed to various ranges of MW (Microwave) irradiations for 1, 2, 3, 4, 5, and 6 min, using an Orient Microwave irradiator (800 W, 2450 MHz). To obtain a higher yield on wool fabric, MW-irradiated (RE) and un-irradiated spent tea leaves extracts were used to dye MW-irradiated (RW) and un-irradiated wool (URW), keeping an extract-to-wool fabric ratio (M: L) of 1:35 at 80°C for 50 min [31]

To isolate colorants, fine plant materials were boiled in aqueous, acidic, and basic solutions for 45 min, keeping the material-to-liquor (M:L) ratio at 1:25. Irradiated and unirradiated extracts were used to dye silk fabric using three different types of medium, including aqueous, acidic, and basic solutions. The fabric and extracts were microwaved for 10 min at 2 min intervals. The extract-to-fabric ratio was kept at 1:25 and irradiated and unradiated extracts were used to dye both treated and untreated fabrics at 80 °C for 45 min [32].

Before extraction of natural dyestuff, the bark samples were rinsed with water and dried at room temperature.

After cleaning and drying, the samples were powdered using a grinding machine. These powder samples were screened by passing through a mesh no.-42 screen and stored for further work. About 3 g of stem bark powder (-42 mesh) and 400 ml of water were boiled in a stainless-steel vessel at 90°C for 1hr to obtain a 200 ml dye solution. This dye solution was cooled and then filtered with filter cloth. It was used for dyeing cotton fabrics [33].

Adeel et al. [34] systematically investigated the microwave-assisted extraction and dyeing of cotton fabric using Peganum harmala (harmal) seeds as a source of natural alkaloid-based dye. The study showed that the use of short periods of microwave irradiation (≈4–5 min) greatly improved the efficiency of dye extraction as compared to conventional boiling methods. The acidified methanolic extracts obtained through microwave treatment showed higher color strength (K/S values), as the rapid rupture of plant cells improved the interaction between the dyes and the solvent. The microwave treatment was also shown not to affect the chemical structure of cellulose, as confirmed by FTIR analysis, but improved the surface morphological properties of the fibers to increase the uptake of the dye. The use of bio-mordants also improved the color fastness of the dyes, thus proving the eco-friendly nature of the MW treatment [34].

Using waste-based dyes, Hayat et al. [31] have proposed the use of waste black tea leaves as an alternate source of tannin-based brown dyes for silk fabrics. The authors have shown that microwave treatment greatly improved the efficiency of extracting tannins from aqueous media to achieve deeper shades of brown colour with good to excellent fastness properties. Optimization of the treatment showed that moderate periods of microwave treatment were essential to achieve efficient extraction of tannins from waste black tea leaves, as lower periods of treatment produced poor-quality extracts while higher periods of treatment risked the co-extraction of non-colouring bio-compounds from the waste material. The surface roughness of the silk fibres was improved by MW treatment, as confirmed by SEM analysis. This work strongly supports microwave processing as an effective route for agro-waste valorisation in sustainable textile dyeing [31]

In addition to dye extraction and application, microwave technology has been successfully employed for sustainable textile recycling. Akhtar et al. [35] developed a microwave absorber-assisted stripping system for removing reactive dyes from cotton fabric. The use of urea as a microwave absorber enabled efficient dye-fiber bond cleavage under mild conditions, achieving stripping efficiencies above 90 % with minimal loss in fabric strength and weight. Compared to conventional stripping methods, the MW-assisted approach significantly reduced processing time, chemical concentration, and thermal damage. Importantly, the stripped fabrics exhibited good re-dyeability, demonstrating the feasibility of circular textile processing through microwave-based systems [35].

It was repeatedly found from the review of the literature that MAE allows for very fast heating of large volumes of material, which considerably decreases the extraction time. The comparison between MAE and Soxhlet extraction showed that MAE usually needs smaller amounts of solvent than Soxhlet. But at the same time, it was stated that higher microwave power and longer exposure time can negatively affect the stability of heat-labile dyes and their colours.

5.3. Soxhlet extraction

Soxhlet extraction is a classical technique that has been used for over a century for extracting compounds from solid materials (Table 7). The method involves placing the sample in a thimble-holder chamber while the extraction solvent is heated in a flask. The solvent vaporizes, condenses, and enters the sample chamber, percolating the matrix material. When the chamber is full, the solution returns to the flask, siphoning the extracted materials. This process repeats several times automatically, taking hours or days to complete.

The basic theory behind Soxhlet extraction is the repeated washing of the solid matrix with a new solvent at constant temperatures, allowing for the complete extraction of bound materials, especially lipophilic compounds and materials with high lipid contents.

Table 7. Optimal Conditions for Soxhlet-Assisted Extraction of Selected Compounds.

S. No.	Plant Material	Target Compound / Dye	Optimal Conditions (Extraction)	Yield / Performance	Reference
1	Onion peels (*Allium cepa*)	Anthocyanins, quercetin (yellow–brown dyes)	Soxhlet extraction using ethanol/acetone; continuous reflux	Higher pigment concentration and better stability compared to direct extraction	[36]
2	Transvaal daisy & Lavender petals	Xanthophylls, flavonoids	Soxhlet extraction and aqueous–ethanol extraction; 60–70% ethanol; 68 °C	Soxhlet gave higher purity and dye yield; acceptable fastness on cotton	[37]
3	Turmeric rhizome (*Curcuma longa*)	Curcumin (yellow dye)	Soxhlet extraction using acetone; 6 h extraction	High color strength and good fastness on PLA fibers	[38]
4	Endemic plants (*Lonchocarpus cyanescens*, *Duranta repens*, *Pentaclethra macrophylla*)	Polyphenolic and flavonoid dyes	Soxhlet extraction at ~56–57 °C; ethanol solvent	Soxhlet most efficient among hot water, cold water, and ethanol methods	[39]
5	*Rothmannia whitfieldii*	Alkaline-sensitive natural dye	1% NaOH extraction; ~43 °C; <1 h	Faster extraction and higher yield than neutral solvents	[39]
6	*Rhamnus tinctoria* seeds	Emodin (anthraquinone dye)	Soxhlet extraction with ethanol; multiple siphon cycles	Higher dye concentration and better DSSC efficiency than ultrasonic method	[40]
7	*Rubia fruticosa* fruits	Alizarin (red dye)	Soxhlet extraction with ethanol	Improved pigment recovery and photovoltaic performance	[40]
8	*Pinus pinea* bark	Quercetin (brown–reddish dye)	Soxhlet extraction with ethanol	Superior dye loading and absorption behavior	[40]

Several studies have been conducted on agro-waste and readily available residues of plants as a source of sustainable dyes. Inbarajan et al. worked on the extraction of anthocyanin and quercetin-based dyes from Allium cepa, commonly known as onion peel, using a method of direct soaking and Soxhlet extraction using ethanol and acetone as solvents [36]. The darker and more concentrated dye solutions were obtained through Soxhlet extraction, and lighter anthocyanin hues were maintained through direct extraction. The hydroxyl and carbonyl groups were identified through spectroscopic analysis, which are essential in dye-substrate interactions. Although this research aimed to study its application in dye-sensitized solar cell technology, it also emphasized the importance of extraction methods in dye composition and performance, a concern equally applicable in textile dyeing.

Similarly, Gayke et al. explored flower-based pigments from Transvaal daisy and lavender petals using aqueous–ethanol and Soxhlet extraction [37]. The Soxhlet technique was found to be more effective in pigment recovery and purity, especially for xanthophyll-type pigments, whereas the aqueous-ethanol method was found to be a more energy-efficient and eco-friendly process. Dyeing tests performed on the cotton fabrics indicated good wash and light fastness properties, although limitations in durability are noted, which again emphasizes the importance of mordanting or the use of a combination of extraction methods.

One such plant used in natural dye production is turmeric *Curcuma longa*, which is one of the best natural dye materials in terms of its high curcumin content. The study by Li and Nasir used a Soxhlet apparatus with acetone as a solvent to obtain curcumin dyes, followed by dyeing on biodegradable (polylactic acid) PLA fibers [38]. The process was optimized using response surface methodology in terms of pH, temperature, and dyeing time to obtain high colour strength and satisfactory fastness properties on fibres, ensuring mechanical integrity. Although the process followed in this study is conventional, it highlights how such a process can be optimized to compensate for a lack of energy-efficient steps in natural dye production.

Apart from dye production on fibres, there have been comparative studies on natural dye production from various plant species to evaluate their extraction efficiency. The study by Adjero et al. compared the Soxhlet, hot water, cold water, and ethanol solvent extraction methods on dye pigments from indigenous plant species such as Lonchocarpus cyanescens, Duranta repens, Pentaclethra macrophylla, and Curcuma longa [39]. The study found that the Soxhlet extraction process at moderate temperatures gave higher concentrations of dye pigments, but alkaline extraction was found to be effective on certain species such as Rothmannia whitfieldii.

Advanced energy-assisted techniques have also been comparatively assessed. Aslan investigated ultrasonic- and Soxhlet-assisted extraction of flavonoid and anthraquinone dyes from Rhamnus tinctoria seeds, Rubia fruticosa fruits, and Pinus pinea bark [40]. Although a higher concentration of pigment and better photovoltaic efficiencies were obtained in the application of Dye-Sensitized Solar Cells (DSSC).

Using Soxhlet extraction, ultrasonic extraction offered the advantages of shorter extraction times and lower thermal stress on the dye molecules. The study pointed out that ultrasonic extraction could be used in place of other methods, especially where there is a concern over the degradation of the pigment, despite a slightly lower yield.

One of the studies proposed a novel approach by using dyes extracted from the tender coconut husk as sensitizers in DSSCs [41]. Dyes were extracted using various solvents, such as acetone and ethanol, using two types of extraction methods, direct and Soxhlet. Interestingly, the dyes extracted from the husk peels showed higher photoconversion efficiency compared to the other dyes. Moreover, the extracted dyes showed the presence of the necessary optical properties through the results of the spectroscopic analysis. In addition, the DSSCs fabricated using the extracted dyes showed photoconversion efficiency of 0.279%, 0.209%, 0.463%, and 0.376%, depending on the solvent and the method used to extract the dyes. Although the traditional Soxhlet method is still the best method for many applications, especially in analytical chemistry for the determination of fat content and quality control, it has been modified to solve the problems associated with the traditional method.

Soxhlet extraction, like other traditional methods, has several significant limitations. Some of the limitations include the large amount of solvent used, which is often in the range of hundreds of milliliters per gram of the substance to be extracted. In addition, the traditional Soxhlet method takes a longer time to extract the substances from the matrix, which ranges from 6 to 24 hours or longer. Moreover, the traditional Soxhlet method may cause the degradation of thermolabile substances because the solvent is boiled for a longer period. In addition, the continuous process without the inclusion of a cooling period may cause the loss of volatile substances.

Furthermore, the traditional Soxhlet method is a very energy-intensive process because the solvent is boiled to extract the substances from the matrix. In addition, the traditional Soxhlet method requires the concentration of the extracted substances, which is a very energy-intensive process.

5.4. Sustainability and comparative evaluation of extraction technologies

Even though plant-mediated synthesis of nanoparticles and natural dye extraction are usually regarded as environmentally friendly alternatives to traditional chemical processes, the sustainability of these processes must be evaluated based on engineering and environmental performance indicators rather than qualitative characteristics only. At present, the majority of papers only mention extraction yield and the characteristics of nanoparticles synthesized, while specific energy consumption, solvent intensity, carbon emissions, waste generation, and life-cycle environmental impact are hardly ever quantified and compared among the extraction processes [42].

5.4.1. Energy efficiency

Energy consumption is one of the key sustainability parameters. While conventional Soxhlet extraction usually implies long extraction time (4-24 hours) and high energy consumption, ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE) allow for shortening the extraction time due to acoustic cavitation and volumetric dielectric heating, respectively, and increase the efficiency of the extraction process and thus reduce energy consumption. However, the majority of existing publications report extraction yield only and do not provide information about specific energy consumption (kWh kg^{-1} extract). Further investigations should include the measurement of energy efficiency along with extraction performance [43].

5.4.2. Solvent consumption and green solvent selection

Reduction in the consumption of solvent is also one of the components of sustainable extraction. UAE and MAE in particular allowed for reducing solvent consumption while at the same time preserving or increasing extraction efficiency compared with traditional solvent extraction. Moreover, substitution of petroleum organic solvents by deep eutectic solvents (DES) and natural deep eutectic solvents (NADES) became very popular recently thanks to the unique properties of those solvents (low volatility, tunable polarity, biodegradability, extraction selectivity). Yet, there are still many issues related to solvent recyclability, recovery efficiency, viscosity, and separation which require further study [44].

5.4.3. Carbon footprint and life cycle assessment

Although there is more and more focus on green extraction technologies, the number of studies that evaluate the environmental performance of these processes using Life Cycle Assessment (LCA) methods is very small. The carbon emissions related to electricity consumption, solvent production, biomass pretreatment, transport, and downstream purification are not quantified yet. A combination of LCA and process simulation along with techno-economic evaluation would allow for identifying the hot spots and comparing extraction technologies from the environmental perspective [45].

5.4.4. Waste generation and circular economy

Plant-mediated nanoparticle synthesis reduces the consumption of harmful reagents, but a considerable amount of residual biomass is generated after extraction. Instead of treating residual biomass as waste, future work should be concentrated on its utilization through integrated biorefinery technologies including production of biochar, activated carbon, compost, bioenergy, secondary phytochemical extraction and other cascade utilization options. This will contribute to improvement of resource efficiency, waste reduction, and implementation of a circular economy approach [43].

Tables 5 to 7 provide evidence that the method employed is very important for the yield, efficiency, sustainability, and feasibility of the dye extraction process. There are no universal optima; each method depends on the plant material, solvent, and extraction conditions used.

5.4.5. Extraction yield

In general, microwave-assisted extraction (MAE) and ultrasound-assisted extraction (UAE) provided higher extraction yield due to the increased disruption of cells and better mass transfer properties (Table 8). Whereas UAE provides more efficient penetration of solvent into the plant material due to acoustic cavitation, MAE increases the extraction efficiency due to volumetric dielectric heating of the solvent–plant matrix. Nonetheless, the degree of improvement largely varied between plant species and types of solvents used, which can be attributed to the high impact of solvent polarity and phytochemical composition on extraction efficiency. Consequently, extraction yield cannot be considered an inherent property of a particular method.

5.4.6. Extraction time

Extraction time turned out to be the parameter with the greatest difference between the three methods. Conventional Soxhlet extraction needs several hours for extraction, while UAE decreases extraction time to below one hour due to disruption of cell walls through cavitation. Further, MAE uses rapid volumetric heating to reduce extraction time even more and provide comparable extraction efficiency. This parameter is a direct factor for increased productivity and decreased cost.

Table 8. Comparative Summary table for all the extraction techniques.

Criterion	Soxhlet	UAE	MAE	Critical observation
Extraction yield	Moderate	High	High	Strongly dependent on plant matrix and solvent composition
Extraction time	Long	Short	Very short	MAE provides the fastest extraction
Solvent consumption	High	Moderate	Low	Advanced techniques improve solvent utilization
Energy requirement	High	Moderate	Low–Moderate	Quantitative reporting remains limited
Scalability	Commercially established	Pilot scale	Pilot scale	Scale-up and continuous processing remain challenges
Environmental impact	High	Lower	Lower	Requires confirmation through LCA and TEA

5.4.7. Scalability and industrial implementation

From the point of view of industrial implementation, Soxhlet extraction is the most developed and applied method of extraction due to its easy operation and design of equipment. In turn, although UAE and MAE demonstrate great extraction efficiency in laboratories, these methods still have limitations in terms of reactor design, process standardization, continuous operation, and economic feasibility of the scale-up. Thus, future research should focus on scaling up and continuous flow reactors.

6. Characterization of Dyes

The characterization of natural dyes plays a crucial role in understanding the chromophore arrangement, functional groups, purity, thermal stability, and dyeability or interaction with fabric or semiconductor materials. Recently, studies on plant-based dyes have consistently utilized a combination of spectroscopic, chromatographic, and structural analysis to verify the composition of dyes and relate it to dyeing properties (Table 9).

The primary technique for the identification of chromophore groups and determination of λ_{max} for dyes involves the use of UV-Visible spectroscopy. In the characterization of the purple dye derived from the leaves of Justicia Spicigera (Chak Lool), a strong band was observed at 581 nm corresponding to anthocyanin-like chromophores under bathochromic influence [46]. For the characterization of Chak Lool dye, hydroxylbenzoic acids and phenolic compounds characteristic of anthocyanin-like chromophores were identified by Pyrolysis GC/MS [46].

The presence of this band in the visible region indicates the presence of conjugated π-electron systems responsible for the purple color. For dye-sensitized solar cells (DSSC), UV-Visible spectroscopy was utilized not only for determining the λmax but also for evaluating the efficiency of light harvesting [47]. As reported, *Neem* and *Rosella* dyes exhibited strong absorbance bands at 550 nm and 660 nm, and the maximum absorbance was found to be 3.5 units at 660 nm for mixed dyes.

Likewise, the combined use of natural dyes from ivy gourd leaves and turmeric exhibited various peaks for the energy band gaps at 1.74, 2.51, and 2.59 eV. This indicates that the dyes have a broader range for the absorption of light and have better photoexcitation properties [48].

Fourier Transform Infrared (FTIR) spectroscopy was also used to validate the presence of polyphenolic compounds. For the characterization of the dye from the leaves of the avocado plant, the FTIR analysis exhibited characteristic peaks for hydroxyl (O-H), carbonyl (C=O), aromatic C=C, and C-O-C stretching vibrations, indicating the presence of flavonoid compounds like quercetin and isoquercetin [49]. High-performance liquid chromatography (HPLC), reversed-phase HPLC (RP-HPLC), and vacuum liquid chromatography (VLC) have also played significant roles in the characterization studies. For the characterization of the dye from the leaves of the avocado plant, HPLC analysis revealed that quercetin and isoquercetin are the primary compounds present in the dye nuclear magnetic resonance (NMR) spectroscopy was also used to validate the molecular structure of quercetin and isoquercetin [49].

Table 9. Comparative table of natural and synthesized dyes and their characterization.

S. No.	Natural / Synthesized Dye	Characterization Techniques	Important Data Observed	Reference
1	Madder (*Rubia tinctorum*)	RP-HPLC-PAD, CIEL*ab**, SEM–EDX	Detection at 255–620 nm; anthraquinones (alizarin, purpurin); optimized microwave extraction (5 min); uniform fibre morphology	[50]
2	Walloon Oak (*Quercus ithaburansis*)	RP-HPLC-PAD, CIEL*ab**, SEM–EDX	Presence of gallic acid & ellagic acid derivatives; strong absorbance peaks in UV region; homogeneous dye penetration	[50]
3	Turmeric (Curcuminoid dye)	LC–MS, UV–Vis (200–900 nm), FTIR (500–4000 cm^{-1}), XRD, FE-SEM, K/S measurement	Curcuminoids confirmed via LC–MS; strong visible absorbance; O–H, C=O, aromatic C=C peaks; preserved silk crystallinity; enhanced K/S values	[51]
4	Cobalt (II) Porphyrin [Co (II)TP-OHPP] (Synthesized dye catalyst)	^{1}H NMR, UV–Vis, FTIR, XRD, TGA, SEM, DLS, TOC, GC–MS	UV–Vis λmax: 416–649 nm (free base), 448–581 nm (Co complex); ν(Co–N) ~1001 cm^{-1}; mineralization up to 85%; first-order kinetic degradation	[52]
5	Dacryodes edulis Leaf Extract	UV–Vis, HPLC (365 nm), FTIR, VLC	λmax = 403 nm; rutin, isoquercetin, tannic acid identified; C=C, C=O, -OH groups detected; optimal extraction at 65.9°C, 2 h	[53]
6	Avocado Leaf Dye (*Persea americana*)	HPLC, NMR, FTIR	Quercetin & isoquercetin identified; flavonoid structure confirmed; strong phenolic functional groups	[49]
7	Bamboo Leaf Dye (*Bambusa vulgaris*)	VLC, HPLC, FTIR	97 fractions isolated; isoquercetin dominant compound; O–H and aromatic C=C peaks observed	[54]
8	Lannea coromandelica Leaf Dye	UV–Vis, FTIR, GC–MS	Reddish-brown dye; phenolic compounds confirmed; pH 5.94; active bio-components identified	[55]
9	Justicia spicigera (Anthocyanin dye)	UV–Vis, Py-GC/MS	λmax = 581 nm; anthocyanin-related compounds; hydroxylbenzoic acid derivatives	[46]
10	Neem & Rosella Extract (DSSC dye)	UV–Vis, FTIR, XRD	Absorbance peaks ~550 & 660 nm; enhanced crystallinity (~126.89 nm grain size); improved TiO_2 interaction	[47]
11	Ivy Gourd + Turmeric (Co-sensitized DSSC dye)	UV–Vis, Band gap analysis	Multiple band gaps: 1.74, 2.51, 2.59 eV; efficiency improved to 0.3%	[48]

The presence of similar groups was also observed in the characterization studies for bamboo leaves. For bamboo leaves, the FTIR analysis exhibited peaks for O-H, C=C, CHO, and C-O-C vibrations. These results indicated the presence of isoquercetin as the primary compound [54]. In the studies for bamboo leaves, column chromatography was used to separate 97 fractions into six groups. Fraction A was characterized as isoquercetin [54].

Similarly, in the case of Lannea coromandelica leaves, FTIR analysis identified phenolic and conjugated functional groups responsible for the reddish-brown coloration of the dye [55]. Arjuna fruit extract, too, displayed characteristic polyphenolic FTIR signals, and the structural stability of silk fibroin after dyeing was confirmed by FTIR analysis, indicating successful dye-metal coordination without disrupting the matrix structure of the silk fibroin [56]. SEM and EDX techniques were used in microwave-assisted cotton dyeing studies, where the surface morphology of the cotton fabric and elemental composition of the dye were analyzed, indicating successful dye distribution and minimal structural damage to the cotton fabric [50]. In the case of Arjuna fruit dye, too, structural analysis using SEM and EDX confirmed successful dye-metal coordination and stability of silk fibroin after dyeing [56].

FTIR analysis in DSSC-related studies identified broad hydroxyl and minor triple bond signals, indicating improved electron transport potential in DSSC systems [47]. Overall, FTIR results indicate the dominant role of hydroxyl-rich phenolic compounds in the chemistry of natural dyes, which enables successful coordination with metal ions in the mordanting process. XRD analysis has been used in dye characterization in DSSC-related studies. When TiO2-coated fluorine-doped tin oxide (FTO) substrates were subjected to adsorption of natural dyes, XRD analysis revealed enhanced crystallinity and a particle grain size of 126.89 nm, indicating successful interaction with the semiconductor surface [47].

In the microwave-assisted extraction of madder and Walloon oak dyes, RP-HPLC with a photodiode array detector was utilized to detect coloring agents such as alizarin, purpurin, gallic acid, and ellagic acid in the extracted dyes to ensure the presence of active dye structures even in rapid microwave treatment [50] .

Gas chromatography coupled with mass spectrometry (GC-MS) and pyrolysis-GC/MS (Py-GC/MS) were utilized to detect phenolic degradation products in the dyes. In the study on *Lannea coromandelica* using GC-MS, the active chemical constituents in the natural dye were detected [55].

In the study on the microwave-assisted extraction and dyeing of madder (Rubia tinctorum) and Walloon oak *(Quercus ithaburansis*), RP-HPLC with a PAD detector was utilized to detect coloring agents in the natural dyes and in the cotton fabrics dyed with the dyes [50]. The detection was performed in the 191 to 799 nm range with detection wavelengths of 255 nm, 268 nm, 276 nm, 350 nm, 491 nm, 520 nm, 580 nm, and 620 nm to identify the presence of anthraquinones in madder and gallic acid and ellagic acid in Walloon oak dyes. The C18 chromatographic column was utilized with gradient elution to separate hydrolyzed dye fractions in the solution. The color characterization was performed by using the CIELab* color scale to quantify color in terms of L* value to indicate brightness changes and a* and b* to indicate color changes.

In the bioactive silk system employing turmeric-derived curcuminoid dyes and chitosan, detailed chromatographic and spectroscopic studies have been conducted [51]. The liquid chromatography-mass spectrometry analysis using a triple quadrupole mass spectrometer verified the existence of curcuminoids within a mass range of 5 to 2900 m/z in positive electrospray ionization mode. The liquid chromatographic separation used a C18 RRHD column held at 30°C with a mobile phase consisting of a water and methanol-acetonitrile solvent mixture. This identified major curcuminoids in the sample. The UV-Visible spectrum of the turmeric dye extract showed absorption within the 200 to 900 nm region, verifying conjugated double bonds in the curcumin chromophore. The Fourier Transform Infrared spectrum of both the lyophilized dye extract and dyed silk fibers showed characteristic bands within the 500 to 4000 cm^{-1} region, including phenolic -OH stretches, conjugated carbonyl stretches, and aromatic CC stretches. The integration of curcuminoids into silk fibers was verified through X-ray diffraction, where Cu-Kα radiation with a wavelength of 1.54 Å verified retention of silk fiber crystalline structure through d-spacing values calculated from Bragg's equation. Field Emission Scanning Electron Microscopy at 2.5 kV verified uniform coating of dye-chitosan on fiber surfaces, and color strength values measured using a D65 light source verified increased chromatic depth in chitosan samples.

In the study on catalytic oxidative degradation using cobalt porphyrin catalysts on bentonite and chitosan supports, structural characterization extended beyond dye to catalyst validation [52]. The free base porphyrin showed characteristic absorption peaks at 416 nm, 516 nm, 554 nm, 592 nm, and 649 nm. Upon complexation with cobalt, the peaks were observed at 448 nm, 544 nm, and 581 nm. The FTIR peaks observed were characteristic of ν(O–H) stretching at 3423 cm^{-1}. ν(C=N) stretching was observed at 1469 cm^{-1}. ν(Co–N) stretching was observed at 1001 cm^{-1}. XRD was done to check the crystal stability of the composite material. The 2θ range was 5° to 90°. TGA was done to check the thermal stability of the catalyst. DLS was done to find the average particle size and the potential of the particles. It was done using a Malvern Zetasizer. The morphology of the catalyst was checked by SEM image. During the degradation of dyes like methyl orange, methyl red, and orange II, the UV-Visible spectrophotometer was used to record the peaks at 464 nm, 505 nm, and 485 nm. The degradation was checked by the TOC method. The percentage of mineralization was 69%, 85%, and 66% for the three dyes.

In the study on the characterization of *Dacryodes edulis* leaf extract as a natural colorant for polyamide fabrics, solvent extraction optimization was statistically validated by Response Surface Methodology (RSM-CCD

(Central Composite Design)), where optimal conditions were found to be 65.9°C for 2 hours [53]. The UV-Visible spectrum showed that the maximum absorption peak was 403 nm, indicative of conjugated phenolic structures. The presence of rutin, isoquercetin, and tannic acid was confirmed by high-performance liquid chromatography (HPLC) using an Xbridge RP18 column with detection at 365 nm. The gradient elution mode with 0.1% acetic acid and acetonitrile was effective in separating the flavonoid compounds. The FTIR spectrum obtained in the 3500 to 1000 cm^{-1} region showed the presence of C=C, C=O, ester (-COO), aldehyde (CHO), and hydroxyl (-OH) groups, indicative of flavonoid-tannin structures. The use of vacuum liquid chromatography (VLC) as a precursor to HPLC was effective in the isolation of the fractions and in improving the resolution of the chromatogram. The chromatographic and spectroscopic methods were effective in identifying the dye and correlating it with the structure and the light fastness values ranging from 4 to 6.

These analysis methods give complementary information concerning the composition of the dye and the characteristics of the nanoparticles. UV–Vis spectrophotometry helps mainly in the detection of chromophores and extraction efficiency. FTIR spectroscopy serves to confirm the presence of functional groups and helps in studying the interactions of the dyes with other components like the plant extracts and the mordants. HPLC and LC–MS help in identifying the dye components qualitatively and quantitatively. The SEM together with EDX helps in obtaining information about the surface morphology, fiber coating, element composition, and the distribution of the dye after application on fabrics.

Comprehensive characterization enables the optimization of dye performance for textile and environmental applications, which are reviewed in the subsequent section.

7. Future Research Directions and Industrial Perspectives

Despite all of the advancements in plant-mediated synthesis of nanoparticles and extraction of natural dyes, several key issues hampering the scaling-up of these approaches from lab-scale to an industrial scale remain open. Thus, future research should shift from the conceptual studies to the improvement of process reproducibility, mechanistic insights, scalability, and sustainability.

One of the first directions for future research is the development of predictive mathematical models based on AI (Artificial Intelligence) and ML (Machine Learning) algorithms that would allow establishing complex relationships between solvent composition, extraction temperature, microwave irradiation power, ultrasound power, pH, precursor concentration, phytochemical composition of the extract, and the physicochemical properties of the nanoparticles. These models can greatly simplify the development of an optimized extraction process. However, the successful implementation of such models requires the creation of a standardized and good-quality experimental dataset.

Digital twin technology also offers an interesting research prospect. The use of digital twins can be highly beneficial for extraction and synthesis processes as it allows simulating, monitoring, and optimizing the processes through the whole lifecycle. In the case of natural dye extraction and green synthesis of nanoparticles, digital twins can be used for dynamic optimization of process parameters, predictive maintenance of extraction systems, quality assurance, and continuous process control. However, the use of digital twin technology poses some difficulties as the necessary kinetic models describing phytochemical extraction and nanoparticle nucleation and growth are not available.

From the perspective of process engineering, the need for process intensification requires additional attention. The majority of published studies employ batch extraction systems characterized by low energy efficiency, poor scalability, and unstable product quality. The investigation of continuous flow microwave reactors, ultrasonic flow-through systems, microreactors, hybrid extraction systems, and integrated extraction-synthesis systems can help to overcome these problems. Moreover, the coupling of extraction with membrane separation, adsorption, or purification processes will provide additional benefits.

Ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE) have shown much higher extraction efficiencies in comparison with traditional Soxhlet extraction. However, systematic comparative studies remain underdeveloped. Future research requires the establishment of standardized operating protocols for various extraction techniques and the comparative evaluation of these technologies based on performance indicators, such as extraction yield, specific energy consumption, solvent recovery, economics, carbon footprint, and overall environmental impact. The evaluation of extraction techniques on the basis of the above-listed criteria is necessary for the appropriate selection of the technique for industrial applications rather than only extraction yield.

The selection of extraction solvents needs further investigation. Despite the environmental concerns associated with conventional organic solvents, they remain the primary choice for the majority of extraction protocols. However, green solvents should be the target of future research due to their ability to adjust the properties of solvent, biodegradability, and high extraction efficiency. The challenges associated with these solvents include their viscosity, recovery efficiency, recyclability, compatibility with downstream processing, and environmental fate.

One of the most critical limitations in the current literature is the absence of process standardization. Due to the variability in plant species, geographical location, harvesting conditions, phytochemical composition of plants, and extraction conditions, there is considerable difference in nanoparticle size, morphology, crystallinity, surface chemistry, and functional properties. Therefore, there are serious problems with the reproducibility of results in different studies. Thus, future research requires the development of standardized reporting guidelines including characterization of plant extracts, phytochemical profiling, and experimental conditions.

Furthermore, the bibliometric analysis reveals that there is an increasing trend towards nanoparticle preparation, characterization, and photocatalysis studies. While these aspects are well developed, relatively few publications focus on scale-up, reactor design, process economics, quality control, regulatory issues, and commercialization. Lack of pilot studies and techno-economic analysis is a serious limitation for practical implementation, which future research must consider. Therefore, in addition to bench-scale experiments, future research should combine process systems engineering, computational fluid dynamics, life cycle assessment (LCA), techno-economic analysis (TEA), and principles of circular economy to determine the potential of industrial-scale implementation.

One other key research direction is related to the integration of natural dye extraction and nanoparticle biosynthesis into a single biorefinery process. Instead of focusing on two separate technologies, future research should pay attention to the cascaded use of biomass for extraction of valuable phytochemical compounds, natural dyes, antioxidants, and reducing agents for nanoparticle synthesis.

8. Conclusion

The present paper performs a bibliometric and technical review of the literature on research on green synthesis of nanoparticles and natural dye extraction technology using plants over the time period between 2015 and 2025. Bibliometric results demonstrate the noticeable increase in scientific output during the past decade due to the growing global interest in sustainable nanotechnology and environmentally friendly dye extraction. The research community is dominated by Asian countries, among which India can be named as a country that plays the role of the leader in the number of publications and international cooperation.

The keyword co-occurrence network analysis, collaboration network analysis, and centrality measures identified the following core topics of research: green synthesis, plant extracts, metal nanoparticles, and natural dyes. The high scores of betweenness and PageRank also show that the synthesis and characterization techniques of nanoparticles and the technique of plant extraction are crucial for connections of different research topics. According to the trend analysis, there is a definite evolution of the research field from fundamental studies devoted to the synthesis and characterization of nanoparticles by using Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), and Scanning Electron Microscopy (SEM) to practical research associated with the application of the synthesized nanoparticles in photocatalysis, antibacterial activity, environmental protection, and multifunctional textile applications.

As per the technical evaluation, UAE and MAE can provide benefits over traditional methods in terms of lower extraction time along with higher efficiency in most of the reported cases, along with less solvent requirement. The benefits provided by these methods depend highly on the type of plant material, solvent mixture used, operating conditions, and the scale of the operation. Moreover, there is a lack of quantified information related to the specific energy consumption in the literature; hence, it cannot be stated conclusively that UAE and MAE provide benefits in terms of energy efficiency and sustainability. Further research is needed to address this gap.

The main contribution of the current paper is the combination of scientometric and technical analysis, as this approach allows getting the quantitative picture of the research area and evaluating the advancements in sustainable extraction and green nanoparticles synthesis qualitatively.

The bibliometric analysis was based solely on the Scopus database and publications written in English, which may have excluded relevant studies indexed in other databases or published in other languages. Additionally, the publication data for 2025 represent records indexed in Scopus up to the retrieval date and should therefore be interpreted as an incomplete publication year. It is necessary to continue the research on the standardization and scalability of the green synthesis protocol, optimization of UAE and MAE processes, the use of artificial intelligence and machine learning for process optimization, life cycle assessment, techno-economic assessment, and industrial implementation of the developed technologies. International and interdisciplinary collaboration is also crucial for the advancement of sustainable synthesis and extraction technologies.

Author Contribution Statement

Swati Dubey: Conceptualization, Data Curation, Investigation, Methodology, Project Administration, Supervision, Software, Validation, Visualization, writing original draft, reviewing, editing

Avanish Kumar: Conceptualization, Data Curation, Investigation, Methodology, Project Administration, Supervision, Validation, Visualization, Writing original draft, reviewing, editing

All authors agree to be accountable for all aspects of the work.

Competing Interests Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The bibliographic dataset and the corresponding analysis files used in this study are available from the corresponding author upon reasonable request.

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