Trends in anti-UV films or composites: A bibliometric study

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Abstract: Anti-UV films and composites play a critical role in protecting materials from ultraviolet-induced degradation, which can weaken polymers, reduce product lifespan, and compromise performance in sectors such as food packaging, outdoor coatings, and biomedical devices. The growing emphasis on sustainability and the need for environmentally friendly protective materials have further accelerated research on UV-shielding technologies that incorporate biopolymers, multifunctional additives, and renewable resources. This study presents a comprehensive bibliometric analysis of global research on anti-UV films and composites over the period 2014–2024. Data were retrieved from the Scopus database and analyzed using Bibliometrix (R package) and VOSviewer were employed to analyze publication patterns, map keyword networks, and visualize thematic evolution, as these tools enable robust quantitative and structural mapping of large bibliographic datasets. Three dominant thematic clusters were identified: (i) nanoparticle-based UV shielding using inorganic fillers such as ZnO and TiO_2, (ii) multifunctional films integrating UV protection with antibacterial and antioxidant properties, and (iii) biopolymer-based matrices emphasizing mechanical durability and environmental sustainability. These clusters highlight the convergence of performance, sustainability, and multifunctionality as key drivers shaping current research directions. Despite significant progress, the analysis reveals limited attention to scalability, industrial compatibility, and long-term performance evaluation. The findings underscore the need for future research to incorporate pilot-scale processing, life-cycle assessments, and interdisciplinary collaboration to bridge the gap between laboratory formulations and commercial implementation. Overall, this bibliometric study provides a consolidated understanding of the evolution and research landscape of anti-UV films and composites.

Keywords: anti-UV films; composites; bibliometric analysis; VOSviewer; sustainable materials

1. Introduction

In recent years, the rapid economic growth and intensified market competition across the ASEAN region have driven a significant increase in the demand for advanced and sustainable materials [1]. At the same time, the continuous rise in energy consumption has highlighted the urgent need for innovative material solutions that can enhance efficiency, reduce environmental impact, and extend product lifetime [2]. This growing demand has also emphasized the importance of developing materials capable of withstanding diverse environmental stressors while maintaining functionality

and sustainability [3], [4]. In particular, the shift toward environmentally conscious design has increased the focus on polymer systems that not only perform well but also resist long-term degradation in realistic service conditions.

Among the key environmental challenges faced by polymer-based materials in such applications is exposure to ultraviolet (UV) radiation, which can severely compromise their durability and performance. UV radiation is a major environmental factor that can cause photodegradation in polymers, leading to discoloration, surface cracking, and significant deterioration of mechanical properties [5]. Such degradation not only compromises material performance but also shortens service life, limiting the practical use of polymers in applications exposed to sunlight [6]. Consequently, achieving effective UV protection has become a central requirement in the development of sustainable polymeric materials. To address this challenge, extensive research has been devoted to developing anti-UV materials that can effectively absorb, reflect, or scatter harmful UV rays, thereby enhancing durability and functionality. Anti-UV films and composites have emerged as a critical class of protective materials with applications spanning food packaging, outdoor coatings, textiles, agricultural films, and biomedical devices [7][8]. In particular, food packaging has seen growing interest in anti-UV technology, as UV exposure can accelerate lipid oxidation, pigment degradation, and microbial growth, reducing shelf life and product quality. These applications highlight the need for UV-protective systems that combine performance, safety, and environmental compatibility.

The integration of UV-blocking capabilities into packaging materials offers a sustainable and active preservation strategy without relying solely on chemical preservatives. A wide range of strategies have been explored to impart UV resistance, including the incorporation of inorganic fillers such as zinc oxide (ZnO) and titanium dioxide (TiO_2), which possess wide bandgap energies enabling efficient absorption of UV-A and UV-B radiation while maintaining high visible light transmittance [9]. Despite their strong UV-shielding efficiency, these inorganic fillers raise concerns regarding cost, long-term stability, agglomeration, and potential regulatory restrictions in food-contact applications, highlighting the need for complementary or alternative approaches. Concurrently, the incorporation of bio-based components such as lignin, tannic acid, and plant extracts aligns with global sustainability goals, enabling the production of multifunctional films that combine UV shielding with antioxidant, antimicrobial, and barrier properties [10], [11], [12]. These hybrid materials bridge the gap between high-performance engineering solutions and environmentally friendly design principles. Biopolymer matrices such as cellulose, polyvinyl alcohol (PVA), and starch have become preferred platforms due to their biodegradability, renewability, excellent film-forming capabilities, and compatibility with diverse UV-blocking agents [13][14]. Compared with synthetic polymers, these biopolymers offer advantages in sustainability and processing simplicity, though reinforcement or modification is often required to reach industrial performance standards.

Recent research trends indicate a paradigm shift toward multifunctionality and sustainability. Many studies report anti-UV films that not only protect against radiation but also offer mechanical reinforcement, hydrophobicity, and bioactivity. Biopolymer matrices such as cellulose, polyvinyl alcohol (PVA), and starch have gained prominence due to their biodegradability and compatibility with both inorganic and organic UV absorbers. However, despite rapid laboratory-scale advances, challenges remain in scaling up production while maintaining consistent performance, cost efficiency, and compliance with food-contact safety standards. These challenges underscore persistent research gaps related to industrial scalability, long-term durability, environmental impact, and the fragmented understanding of global research directions.

Bibliometric analysis provides a valuable tool to assess research landscapes, identify thematic clusters, and uncover emerging trends in this rapidly evolving domain [15], [16]. By systematically mapping global scientific output, citation patterns, and keyword networks, it is possible to highlight

both the maturity of certain research areas and the opportunities for future exploration [17], [18]. However, no previous bibliometric study has comprehensively synthesized the development of anti-UV films and composites over the past decade, nor linked thematic evolution with sustainability and industrial applicability. In this context, the present study addresses the following research questions:

(i) How has global research on anti-UV films and composites evolved in the last ten years?
(ii) Which materials, methods, and countries dominate the field?
(iii) What thematic structures define current research directions, and where do critical gaps remain?

To answer these questions, this work provides a comprehensive bibliometric evaluation of research on anti-UV films and composites from 2014 to 2024, focusing on publication trends, influential journals, leading countries, and keyword co-occurrence networks. The findings aim to guide future research toward integrating high UV-shielding performance, multifunctionality, environmental sustainability, and industrial scalability.

2. Methodology

2.1 Data source

The bibliometric data was retrieved from the Scopus database, which was selected due to its extensive coverage of peer-reviewed literature in materials science, engineering, and polymer composites. The search was conducted on 13 August 2025, and only journal articles, conference papers, and reviews were considered. Scopus was deemed particularly suitable for this study because it indexes a large proportion of journals that frequently publish research on polymer films, coatings, and composites, including those focused on sustainable and functional packaging. In contrast, Google Scholar aggregates non-curated sources and grey literature, while Web of Science, although highly selective, offers narrower coverage for some emerging journals in food packaging and biopolymer research. Therefore, Scopus provided a balanced combination of breadth and quality for mapping global research on anti-UV films and composites.

2.2 Search strategy

The literature search was conducted using a Boolean query designed to capture publications related to UV-resistant films and composites. Following the PRISMA approach, records were identified from the Scopus database within the period 2014–2024. As illustrated in Figure 1, the initial dataset (n = 3,779) was exported in CSV format for screening and eligibility assessment. During the screening phase, duplicate records (based on Scopus EID, DOI, and exact title matching) were removed. Titles and abstracts were then examined to exclude documents that: (i) did not focus on UV protection or UV-related performance in films or composites, (ii) addressed UV-related biological or clinical topics unrelated to materials, or (iii) did not provide experimental, modeling, or review content on polymer-based systems. Full-text checks were conducted when relevance was unclear from the abstract. Only studies explicitly addressing anti-UV properties in films, coatings, or composites were retained in the final dataset.

Two researchers independently screened the records against these criteria. Any disagreement regarding inclusion was resolved through discussion, and when necessary, a third senior researcher was consulted to reach consensus. This procedure served as a quality assurance step to minimize selection bias.

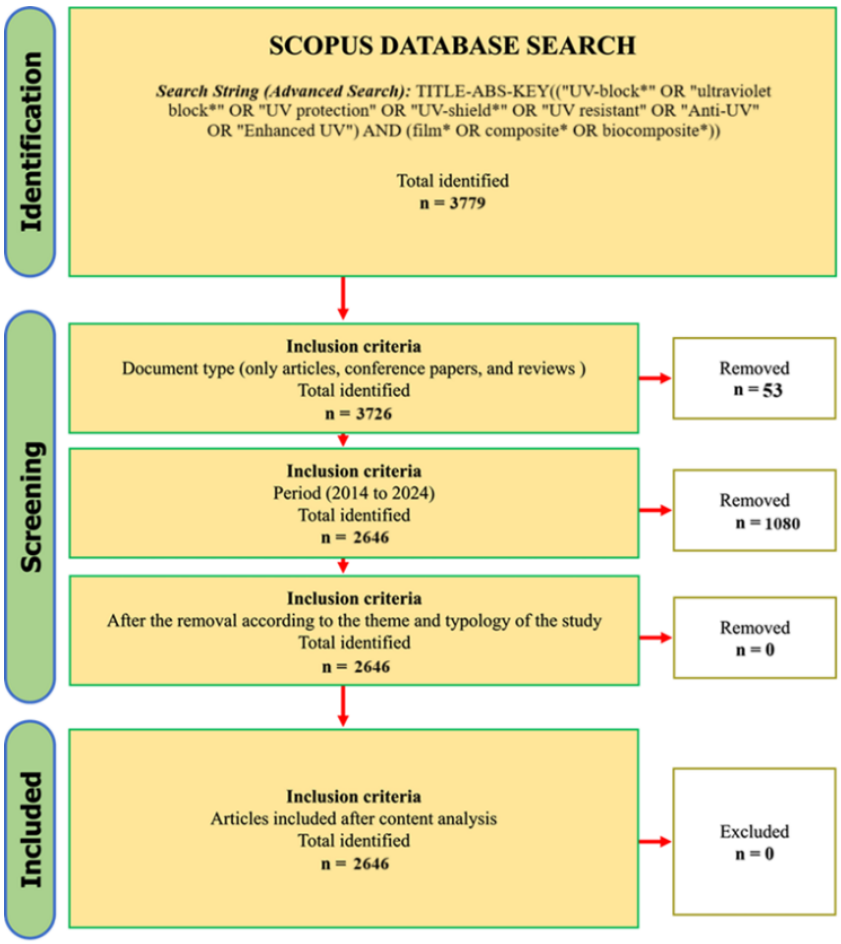

Figure 1. PRISMA-style flow diagram of the literature search and screening process

2.3 Bibliometric analysis

Bibliometric analysis was conducted to evaluate the scientific landscape and research trends in the field of anti-UV films or composites. The cleaned dataset was analyzed using Bibliometrix (R package) for descriptive performance metrics, including annual scientific production, country and institutional productivity, authorship patterns, and citation impact. Country and institutional productivity were quantified based on total publications and fractional counting of co-authored papers, while authorship patterns were evaluated using the number of single-authored versus multi-authored documents and collaboration indices. Citation impact was assessed through total citations, average citations per document, and citation rates normalized by publication year to account for differences in exposure time. These indicators collectively provide insight into both the volume and influence of research activity. Prior to analysis, the dataset underwent a data-cleaning process. Duplicates were removed using unique identifiers (EID and DOI), and records with missing or incomplete bibliographic fields (e.g., no author name or no source title) were inspected and either corrected manually when possible or excluded if essential information could not be recovered. Author names and affiliations were standardized to merge variations in spelling or formatting, and journal titles were harmonized to reduce redundancy.

VOSviewer was employed to generate network visualizations, such as keyword co-occurrence maps. The co-occurrence analysis was performed with a minimum threshold of 37 keyword occurrences. Keyword standardization was ensured through a thesaurus file to merge synonymous terms and variations. In the network maps, node size represents the frequency of keyword occurrence, link thickness reflects the strength of co-occurrence between terms, and different colors indicate distinct thematic clusters. These maps were interpreted to identify core research

themes, emerging topics, and relationships between materials, functionalities, and application domains in anti-UV films and composites. Origin was used for additional tabulation and to generate publication trend graphs. Specifically, Origin was applied to plot annual publication counts, document-type distributions, and leading journals, enabling clear visualization of temporal evolution and source contributions. Thematic categorization was carried out by combining quantitative keyword co-occurrence analysis with qualitative examination of highly cited articles and cluster contents. This approach enabled synthesis of the findings into major thematic groups (e.g., nanoparticle-based UV shielding, multifunctional films, biopolymer matrices) and facilitated comparison across countries, journals, and application areas. Finally, several methodological limitations should be acknowledged. The exclusive reliance on Scopus may introduce database bias and may omit relevant studies indexed only in other platforms. The language restriction to English can underrepresent contributions published in other languages. Furthermore, the analysis is based on bibliographic metadata rather than full-text content, which may limit the depth of qualitative interpretation. Nevertheless, the chosen approach provides a transparent and replicable framework for capturing global trends and structures in anti-UV film and composite research.

3. Results and discussion

3.1 Publication trends

The annual publication output on anti-UV films or composites from 2014 to 2024 demonstrates a clear upward trajectory, with a marked acceleration after 2020 (Figure 2). From a modest 59 articles in 2014, the number of publications increased gradually until 2019, followed by a substantial surge, rising from 178 articles in 2019 to 637 articles in 2024. This pattern suggests that research interest in anti-UV materials, particularly in films and composites, has intensified in recent years, potentially driven by the growing demand for sustainable packaging solutions, multifunctional coatings, and advanced protective materials.

The document type distribution, shown in the inset pie chart of Figure 2, reveals that journal papers overwhelmingly dominate the field, accounting for 96.7% of publications, whereas conference papers contribute only 3.3%. This dominance reflects the maturity and depth of the research area, where comprehensive studies are more often disseminated through peer-reviewed journals rather than preliminary conference proceedings. Analysis of the top publishing journals (Table 1) indicates that the International Journal of Biological Macromolecules leads by a significant margin with 249 articles, highlighting its role as a primary outlet for bio-based and macromolecular anti-UV research. Other high-ranking journals such as Polymers, Food Hydrocolloids, and Carbohydrate Polymers suggest strong interdisciplinary interest, bridging polymer science, food packaging, and sustainable materials development. The presence of journals like Applied Surface Science and Progress in Organic Coatings also indicates that beyond packaging, anti-UV technologies are relevant in surface engineering and protective coatings. Overall, the trends highlight a rapidly expanding and diversifying research field, with strong contributions from journals that cover both bio-based innovations and advanced material engineering. The post-2020 growth suggests that the convergence of sustainability goals, functional performance requirements, and material innovation will likely continue to drive publication output in the coming years.

The increasing publication trend is not only a reflection of scientific interest but also corresponds to broader global drivers. Over the past decade, advancements in nanotechnology, biopolymer processing, and green additive development have expanded the range of viable anti-UV formulations. At the policy level, sustainability frameworks such as the UN Sustainable Development Goals, circular economy programs, and plastic reduction policies have further motivated research into environmentally friendly UV-protective materials. The sharp increase in publications after 2020 coincides with heightened global attention to packaging safety and shelf-life

stability during the COVID-19 pandemic, alongside intensified government funding for sustainability-focused materials research. Additionally, the rise of bio-based packaging markets and the growing restriction of petroleum-derived stabilizers have accelerated research output in multifunctional and biodegradable anti-UV films. In terms of article type, basic research continues to dominate, particularly studies on material synthesis, nanocomposite formulation, and characterization. However, applied research has grown significantly in areas such as food packaging, biomedical films, and outdoor coatings, reflecting the translation of laboratory advances into practical applications. This shift illustrates the alignment of anti-UV film development with broader themes of sustainability and technological modernization.

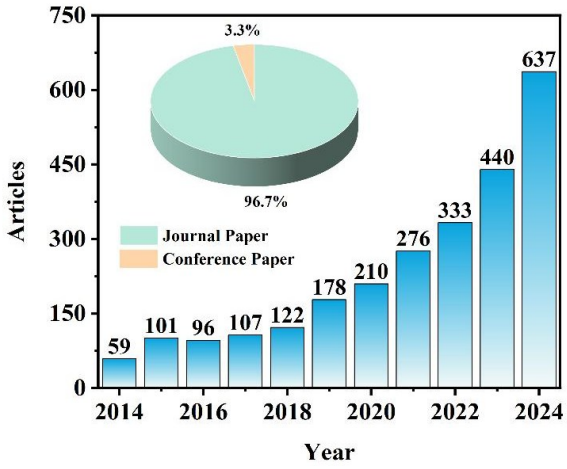

Figure 2. Annual publication trends on anti-uv films or composites from 2014 to 2024

Table 1. Top 15 journals with most publications on anti-UV films or composites

No	Journal	Articles
1	International Journal of Biological Macromolecules	249
2	Polymers	66
3	Food Hydrocolloids	61
4	Carbohydrate Polymers	59
5	Chemical Engineering Journal	59
6	Journal of Applied Polymer Science	57
7	ACS Applied Materials and Interfaces	54
8	Industrial Crops and Products	53
9	ACS Sustainable Chemistry and Engineering	47
10	Cellulose	44
11	Progress in Organic Coatings	42
12	Food Packaging and Shelf Life	36
13	RSC Advances	33
14	Applied Surface Science	28
15	ACS Applied Polymer Materials	27

3.2 Global citation metrics

Figure 3 and the accompanying data show the citation performance of 20 top-cited countries in anti-UV film and composite research, based on Scopus records. China leads with a total of 32,067 citations, far surpassing other countries, indicating its dominant role in both research output and global impact. However, its average article citations (25.4) are lower than several smaller-volume

contributors. South Korea ranks second in total citations (8,055) but records an impressive average of 50 citations per article, demonstrating both high productivity and high per-paper impact.

India (5,028 citations, 22 average) and the USA (3,168 citations, 43.4 average) also show strong influence, with the USA standing out for combining substantial output with a high citation average. Smaller but high-impact countries emerge when focusing on average article citations. Portugal tops the list with 60.2 citations per article despite a modest total of 542 citations, followed closely by Finland (53.9) and South Korea (50). Australia also performs strongly (47.5 average), supported by a mid-level citation volume (1,330). Mid-tier performers, such as Iran (2,174 total, 32 average), Egypt (1,331 total, 26.6 average), and Spain (1,076 total, 34.7 average), maintain balanced performance between quantity and impact. Sweden (632 total, 35.1 average) and Hong Kong (401 total, 40.1 average) show relatively high efficiency despite smaller total volumes. At the lower end of total citations, countries such as Saudi Arabia (419 total, 13.5 average), Malaysia (394 total, 20.7 average), and Thailand (682 total, 17.5 average) still contribute to the field but with limited reach compared to global leaders. While not in the original top-ranked group, Indonesia is included in Figure 3 for comparative purposes. Its highest-cited article achieves an average citation of 22.6, a figure that rivals or exceeds some mid-tier countries, suggesting that focused, high-quality research can enable emerging contributors to compete in terms of citation efficiency. Overall, the data reveal two clear patterns: (i) high-volume producers such as China and India dominate in total citations but may not always achieve top rankings in per-paper impact, and (ii) countries with lower output can still achieve exceptional impact per article through targeted, specialized, and high-quality research as demonstrated by Portugal and Finland.

Although China and South Korea lead in publication volume, their citation rates differ due to variations in funding intensity, international collaboration networks, and institutional specialization. China's large-scale investment in nanotechnology and biopolymer research contributes to high output, while South Korea's strong industry-university partnerships and focus on electronic and optical materials enhance citation quality. Emerging contributors such as Indonesia, Malaysia, and Thailand demonstrate increasing impact despite lower publication counts. Their strength lies in niche expertise related to biopolymer matrices, natural UV-blocking extracts, and sustainability-driven materials. To increase research visibility, these countries may benefit from strengthened international collaborations, cross-institutional consortia, and engagement in global open-access research platforms.

In addition to high-output countries, several emerging contributors including Indonesia, Malaysia, Thailand, and other ASEAN nations, demonstrate notable citation efficiency despite producing fewer publications. Their research often focuses on biopolymer-based matrices, natural UV-blocking extracts, and multifunctional films derived from regionally abundant biomass resources such as lignin, tannins, and plant-derived antioxidants. This specialization enables smaller research communities to generate high-impact studies that align strongly with global sustainability trends. As the demand for eco-friendly and biodegradable anti-UV materials grows, these emerging countries are well positioned to influence future developments through niche expertise, abundant renewable feedstocks, and increasing participation in international collaborations. Strengthening research networks, improving access to advanced characterization facilities, and expanding funding for sustainable materials research may further enhance their long-term impact on the field.

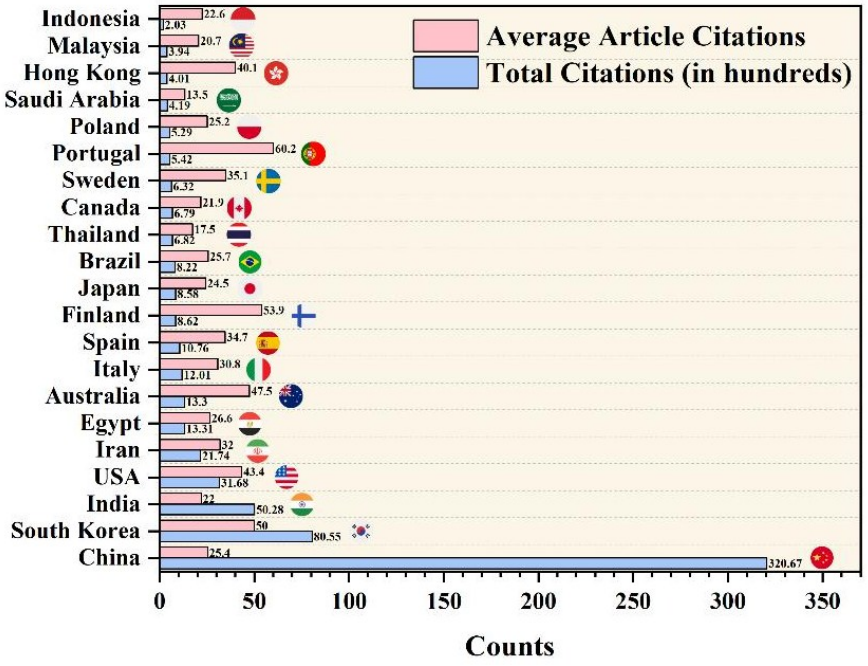

Figure 3. Average article citations and total citations (in hundreds) for the top-cited countries in the field of anti-UV films or composites

3.3 Most influential articles

Table 1 presents the top-cited articles in the field of anti-UV films or composites, ranked by citation rate per year to normalize for publication age. The results highlight several key patterns in research productivity and influence. Firstly, high-impact publications in this domain are concentrated in high-visibility journals such as Materials Horizons, ACS Sustainable Chemistry & Engineering, Food Hydrocolloids, and Advanced Functional Materials. These outlets reflect both fundamental material science and applied food packaging research, indicating that the field bridges basic and applied sciences. Notably, Food Hydrocolloids appears multiple times, emphasizing the strong research momentum toward edible or biodegradable UV-blocking films for food preservation.

Geographically, the dominance of East Asia, particularly South Korea and China, is evident, with South Korean researchers contributing at least four of the top-ranking papers. This suggests that these countries are actively investing in functional packaging and biopolymer-based materials with anti-UV capabilities. The USA also features prominently, particularly in lignin-based research, underscoring a parallel interest in renewable feedstocks for UV protection. Thematically, the leading topics span natural polymer matrices functionalized with UV-blocking agents such as lignin, polydopamine, curcumin, tannic acid, and nanoparticles (ZnO, sulfur nanoparticles, carbon dots). Reviews on lignin and sustainable UV-screening materials achieve high citation rates, reinforcing the role of review articles as citation magnets that consolidate emerging knowledge.

Interestingly, several papers combine multifunctional properties, anti-UV activity is often integrated with antioxidant, antimicrobial, or intelligent packaging capabilities. Examples include Ezati (2020, 2023) and Lee (2023), which target both food quality monitoring and preservation, reflecting a shift toward active packaging systems. Additionally, works such as Huang (2015) on robust superhydrophobic fabrics show that UV protection research also extends beyond food packaging into broader surface engineering applications.

The high citation-per-year scores of recent papers (e.g., Alizadeh Sani, 2024; Khan, 2024) suggest that the research front in anti-UV biopolymer films is rapidly expanding. This may be attributed to

growing environmental concerns and the push for plastic alternatives that retain functional performance. Continued monitoring of these trends will be crucial to understanding the trajectory of this research area and identifying emerging leaders and collaborations.

Table 2. Top-cited articles in the field of anti-UV films or composites ranked by citations per year

Author	Year	First Author Country	Title	Journal	Citation per Year	Ref
Yu Fu	2021	China	Polydopamine antibacterial materials	Materials Horizons	85	[19]
Yi Zhang	2021	Australia	Lignin: A Review on Structure, Properties, and Applications as a Light-Colored UV Absorber	ACS Sustainable Chemistry & Engineering	69	[20]
Parya Ezati	2020	South Korea	pH-responsive chitosan-based film incorporated with alizarin for intelligent packaging applications	Food Hydrocolloids	63.7	[21]
Bo Jiang	2020	USA	Lignin as a Wood-Inspired Binder Enabled Strong, Water Stable, and Biodegradable Paper for Plastic Replacement	Advanced Functional Materials	58.8	[22]
Su Jin Lee	2023	South Korea	Multifunctional chitosan/tannic acid composite films with improved anti-UV, antioxidant, and antimicrobial properties for active food packaging	Food Hydrocolloids	54	[23]
Hasan Sadeghifar	2020	USA	Lignin as a UV Light Blocker—A Review	Polymers	51.2	[24]
Parya Ezati	2023	South Korea	Biopolymer-based UV protection functional films for food packaging	Food Hydrocolloids	51	[25]
Mahmood Alizadeh Sani	2024	Iran	Development of sustainable UV-screening food packaging materials: A review of recent advances	Trends in Food Science & Technology	51	[26]

Author	Year	First Author Country	Title	Journal	Citation per Year	Ref
Xiao Zhang	2019	China	Biomimetic Supertough and Strong Biodegradable Polymeric Materials with Improved Thermal Properties and Excellent UV-Blocking Performance	Advanced Functional Materials	49.4	[27]
Jianying Huang	2015	China	Robust superhydrophobic TiO2@fabrics for UV shielding, self-cleaning and oil–water separation†	Journal of Materials Chemistry A	46.1	[28]
Hyun-Ji Kim	2022	South Korea	Gelatin/agar-based color-indicator film integrated with Clitoria ternatea flower anthocyanin and zinc oxide nanoparticles for monitoring freshness of shrimp	Food Hydrocolloids	45.5	[28]
Parya Ezati	2020	South Korea	pH-responsive pectin-based multifunctional films incorporated with curcumin and sulfur nanoparticles	Carbohydrate Polymers	44.8	[29]
Hasan Sadeghifar	2017	Iran	Cellulose-Lignin Biodegradable and Flexible UV Protection Film	ACS Sustainable Chemistry & Engineering	43.9	[30]
Yu-Yao Liu	2021	China	Biobased High-Performance Epoxy Vitrimer with UV Shielding for Recyclable Carbon Fiber Reinforced Composites	ACS Sustainable Chemistry & Engineering	41.2	[31]
Ajahar Khan	2024	South Korea	Carrageenan-based multifunctional packaging films containing Zn-carbon dots/anthocyanin derived from Kohlrabi peel for monitoring quality	Food Chemistry	39.5	[32]

Author	Year	First Author Country	Title	Journal	Citation per Year	Ref
Dieter Rahmadiawan	2022	Indonesia	and extending the shelf life of shrimps The Enhanced Moisture Absorption and Tensile Strength of PVA/Uncaria gambir Extract by Boric Acid as a Highly Moisture-Resistant, Anti-UV, and Strong Film for Food Packaging Applications*	Journal of Composites Science	9.0	[33]

*Included for comparative purposes; represents the highest-cited article by an Indonesian author.

3.4 Keyword co-occurrence network

The trend toward multifunctional anti-UV films is evident in the frequent co-occurrence of keywords related to antibacterial, antioxidant, and barrier properties. The convergence of these functionalities is particularly relevant in active food packaging, where UV shielding can work synergistically with antioxidant activity to delay lipid oxidation and with antibacterial effects to inhibit microbial growth. In biomedical applications, UV shielding combined with antimicrobial functionality supports long-term stability of wound dressings, wearable sensors, and implant coatings. Real-world examples include ZnO- or TiO_2-reinforced biopolymer films with natural extracts used for perishable food packaging, and cellulose–polymer hybrid films designed for wearable healthcare devices. The keyword co-occurrence network (Figure 4) revealed three major thematic clusters in the research landscape of anti-UV films or composites.

The green cluster is centered on material composition and UV-blocking mechanisms, dominated by keywords such as uv-block, nanocomposites, nanoparticles, TIo_2, ZnO, optical properties, coatings, irradiation, and particle size. This cluster highlights the critical role of metal oxide nanoparticles, particularly ZnO and TiO_2, as UV absorbers due to their wide bandgap energies (~3.2 eV for TiO_2 and ~3.3 eV for ZnO), enabling efficient absorption of UV-A and UV-B radiation while maintaining visible light transparency [34], [35]. The inclusion of terms like particle size, morphology, and hydrophobicity suggests that optimization of nanoparticle dispersion and surface chemistry is a recurring focus, aimed at minimizing light scattering and enhancing weathering resistance.

The red cluster represents functional performance, bioactivity, and characterization techniques, with major keywords such as uv rays, antibacterial, antioxidants, *escherichia coli*, antiinfective agent, SEM, FTIR, and X-ray diffraction. This cluster emphasizes the growing multifunctionality trend in anti-UV films, where UV-blocking capability is combined with antibacterial and antioxidant activities for broader application potential, particularly in active packaging and biomedical uses. The frequent appearance of microbial species and assay-related terms indicates that bioactivity testing is commonly integrated alongside UV-shielding performance evaluations. Additionally, the co-occurrence of key analytical techniques highlights the importance of correlating microstructural and chemical data with functional outcomes, such as thermal stability and optical retention under UV exposure.

The blue cluster highlights biopolymer matrices, mechanical durability, and sustainability, characterized by keywords such as tensile strength, cellulose, nanocellulose, nanofibers, lignin, films, PVA, biodegradable polymers, and hydrogen bonds. This cluster underlines the increasing use of renewable and biodegradable polymers as matrices for anti-UV films, where materials such as cellulose and lignin serve dual roles as structural reinforcements and carriers for UV-blocking agents [36], [37]. The central positioning of tensile strength across clusters demonstrates its bridging role between material formulation and application readiness, reflecting the necessity for anti-UV films to maintain both functional performance and mechanical integrity.

Overall, the network suggests that current research is driven by three converging themes: (i) nanoparticle-based UV protection through metal oxide and hybrid nanofillers, (ii) multifunctionality combining UV-blocking with antibacterial, antioxidant, and stability enhancements, and (iii) sustainability via biopolymer-based matrices with balanced mechanical and functional properties. However, the absence of keywords related to scalability and industrial-scale processing indicates that most developments remain at the laboratory stage. Future research should explore pilot-scale manufacturing approaches such as continuous casting and roll-to-roll coating to accelerate the transition from experimental innovation to commercial deployment of anti-UV films or composites.

Although the bibliometric mapping highlights strong growth in laboratory-scale research on nanoparticle-based UV shielding, multifunctional films, and biopolymer matrices, the transition of these materials to industrial manufacturing remains a major challenge. Most of the reported anti-UV films are produced through solvent casting, batch blending, or small-scale composite synthesis, which are not directly compatible with large-scale processing such as roll-to-roll coating, blown-film extrusion, or multilayer lamination used in commercial packaging [38][39]. The incorporation of UV-blocking nanoparticles or plant-derived extracts may also increase production costs due to additional dispersion, stabilization, or surface-modification steps. Furthermore, for applications such as food packaging and biomedical coatings, regulatory frameworks (e.g., migration limits, nanoparticle toxicity, long-term weathering stability, and environmental compliance) impose additional requirements that are rarely addressed in laboratory studies. These industry-level considerations highlight a significant gap between academic research and practical adoption, indicating that future work must integrate pilot-scale trials, cost-benefit assessments, and regulatory evaluations to accelerate commercialization of anti-UV films and composites.

In addition to these processing and regulatory barriers, economic considerations further influence the feasibility of scaling anti-UV film production. Beyond material performance and sustainability goals, the economic viability of large-scale anti-UV film production remains a critical yet underexplored dimension in current research. Many formulations reported in literature rely on nanoparticles, natural extracts, or hybrid biopolymer matrices that may introduce higher material costs, additional processing steps, and quality-control requirements. These factors can significantly increase the cost per unit area when compared with conventional petroleum-based UV stabilizers. Moreover, only a limited number of studies incorporate cost-benefit analysis or life-cycle assessment (LCA), which are essential for quantifying the environmental and economic trade-offs associated with raw material sourcing, energy consumption, solvent use, and end-of-life impacts. As global packaging and coating industries increasingly adopt sustainability metrics, integrating LCA-based evaluations into anti-UV film development becomes essential for validating the financial feasibility and long-term competitiveness of these eco-friendly materials.

When placed within the broader landscape of protective materials, anti-UV films demonstrate distinct advantages and challenges compared with other barrier technologies. Traditional oxygen- and moisture-barrier films, for example, primarily aim to reduce gas or vapor transmission and do not require the careful balance between transparency and UV-shielding efficiency that anti-UV films

must achieve. Likewise, commercial surface coatings such as polyurethane, acrylic-based UV varnishes, and weather-resistant paints offer strong outdoor durability but typically rely on petroleum-derived stabilizers and are not biodegradable, limiting their alignment with current sustainability priorities.

By contrast, emerging anti-UV films, particularly those based on biopolymers, natural extracts, and hybrid nanostructures, provide multifunctionality and improved environmental performance, yet still face hurdles related to industrial scalability, cost, and long-term weathering stability. This comparison highlights the niche in which anti-UV films operate: a space where optical clarity, functional bioactivity, and sustainability converge, offering unique opportunities that differ from conventional protective coatings and barrier materials.

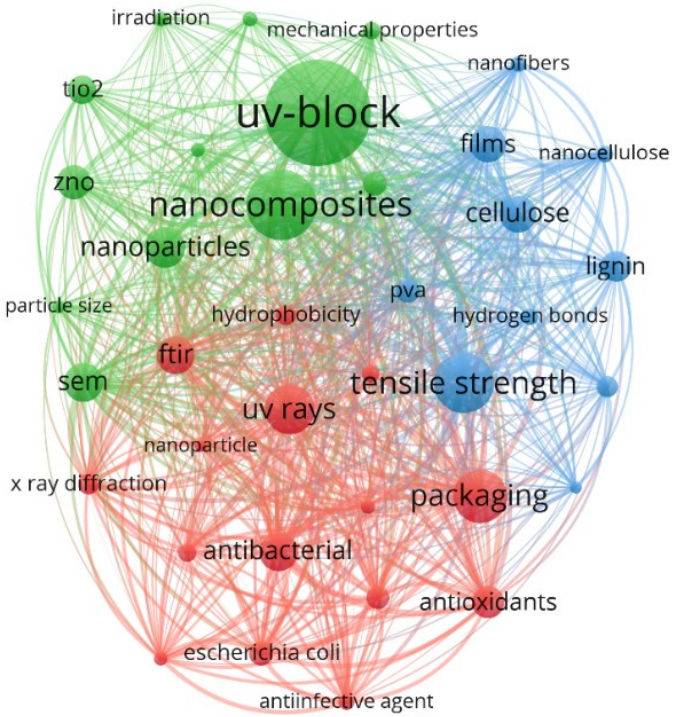

Figure 4. Keyword co-occurrence network of research on anti-UV films or composites generated using VOSviewer

4. Conclusion

This bibliometric analysis provides a comprehensive overview of global research developments on anti-UV films and composites over the past decade, revealing steady growth in scientific output and a marked acceleration after 2020 as sustainability-driven materials innovation gained momentum. Thematic mapping identified three main research directions: (i) nanoparticle-based UV shielding using inorganic fillers such as ZnO and TiO_2, (ii) multifunctional films integrating UV protection with antibacterial, antioxidant, and stability enhancements, and (iii) biopolymer-based matrices emphasizing mechanical durability and environmental sustainability.

The analysis also highlights that while laboratory-scale innovations are abundant, research on industrial scalability, pilot-scale manufacturing, and long-term performance remains limited. Emerging countries have shown potential to achieve high citation efficiency through focused, high-quality studies, while established research hubs continue to dominate in output volume. Despite the rapid advancement of laboratory-scale formulations, the analysis highlights a notable gap in industrial scalability, pilot-scale validation, and comprehensive long-term performance evaluation. Established research hubs such as China, South Korea, and the USA dominate global output, while

several emerging countries demonstrate strong citation efficiency through targeted, high-impact publications. Overall, future work should focus on bridging the gap between laboratory research and commercial deployment by developing cost-effective, scalable manufacturing techniques, expanding life-cycle assessments, and ensuring compliance with safety and regulatory standards. Strengthening interdisciplinary collaborations will be essential to accelerate the translation of anti-UV film and composite technologies into real-world applications.

To address the gaps identified in this bibliometric review, future research should adopt a more structured and collaborative roadmap. First, interdisciplinary integration is essential, linking materials science, surface engineering, food packaging technology, and nanotechnology to accelerate multifunctional film development. Second, pilot-scale studies using industrially relevant processes such as roll-to-roll coating, blown-film extrusion, and multilayer lamination. These should be prioritized to validate laboratory formulations under real manufacturing conditions. Third, long-term performance assessments, including accelerated weathering, UV-cycling durability, migration tests, and biodegradation behavior, are needed to ensure regulatory compliance and industrial reliability. Finally, integrating digital tools such as machine-learning-based material optimization and process modeling may enhance scalability and reduce development time. Together, these strategies form a practical pathway toward bridging laboratory advances with commercial implementation of sustainable anti-UV films and composites.

Author's declaration

Author contribution

Dieter Rahmadiawan: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing-original draft, Writing-review & editing. **Thiago F. Santos:** Methodology, Formal analysis, Validation, Writing-review & editing. **Navid Aslfattahi:** Validation, Writing-review & editing. **Eko Indrawan:** Writing-review & editing. **Athaya Ramadhan:** Writing-review & editing. **Zainal Abadi:** Writing-review & editing.

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Ethical clearance

This research does not involve humans as subjects; thus, approval from the ethics committee was not required.

AI statement

The article is the author's original work. The authors have thoroughly reviewed the accuracy and relevance of the statements in relation to the study's topic and data, and no AI-generated content has been included in the manuscript.

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