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Recent Trends in Electrospun Polycaprolactone Nanofibers: A Five-Year Bibliometric Perspective from 2019 to 2023

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Abstract: Nanofiber materials have emerged as a focal point of advanced research due to their exceptional properties. Polycaprolactone, a biodegradable and biocompatible polyester, has garnered particular interest for applications spanning tissue engineering, drug delivery, wound healing, and filtration. The electrospinning process facilitates precise control over PCL nanofiber morphology and functionality, enhancing its application potential. This investigation employs bibliometric analysis to elucidate global research trends in electrospun PCL nanofibers from 2019 to 2023. Utilizing the Scopus database, 255 relevant publications were identified through rigorous inclusion criteria, focusing on works that address PCL nanofibers, are published in English, and meet peer-reviewed standards. Quantitative tools, including VOSviewer and Harzing's Publish or Perish, were utilized to analyze research trajectories, citation dynamics, and collaborative networks. Results underscore a predominant focus on biomedical applications, particularly drug delivery and tissue engineering. Geographically, research contributions are led by the Netherlands (28.63%), the United States (25.10%), and the United Kingdom (24.31%). The International Journal of Biological Macromolecules emerged as the most influential journal, contributing 22 articles (10%) and receiving 1,424 citations. Despite significant advancements, critical gaps remain, notably in scaling production processes and diversifying applications beyond the biomedical domain.

Keywords: Citation; Networks; Overview; Publication; Research

Introduction

The development of nanofiber materials has drawn significant academic and industrial interest due to their unique attributes, including a high surface area-to-volume ratio, adjustable porosity, and extensive functionalization potential. Polycaprolactone (PCL) has emerged as a standout material among the various polymeric candidates for nanofiber fabrication. PCL is lauded as a biodegradable synthetic polyester for its exceptional biocompatibility, mechanical resilience, and ease of processing (Mohandesnezhad et al., 2020; Raj Preeth et al., 2021). These intrinsic properties position PCL as a versatile material suitable for diverse applications such as tissue engineering, drug delivery systems, wound healing, and filtration technology (Cui et al., 2022; Hwang et al., 2019). Electrospinning, the dominant technique for generating PCL nanofibers, employs electrostatic forces to create ultrafine fibers from polymer solutions or melts (Eren Boncu et al., 2022; Yalcinkaya, 2019). This technique offers unparalleled control over nanofiber morphology and properties through carefully modulating parameters such as polymer concentration, applied voltage, and solvent system composition (Liang Ma et al., 2019; Yalcinkaya, 2019). Over time, these optimizations have propelled the development of PCL nanofibers tailored for specific applications, driving rapid advancements in this field.

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In the biomedical domain, PCL nanofibers exhibit transformative capabilities. For instance, PCL's slow degradation profile and inherent biocompatibility render it an ideal candidate for scaffolds in tissue engineering, exemplified by its applications in cartilage regeneration and vascular growth. Electrospun PCL scaffolds promote cellular adhesion, proliferation, and differentiation, fostering tissue regeneration (Liang Ma et al., 2019; Sadeghianmaryan et al., 2020). Furthermore, PCL nanofibers are extensively employed in drug delivery systems, where their high surface area supports controlled and sustained drug release, enhancing therapeutic outcomes. However, significant challenges remain, such as the scalability of electrospinning processes, functionalization for specific applications, and addressing environmental concerns associated with synthetic polymers (Fahimirad et al., 2021a; Zhang et al., 2021). Resolving these challenges is critical to ensuring PCL nanofiber technology's sustainable growth and impactful evolution.

Bibliometric analysis offers a robust framework for systematically examining a research field's progression and current state (Abduh et al., 2023; Zaidi & Azmi, 2024). By processing extensive datasets of academic publications, bibliometric methodologies elucidate publication trends, key contributors, leading journals, and collaborative networks. This analytical approach is particularly advantageous for rapidly growing domains like PCL nanofiber research, where the literature volume often surpasses traditional reviews' capacity (Lim & Kumar, 2024). Additionally, bibliometric studies identify emerging research themes, highlight unaddressed gaps, and provide strategic direction for future investigations (Munir et al., 2022; Öztürk, Kocaman, & Kanbach, 2024).

Despite its potential, a focused bibliometric analysis of PCL nanofiber applications remains absent. Existing studies in nanotechnology and polymer science typically neglect the nuanced dynamics of this specialized area. To address this gap, the current study conducts an in-depth bibliometric analysis of PCL nanofiber research, emphasizing its diverse applications. This research seeks to answer pivotal questions: What are the prevailing trends in annual publication outputs? Which research areas receive the most attention? How is the geographical distribution of research structured, and which journals serve as primary dissemination platforms? Moreover, this study investigates highly cited works to identify influential contributions. The findings aim to provide actionable insights for researchers and policymakers by addressing these aspects, optimizing resource allocation, and shaping the future trajectory of PCL nanofiber research.

This study's novelty lies in its dedicated bibliometric exploration of PCL nanofibers, a dimension largely unexplored in prior research. By elucidating dominant trends, research voids, and emerging directions, this work enhances the understanding of the field's evolution and underscores its significance for future advancements. The study consolidates existing knowledge and charts innovative pathways, solidifying its contribution to advancing the applications of PCL nanofibers.

Method

This study systematically evaluates the scientific literature on electrospun nanofiber polycaprolactone through a bibliometric analysis framework. This approach identifies key contributors, such as individuals, institutions, and nations, while mapping interconnections among research outputs within the field. Furthermore, bibliometric analysis enables an in-depth assessment of influence by highlighting highly cited documents, prominent authors, leading institutions, impactful countries, and influential source titles.

Database Utilization

The Scopus database was selected as the foundational resource for accessing relevant publications on electrospun nanofiber polycaprolactone. Recognized for its comprehensive coverage of peer-reviewed materials and citation data, Scopus was deemed optimal for this investigation (Al-Khoury et al., 2022; Duplančić Leder, Baučić, Leder, & Gilić, 2023). Data retrieval was conducted on December 22, 2023, encompassing publication year, author affiliations, subject areas, source titles, and geographic origins. The dataset spanned publications from 2019 to 2023, ensuring a contemporary overview of research trends. Supplementary data (*Supplementary data 1* and *Supplementary data 3*) enriched the analysis by providing granular insights, including annual publication trends, geographical distributions, leading journals by publication volume, highly cited documents, and keyword analyses.

Search Methods and Selection Criteria

The literature search employed the following query: TITLE ("electrospun nanofiber polycaprolactone"), targeting journal articles and conference proceedings. Scopus was selected due to its expansive scope and stringent peer-review standards. The initial query yielded 804 documents spanning 2019–2023, forming the basis for a comprehensive trend analysis. Inclusion Criteria: Topic relevance: Articles focused on electrospun nanofiber polycaprolactone. Document type: Peer-reviewed journal articles and conference papers. Language: Publications in English. Exclusion Criteria: Articles unrelated to polycaprolactone or nanofiber electrospinning. Non-peer-reviewed materials, such as editorials or book chapters. Documents not available in English. During the identification phase, duplicate entries were excluded. Subsequent filtering applied inclusion criteria emphasizing topical relevance (cellulose nanofibers), document type (articles and conference papers), and publication language (English). Documents not meeting these criteria were excluded. Screening involved title and abstract evaluations and a detailed review of full-text documents to ensure methodological and data relevance. Studies lacking substantial empirical contributions were removed. Ultimately, 255 high-quality documents were selected for analysis. This curated dataset provides a nuanced understanding of evolving research trends, key scientific contributions, and focal points within cellulose nanofiber research over the past five years.

PRISMA Flowchart

A PRISMA flowchart (Figure 1) represents the selection process, ensuring visual clarity and transparency. The flowchart outlines the document selection's identification, screening, eligibility, and inclusion stages.

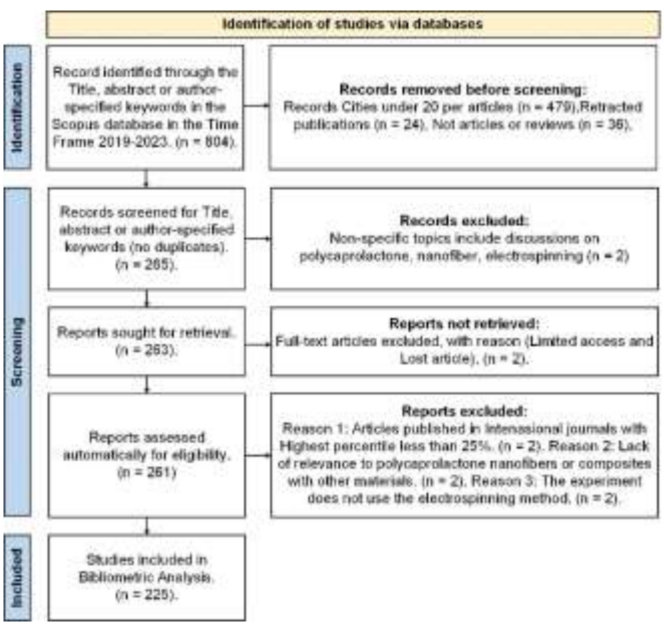

Figure 1. PRISMA flowchart illustrating the process of study selection

Software for Analysis

The collected data were systematically analyzed using specialized software tools for a thorough bibliometric analysis. Microsoft Excel organized raw data, enabling efficient categorization and sorting of key bibliometric indicators such as publication year, author contributions, journal sources, and citation counts. Harzing's Publish or Perish software was utilized for citation performance evaluation, generating metrics such as the h-index, g-index, and total citations, which are crucial for assessing research impact (Zakaria et al., 2021). To gain deeper insights into the research landscape, VOSviewer was applied for network visualization, including co-authorship, keyword co-occurrence, and citation network analysis. This process identified prominent authors, recurring themes, and influential articles within the electrospun nanofiber polycaprolactone domain (Munir et al., 2022; Setiyo, Yuvenda, & Samue, 2021). Specific clustering algorithms in VOSviewer further elucidated relationships among contributors and thematic clusters, revealing the field's structural composition and collaborative dynamics. Through this integrative approach, the analysis uncovered publication trends and patterns and highlighted influential contributions and potential gaps in the literature. This comprehensive exploration provided valuable insights into the domain's evolution and emerging research directions.

Result and Discussion

Publications by Year

Table 1 provides a detailed analysis of publication and citation metrics in research, evaluated using bibliometric indicators from 2019 to 2023. The complete analysis results are available in *Supplementary data 2*. Key metrics, including Total Publications (TP), Total Citations (TC), Annual Contribution Percentage to Citations (Per), Citations Per Publication (C/P), h-index, and g-index, offer insights into research trends and impact over this period (Punj et al., 2023). The number of publications (TP) varied considerably, peaking at 69 articles in 2020 and declining to 36 in 2022 and 22 in 2023. This reduction may reflect natural fluctuations in research output or changes in publication strategy within the domain. However, publication volume alone does not definitively measure research quality (Al-Khoury et al., 2022; Setiyo et al., 2021). Regarding TC, articles from earlier years, such as 2019, have accumulated significantly more citations (3766) than those published in 2023 (852). This observation aligns with the common bibliometric trend that older publications generally receive more citations due to their more extended availability (Alfawareh & Al-Kofahi, 2024; Santoso et al., 2022). Nevertheless, the relevance of more recent publications remains evident, as reflected in other metrics.

The percentage contribution to total citations (Per) decreased steadily from 24.80% in 2019 to 8.66% in 2023, highlighting the dominance of earlier publications in citation metrics due to their foundational contributions. Conversely, the C/P metric declined from 59.78 in 2019 to 38.73 in 2023. Despite the decline, these values underscore individual articles' continued relevance and influence (Abduh et al., 2023; Duplančić Leder et al., 2023). The h-index and g-index, which reflect research productivity and cumulative impact, also decreased over the years. For instance, the h-index dropped from 38 in 2019 to 20 in 2023, consistent with the limited citation window for recent articles. Interestingly, the C/Y metric peaked in 2023 at 852 despite a reduced publication count. This suggests that newer studies are gaining more attention, highlighting their alignment with current research priorities.

Table 1. Annual Publication and Citation Metrics on Electrospun PCL Nanofibers (2019–2023)

Year	TP	TC	Per (%)	C/Y	C/P	h	g
2019	63	3766	24.80	753	59.78	38	61
2020	69	3292	27.17	823	47.71	37	54
2021	64	2726	25.20	909	42.59	31	49
2022	36	1392	14.17	696	38.67	26	36
2023	22	852	8.66	852	38.73	20	22

Subject Area

Figure 2 illustrates the distribution of subject areas, clearly representing dominant research trends from 2019 to 2023. The detailed analysis results are summarized in *Supplementary data 2*. Several key subjects underscore the multifaceted applications of electrospun PCL nanofibers across diverse sectors. Biology and Medicine account for 28.24% of the total contributions and represents the largest share. This predominance highlights the pivotal role of PCL nanofibers in biomedical applications, driven by the growing demand for advanced materials in tissue engineering and regenerative medicine. Within this field, research has increasingly focused on scaffolds for tissue regeneration, leveraging PCL's biodegradability and biocompatibility to promote cellular growth and repair (Arampatzis et al., 2021; Fahimirad et al., 2023). Additionally, controlled drug release systems remain a significant subtopic, where the ability of PCL nanofibers to encapsulate therapeutic agents and release them in a sustained manner addresses critical challenges in chronic disease management (Güneş et al., 2022; Xu et al., 2022). Recent studies indicate a trend toward integrating nanotechnology with PCL scaffolds to enhance performance, such as incorporating bioactive molecules or nanoparticles to improve tissue integration and functionality.

Pharmaceutical Science and Pharmacology, the second-largest subject area at 19.22%, reflects the importance of nanofibers in drug delivery systems. The unique structural characteristics of PCL nanofibers, including their high surface area and tunable porosity, enable precise drug release profiles, making them particularly advantageous for treating chronic conditions such as cancer and diabetes (Anand et al., 2022). The development of innovative drug delivery technologies remains a key research focus, with recent trends emphasizing the design of multifunctional nanofibers that combine therapeutic and diagnostic capabilities (Mashayekhi et al., 2020; Venugopal et al., 2019). Concurrently, there is a growing emphasis on evaluating PCL nanofibers' long-term toxicity and biocompatibility to ensure their safety for human use, underscoring an emerging subtopic within this domain.

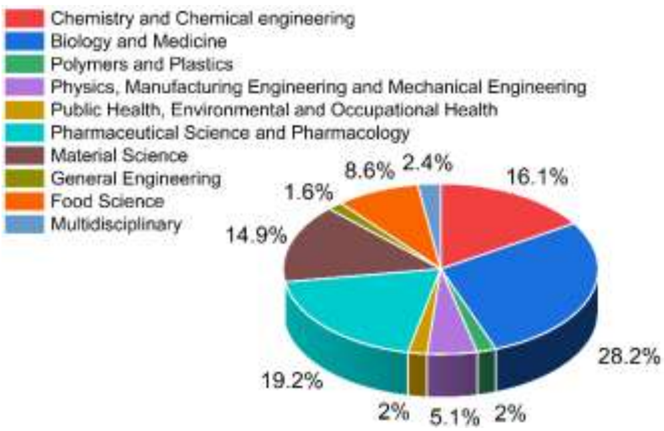

Figure 2. Illustrates a bar chart representing the distribution of research subject areas identified in the bibliometric analysis of electrospun PCL nanofibers (2019–2023)

Material Science contributes 14.90%, highlighting the exploration of fundamental material properties in nanofibers. Research in this field has made significant strides in enhancing PCL nanofibers' mechanical, chemical, and physical performance. For instance, recent innovations include the incorporation of reinforcements such as nanoparticles and cross-linking agents to improve tensile strength and elasticity. Studies also focus on optimizing fabrication techniques, such as electrospinning parameters, to achieve uniform fiber morphology and consistency (Bhattarai et al., 2019; Chen et al., 2021; El-Naggar et al., 2021). These advancements facilitate the integration of PCL nanofibers into various industrial and technical applications, such as filtration, protective textiles, and structural composites.

Chemistry and Chemical Engineering account for 16.08%, emphasizing the critical role of chemical synthesis and modification in advancing PCL nanofibers. Efforts to enhance material properties such as hydrophilicity, mechanical strength, and antimicrobial activity have driven research in this field (Lanno et al., 2020; Tian et al., 2022). Modifying PCL nanofibers using surface functionalization and blending techniques has opened new avenues for their application in fields such as wound healing and environmental remediation. The substantial proportion of this field in the distribution indicates that chemistry-driven advancements continue to play a pivotal role in expanding the versatility and applicability of PCL nanofibers.

Food Science, representing 8.63%, signifies the potential applications of nanofibers in the food industry. Research has increasingly explored using PCL nanofibers for active food packaging, focusing on their antimicrobial properties and ability to enhance protection against spoilage (Beikzadeh et al., 2021). Although smaller compared to other domains, this contribution reflects a diversification of applications, particularly in addressing sustainability challenges through biodegradable and eco-friendly packaging solutions (Bandatang et al., 2021). Emerging trends include developing innovative packaging systems that monitor food quality and safety.

Smaller contributions from Physics, Manufacturing Engineering, and Mechanical Engineering (5.10%) and Public Health, Environmental, and Occupational Health (1.96%) remain valuable. Research in these areas often examines technical aspects of nanofibers, including advanced manufacturing processes to achieve large-scale production and sustainability assessments to minimize environmental impact (Hussain et al., 2022; Ullah et al., 2023). Multidisciplinary applications (2.35%) further underscore the adaptability of PCL nanofibers, particularly in cross-disciplinary projects involving energy storage, water purification, and environmental science (Do Pham et al., 2021; Lan Ma et al., 2021).

Geographical Distribution of Journal Publications

Figure 3 presents the geographical distribution of journal publications, revealing notable concentrations in specific countries. The detailed analysis results are summarized in *Supplementary data 2*. These data provide insights into the global contributions to PCL nanofiber research. The Netherlands leads with 28.63% of total publications. This leadership is facilitated by advanced research infrastructure and robust academia-industry collaborations (Nierse et al., 2012). The focus on sustainable and application-oriented material innovations also bolsters the Netherlands' standing in this domain. The United States ranks second, contributing 25.10% of publications. Renowned for its advanced research ecosystem, the U.S. encompasses numerous leading institutions actively engaged in nanotechnology and biomedical research (Kwiek, 2021). U.S. studies span diverse applications, including biomedical, pharmaceutical, and materials engineering, reflecting the broad utility of PCL nanofibers. The United Kingdom is third with a 24.31% contribution. As a global academic hub, the U.K. hosts influential universities and research institutions. Research from the UK (Kwiek, 2021). Predominantly focuses on biomedical applications of PCL materials, particularly in tissue engineering and drug delivery.

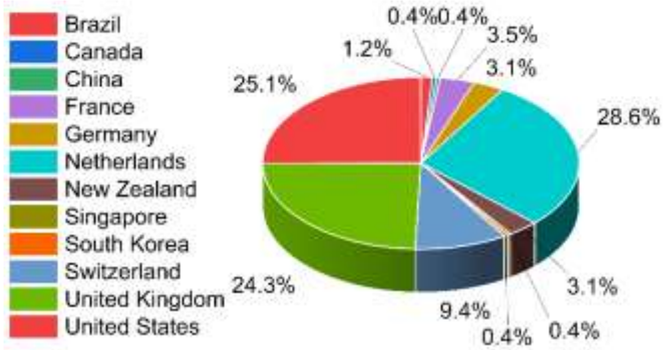

Figure 3. The geographical distribution of journal publications on electrospun PCL nanofibers (2019–2023) is presented, highlighting key publishing regions and countries contributing to the research field

Switzerland accounts for 9.41%, a significant share given its small size. Renowned research institutions and substantial funding for innovation, coupled with ties to the pharmaceutical sector, position Switzerland as a key player in advancing biomedical and pharmaceutical applications (Guignard & Bugnon, 2006). Germany and New Zealand each contribute 3.14% of publications. Germany's contributions reflect its expertise in engineering and material sciences, emphasizing material characterization and industrial applications (Danzon & Ketcham, 2004). Despite its smaller research footprint, New Zealand excels in innovative studies, often in collaboration with other countries, particularly in biotechnology and agriculture. France, with a contribution of 3.53%, focuses on the biomedical applications and material properties of PCL nanofibers. Countries such as Brazil, Canada, China, Singapore, and South Korea contribute smaller percentages, ranging from 0.39% to 1.18%. Although their contributions are modest, these nations play critical roles as collaborators in global research endeavors (Kwiek, 2021; Nierse et al., 2012). Their studies address varied focuses, from localized applications to pioneering innovations that enrich the global knowledge base.

Preferred Journals

Table 4 provides an analysis of journals contributing to the field of macromolecular research, evaluated through metrics such as total publications

(TP), percentage contribution (Per%), total citations (TC), Cite Score, SJR, and SNIP. This evaluation underscores the distinctive roles of these journals in advancing the discipline. The International Journal of Biological Macromolecules (2024) leads with 22 publications (10%) and 1,424 citations, complemented by a Cite Score of 13.7, SJR of 1.245, and SNIP of 1.462. This journal's focus on biological macromolecules aligns with contemporary research priorities, and its high citation count reflects its significant influence in the field.

The International Journal of Pharmaceutics (2024) ranks second, contributing 14 publications (6%) and 810 citations. With a Cite Score of 10.7, SJR of 0.954, and SNIP of 1.132, it plays a critical role in pharmaceutical sciences, particularly in drug development and delivery. Despite slightly lower metrics than the leading journal, its contributions remain essential. Carbohydrate Polymers (2024), with 10 publications (4%) and 826 citations, achieves the highest Cite Score (22.4), SJR (1.831), and SNIP (1.807) among the listed journals. This journal's specialization in polysaccharides and related materials serves a broad and impactful research community, spanning disciplines like materials science and biochemistry.

Table 2. Top 10 Journals Contributing to Publications (2019–2023)

Source Title	TP	Per (%)	TC	Publisher	Cite Score	SJR 2023	SNIP 2023
International Journal of Biological Macromolecules	22	10%	1424	Elsevier	13.7	1.245	1.462
International Journal of Pharmaceutics	14	6%	810	Elsevier	10.7	0.954	1.132
Carbohydrate Polymers	10	4%	826	Elsevier	22.4	1.831	1.807
Acta Biomaterialia	10	4%	638	Acta Materialia Inc.	16.8	1.925	1.561
Journal of Drug Delivery Science and Technology	9	4%	274	Editions de Sante	8.0	0.719	0.918
ACS Applied Materials and Interfaces	8	4%	406	American Chemical Society	16.0	2.058	1.283
International Journal of Nanomedicine	8	4%	279	Dove Medical Press	14.4	1.273	1.250
Journal of Biomedical Materials Research-Part B	6	3%	162	John Wiley & Sons	7.5	0.634	0.793
Scientific Reports	6	3%	157	Springer Nature	7.5	0.900	1.182
Journal of Biomedical Materials Research-Part A	5	2%	181	John Wiley & Sons	10.4	0.807	0.846

Acta Biomaterialia (2024), with 10 publications (4%) and 638 citations, further exemplifies excellence in biomaterials research, boasting a Cite Score of 16.8, SJR of 1.925, and SNIP of 1.561. The (Journal of Drug Delivery Science and Technology (2024) contributes nine publications (4%) and 274 citations, with a Cite Score of 8.0, SJR of 0.719, and SNIP of 0.918. While its metrics are modest, its emphasis on drug delivery systems ensures its relevance to macromolecular and pharmaceutical applications. ACS Applied Materials and Interfaces (2024) and the International Journal of Nanomedicine (2024) each contribute eight publications (4%). The former strongly influences applied materials research with 406 citations, a Cite Score of 16.0, and an SJR of 2.058. With 279 citations, a Cite Score of 14.4, and an SJR of 1.273, the latter highlights its contributions to nanotechnology and medicine, particularly macro-nanocarriers.

The Journal of Biomedical Materials Research - Part B (2024) and Scientific Reports each contribute six publications (3%). The former, with 162 citations and metrics including a Cite Score of 7.5, SJR of 0.634, and SNIP of 0.793, focuses on biomedical materials. With 157 citations, the latter offers a broader scope yet supports macromolecular research with a Cite Score of 7.5, SJR of 0.900, and SNIP of 1.182. Finally, the Journal of Biomedical Materials Research - Part A (2024) contributes five publications (2%) and 181 citations, with a Cite Score of 10.4, SJR of 0.807, and SNIP of 0.846.

Highly Cited Papers

Highly cited papers are pivotal in evaluating research impact, representing the most influential contributions within a field. Table 3 identifies the 10 most cited papers between 2019 and 2023, showcasing notable biomedical applications and food packaging advancements. These studies emphasize functional property enhancement and broaden the scope of PCL nanofiber applications. Fahimirad et al. (2021) lead with 216 citations, reflecting a citation rate 72 per year. Their research explores PCL/chitosan-based nanofibers combined with curcumin-loaded nanoparticles for wound healing (Fahimirad et al., 2021a). This study demonstrates how bioactive compounds enhance nanofibers' antimicrobial and anti-inflammatory properties, addressing key challenges in regenerative medicine. Li et al. (2019) garnered 195 citations for their work on nanofiber-hydrogel composites designed to improve angiogenesis in soft tissue reconstruction. This research highlights the synergy between nanofibers and hydrogels to replicate extracellular matrix (ECM) structures, facilitating vascularization and tissue regeneration (X. Li et al., 2019a). Similarly, Wang et al. (2019) achieved 165 citations for developing conductive, aligned core-shell biomimetic scaffolds tailored for nerve tissue engineering. By leveraging nanofiber threads and hydrogels, this study advances biomimetic materials to support neurite growth and alignment, addressing critical needs in nerve regeneration therapy (Wang et al., 2019a).

Table 3. Top 10 Highly Cited Papers (2019–2023)

First Author	Title	Year	Cites	Cites Per Year
(Fahimirad et al., 2021b)	Wound healing performance of PCL/chitosan based electrospun nanofiber electrosprayed with curcumin loaded chitosan nanoparticles	2021	216	72.0
(Li et al., 2019)	Nanofiber-hydrogel composite–mediated angiogenesis for soft tissue reconstruction	2019	195	39.0
(Wang et al., 2019)	Aligned conductive core-shell biomimetic scaffolds based on nanofiber yarns/hydrogel for enhanced 3D neurite outgrowth alignment and elongation	2019	165	33.0
(Eskandarinia et al., 2020)	A Novel Bilayer Wound Dressing Composed of a Dense Polyurethane/Propolis Membrane and a Biodegradable Polycaprolactone/Gelatin Nanofibrous Scaffold	2020	144	36.0
(Ajmal et al., 2019)	Biomimetic PCL-gelatin based nanofibers loaded with ciprofloxacin hydrochloride and quercetin: A potential antibacterial and anti-oxidant dressing material for accelerated healing of a full thickness wound	2019	141	28.2
(Adeli-Sardou et al., 2019)	Controlled release of lawsone from polycaprolactone/gelatin electrospun nano fibers for skin tissue regeneration	2019	139	27.8
(Sadeghi et al., 2019)	Investigating the effect of chitosan on hydrophilicity and bioactivity of conductive electrospun composite scaffold for neural tissue engineering	2019	139	27.8
(Liang et al., 2020)	Implantable and degradable antioxidant poly(ε-caprolactone)-lignin nanofiber membrane for effective osteoarthritis treatment	2020	130	32.5
(Hasanpour Ardekani-Zadeh & Hosseini, 2019)	Electrospun essential oil-doped chitosan/poly(ε-caprolactone) hybrid nanofibrous mats for antimicrobial food biopackaging exploits	2019	126	25.2
(Zou et al., 2020)	Electrospun chitosan/polycaprolactone nanofibers containing chlorogenic acid-loaded halloysite nanotube for active food packaging	2020	124	31.0

In wound care, Eskandarinia et al. (2020) introduced a bilayer wound dressing combining dense polyurethane/propolis membranes with PCL/gelatin nanofiber scaffolds, earning 144 citations. This innovation enhances wound healing through mechanical robustness and bioactivity (Eskandarinia et al., 2020). Similarly, Ajmal et al. (2019) developed antibacterial and antioxidant PCL-gelatin nanofibers loaded with ciprofloxacin hydrochloride and quercetin, achieving 141 citations. By integrating therapeutic agents, these nanofibers accelerate healing and mitigate infection risks, addressing gaps in wound management technologies (Ajmal et al., 2019). Research by Adeli-Sardou et al. (2019) and Sadeghi et al. (2019) focuses on controlled release systems and enhanced bioactivity. Adeli-Sardou et al. earned 139 citations for their work on PCL/gelatin nanofibers loaded with lawsone for skin tissue regeneration (Adeli-Sardou et al., 2019). Sadeghi et al., with an equivalent citation count, investigated chitosan-functionalized electrospun scaffolds for nerve tissue engineering, demonstrating improved hydrophilic properties and bioactivity (Sadeghi et al., 2019).

In the field of food packaging, Liang et al. (2020), Hasanpour Ardekani-Zadeh and Hosseini (2019), and Zou et al. (2020) made substantial contributions to sustainable and bioactive materials. Liang et al. developed antioxidant PCL-lignin nanofibers for osteoarthritis treatment, attracting 130 citations. Hasanpour Ardekani-Zadeh and Hosseini received 126 citations for antimicrobial chitosan/PCL hybrid mats, while Zou et al. earned 124 citations for their work on chlorogenic acid-loaded PCL nanofibers designed for active food packaging (Hasanpour Ardekani-Zadeh & Hosseini, 2019; Liang et al., 2020; Zou et al., 2020).

Keyword Analysis

A bibliometric review of electrospun polycaprolactone (PCL) nanofibers reveals key themes through keyword network analysis. Using VOSviewer, three primary clusters emerge, as illustrated in Figure 4. These clusters—red, green, and blue—represent distinct but interconnected domains in PCL research. The red cluster focuses on "tissue engineering," "proliferation," "adhesion," and "stem cell," underscoring the use of PCL in tissue regeneration via nanofiber scaffolds. Tissue engineering aims to construct biomimetic structures replicating natural ECM, supporting optimal cell proliferation and differentiation (Ghomi et al., 2023; Jin et al., 2019; Mashayekhi et al., 2020). PCL's capacity to promote cell adhesion makes it a staple scaffold material in stem cell-based therapies. Research indicates that mechanical properties, such as elasticity modulus and tensile strength, can be tailored by adjusting electrospinning parameters, including electric voltage, polymer solution flow rate, and solvent concentration (Khunová et al., 2022; Y. Li et al., 2019). Enhancements in biocompatibility are often achieved by combining PCL with other materials, such as collagen or gelatin, or through chemical modifications that improve cell adhesion and accelerate tissue regeneration.

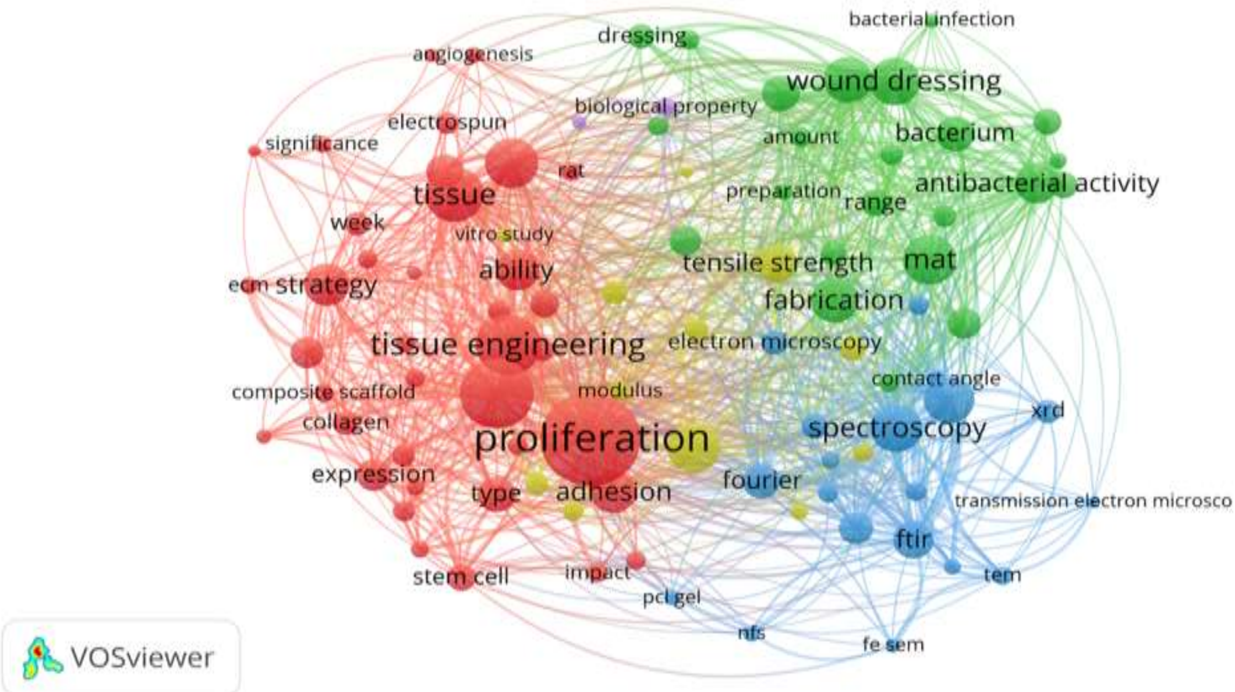

Figure 4. Network visualization of keyword co-occurrence from bibliometric analysis on electrospun nanofiber polycaprolactone research

The green cluster emphasizes "wound dressing," "antibacterial activity," and "bacterium," reflecting the medical applications of electrospun PCL nanofibers. In modern wound dressings, PCL's lightweight and flexible nature and ECM-like properties provide an optimal environment for skin cells to migrate, proliferate, and regenerate damaged tissues (Bandatang et al., 2021; Hassan et al., 2021). Research in this cluster often integrates active components, such as silver nanoparticles, chlorhexidine, or essential oils, to impart antibacterial properties to nanofibers. This approach is critical in treating chronic or infected wounds where bacterial infection impedes healing. By reducing infection risks and accelerating tissue regeneration, PCL-based wound dressings demonstrate significant therapeutic potential (Farzaei et al., 2023; Hassan et al., 2021). Mechanical properties, including tensile strength and absorbency, remain central to developing these advanced wound dressings.

The blue cluster addresses technical aspects and material characterization methodologies. Keywords such as "spectroscopy," "FTIR," "electron microscopy," and "transmission electron microscopy" highlight techniques used to analyze the physical and chemical properties of PCL nanofibers (Daelemans et al., 2021). Fourier-transform infrared (FTIR) spectroscopy, for instance, confirms the presence of specific chemical functional groups, ensuring that modifications do not compromise the fundamental properties of PCL. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) provide detailed insights into nanofiber morphology, including diameter distribution and structural homogeneity (Ajmal et al., 2019; Fahimirad et al., 2021). Mechanical characterization, such as elasticity modulus and tensile strength, is also prominent in this cluster. Techniques like tensile testing and contact angle measurements help assess the physical properties of nanofibers, including hydrophobicity. At the same time, PCL's inherent hydrophobicity can hinder biological interactions, chemical modifications, or the incorporation of hydrophilic materials, which often address this limitation.

Conclusion

This paper employs bibliometric analysis to provide a comprehensive overview of the developments, trends, and research prospects related to electrospun polycaprolactone (PCL) nanofibers. The number of publications on PCL nanofibers has experienced fluctuations from 2019 to 2023, peaking in 2020 with 69 articles. However, the subsequent decline in 2022 and 2023 suggests a potential shift in research focus or publication trends. While speculative, this trend highlights the need to explore evolving research priorities. Notably, the quality of recent publications remains high, as evidenced by citation metrics. Biomedical applications dominate research on PCL nanofibers, with Biology and Medicine contributing the largest share (28.24%). Pharmaceutical Science and Pharmacology (19.22%) also play a pivotal role, underscoring the material's significance in drug delivery systems. Additionally, Material Science, Chemistry, and Chemical Engineering contribute substantially to enhancing nanofiber properties, reflecting interdisciplinary efforts to advance the material's applications—geographically, the Netherlands, the United States, and the United Kingdom lead research output. The Netherlands ranks highest (28.63%), followed by the United States (25.10%) and the United Kingdom (24.31%). These nations leverage robust research infrastructures and international collaborations to drive innovation in PCL nanofibers. Key journals supporting the dissemination of PCL nanofiber research include the International Journal of Biological Macromolecules, which has published 22 articles (10% of the total) and amassed 1,424 citations. Other significant contributors include the International Journal of Pharmaceutics, Carbohydrate Polymers, and Acta Biomaterialia. This analysis highlights the current state of PCL nanofiber research and its implications. Future studies should address emerging applications and potential technological advancements, ensuring the field continues to evolve to meet biomedical and industrial demands.

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Conflicts of Interest
"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."

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