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Advances and Prospects of Carbon Nanotubes in Cancer Research: Drug Delivery, Therapeutics, and Diagnostics

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Islam Hamad[1,*], Amani Harb[2], Shrouq Twal[1], Adi I Arida[1], Amal Mayyas[1], Rula Amr[3], Nour Bustanji[4], Mona Al Olabi[5], Yasser Bustanji[4,6]

1. Department of Pharmacy, Faculty of Health Sciences, American University of Madaba, Madaba 11821, Jordan
2. Department of Allied Sciences, Faculty of Arts and Sciences, Al-Ahliyya Amman University, Amman 19111, Jordan
3. Department of Nutrition and Health Psychology, Faculty of Health Sciences, American University of Madaba, Madaba, Jordan
4. School of Pharmacy, The University of Jordan, Amman 11942, Jordan
5. Faculty of Pharmacy and Medical Sciences, University of Petra, Amman 1196, Jordan
6. College of Medicine, University of Sharjah, Sharjah 27272, United Arab Emirates

* i.hamad@aum.edu.jo

ABSTRACT

Background: Carbon nanotubes (CNTs) have gained significant attention in cancer therapy due to their unique physicochemical properties, including a high surface area- to- volume ratio, mechanical strength, and nanoscale interactions with biological systems. Their versatility has advanced drug delivery, photothermal therapy, and targeted cancer treatments. This study employs bibliometric analysis to examine global research on CNT applications in oncology.

Methods: A comprehensive Scopus search identified 1,221 English-language, peer- reviewed publications published between 2003 and 2024. Bibliometric indicators were analyzed using Biblioshiny and VOSviewer, generating visualization, thematic, and conceptual maps.

Results: Findings show that Chinese researchers lead in publication output, while the United States has the greatest scientific impact. Keyword mapping identified key research areas and emerging trends, including CNT-based drug delivery, tumor- targeting strategies, photothermal and photodynamic therapies, and biosensing applications.

Conclusion: This study provides a comprehensive bibliometric analysis of global research trends on CNT applications in oncology, highlighting key research areas, collaborations, and emerging directions.

INTRODUCTION

Carbon nanotubes, which are cylindrical nanostructures comprised of carbon atoms arranged in a hexagonal lattice, are garnering considerable interest among researchers owing to their remarkable and tunable properties. These characteristics have led to widespread applications across various fields, including electronics, medicine, material science, and energy storage [1-4]. In particular, carbon nanotubes are of great scientific interest due to their exceptional mechanical strength, high electrical and thermal conductivity, and large surface area, making them highly valuable for biomedical applications, including drug delivery, biosensing, and tissue engineering [5-9].

The integration of carbon nanotubes into cancer therapy represents a transformative shift in nanomedicine. Their exceptional properties, that include high surface area, structural stability, and the ability to functionalize with therapeutic agents, have positioned them as promising candidates for targeted drug delivery, photothermal therapy, and imaging applications [10-13]. The controlled functionalization of carbon nanotubes enables their use as carriers for anticancer drugs, improving bioavailability and reducing off- target effects. Additionally, their strong optical absorption in the near-infrared region allows for effective photothermal therapy, where localized heating can selectively destroy cancerous cells while minimizing damage to surrounding healthy tissues [14-17].

One of the most significant applications of carbon nanotubes in cancer therapy is their role in drug delivery systems. The ability of these nanomaterials to encapsulate or covalently bind anticancer drugs offers several advantages over conventional chemotherapy [18-21]. Carbon nanotubes can protect drugs from premature degradation, enhance their solubility, and facilitate controlled and sustained release, thereby increasing therapeutic efficacy. Their high surface area allows for the attachment of multiple drug molecules, imaging agents, or targeting ligands, enabling multifunctional therapeutic platforms [22,23]. Moreover, functionalized carbon nanotubes can be engineered to respond to specific physiological conditions, such as pH or enzymatic activity, ensuring that the drug is released at the tumor site with minimal systemic toxicity [24-27].

Beyond passive drug accumulation through the enhanced permeability and retention effect, active targeting strategies have been developed by conjugating carbon nanotubes with tumor-specific ligands, such as antibodies, peptides, or small molecules that recognize overexpressed receptors on cancer cells [28-31]. This targeted approach significantly improves drug selectivity and reduces the risk of adverse side effects associated with traditional chemotherapeutics [29,32,33]. Additionally, carbon nanotubes have demonstrated potential as gene delivery vectors, facilitating the transport of genetic material into cells for applications in gene therapy and immunotherapy [22,34-36].

Various approaches have been explored to enhance the biocompatibility and efficiency of carbon nanotubes in medical applications. These include chemical functionalization strategies that improve their dispersibility in biological environments, hybrid nanostructures that combine carbon nanotubes with biopolymers or metal nanoparticles, and targeted delivery systems that exploit ligand- receptor interactions for improved cellular uptake [37-50]. The continuous refinement of these methodologies aligns with the broader goals of advancing precision medicine and minimizing potential risks associated with nanomaterials in clinical settings.

Given the growing interest in the role of carbon nanotubes in cancer therapy, it is essential to perform a comprehensive analysis of the current research landscape. Examining key advancements, notable contributions, and emerging trends in this field offers significant insights into both the scientific progress and the translational potential of these nanomaterials in oncology. Additionally, considering significant literature underscores industrial developments and practical applications of carbon nanotube- based cancer therapies, complementing the perspectives from academic research [3].

The purpose of this bibliometric study is to examine the state of research on carbon nanotubes in cancer therapy. The following sections will explore the advantages of carbon nanotubes in addressing the limitations of conventional cancer treatment strategies, their diverse applications in therapeutic and diagnostic modalities, and the critical considerations regarding their safety and biocompatibility. Furthermore, this study provides an overview of the methodological approach used to examine bibliometric trends, key contributors, and future directions in this rapidly evolving domain. By analyzing publication trends, collaboration networks, and citation patterns, this work seeks to present a nuanced understanding of the field, offering insights that may inform future research and clinical translation efforts [51-55].

Despite extensive experimental and clinical studies on carbon nanotubes in cancer therapy, there remains a lack of comprehensive bibliometric analyses that map global research trends, collaborations, and emerging themes in this field. Therefore, this study aims to fill this gap by providing a systematic bibliometric evaluation.

METHODS

Search plan and refinement of the acquired papers

A search of the Scopus database was carried out on February 5th, 2025, to identify and assess global research outputs related to the application of carbon nanotubes in cancer therapy over the past two decades. The search term ("carbon nano*" OR "carbon-nano*" OR "carbon AND nanotube*") AND ("Cancer") encompassed abstracts, keywords, and titles.

Only research articles published between 2003 and 2024 in English-language, peer-reviewed journals were included. The search excluded materials such as letters, press releases, notes, editorials, errata, reviews, conference articles, and other publishing forms. Book chapters, conference proceedings, as well as publications in books were additionally excluded.

Data Export

The collected documents went through conversion into CSV file format for the purpose of further examination. The analyzing of bibliometric data demanded a usage of the Microsoft Office Excel 365 (Microsoft Corporation, Redmond, WA, USA) in addition to Scopus platform. This facilitated the collection of information throughout numerous disciplines of study as well as publishing journals.

Data Visualization and Bibliometric Analysis

The latest released version of the visualization of similarities software programs, VOSviewer 1.6.20, was employed in the investigation for assessing as well as mapping collaborations, keywords, and citations within the set of collected documents. In order to elucidate author-author networking, author keywords, and international network partnerships, the VOSviewer mapping approach and also cluster analysis were utilized. To further illustrate all keywords, cluster density maps were implemented. Supplementary analyses regarding author keywords were carried out utilizing the biblioshiny program, an element of the bibliometric package[56,57]. The utilization of this software supported patterns recognition as well as focused areas evaluation by examination of trends in the author keywords [57].

Duplicate records were removed during data preprocessing. Author name inconsistencies and variations were standardized through manual verification and the use of a thesaurus file in VOSviewer. Similarly, keyword variations and synonyms were unified to ensure consistency in bibliometric mapping.

When assessing authors' bibliometric indicators, we manually verified the names and initials of distinguished researchers to ensure accuracy. Additionally, we afterwards merged authors with different initials, who had previously been categorized into two different entities, by applying a thesaurus file, resulting in unified designation. Complementary methods were implemented for investigating keywords and countries that are participating. A single term was created via the combination of synonymous or related keywords on the basis of the keyword analysis process. The implementation of the two software tools, VOSviewer and Biblioshiny, allowed it feasible to carry out such modifications [56,58].

RESULTS

Annual Publications Analysis

A comprehensive search was conducted by applying the search terms "carbon nanotubes*" AND (cancer) to collect publications pertaining to the application of CNTs in cancer therapy regarding 2003 to 2024. In total, 1221 relevant documents were retrieved from the search. A significant portion (363, equivalent to 30%) of the aforementioned documents was published in the most recent five- year time frame, which occurred between 2020 and 2024. The yearly volume of research documents constructed is shown in Figure 1.

Contributing Journals Analysis

From an assortment of about 445 Scopus- indexed peer- reviewed journals, 1221 documents were obtained. Only 25 journals published 10 or more documents. Table 1 highlights the ranks of the top 10 most frequently published as well as widely viewed journals. The Journal of Biosensors and Bioelectronics distinguishes as the most productive among the participating journals, with 31 published articles that constitute 2.5% of the total publications. The International Journal of Nanomedicine follows, having published 26 articles. As stated by Scopus, each of the top 10 journals is considered into Q1 category.

Articles Analysis

The articles selected for study reveal *h*-index of 124 as well an overall total citation number of 72,181. The average number of citations per individual document in the entire database is 59.1. In addition, citations equal to or more than 20 have been observed in a total of 710 articles. The ten documents with the most citations, accompanied by their yearly citation normalization, are shown in Table 2.

Authors Analysis

The publications that were gathered included 5,983 authors in total, having an average of 4.9 authors as per document. A sum of 54 researchers has provided substantial contributions through authoring not less than five or more publications addressing authors mentioned previously. Dai, Hongjie, has an association with the Department of Chemistry at Stanford University in USA, is recognized as one of the most prolific authors, with 16 published documents, comprising 1.3% of total publications, as well as garnering 11,356 citations.

Active Countries

In all, a total of 75 distinct countries participated in publications in this precise realm within Scopus, as revealed by the analysis throughout our study keywords. Table 3 depicts the countries with the greatest rankings based on publication volume, highlighting the 10 foremost countries. Twenty different countries were accountable for publishing 15 manuscripts and above.

According to the subject, Chinese scholars have achieved significant contributions, as evidenced by considering that they have authored 333 papers, which stands for 27 percent of the entire number of publications. 283 documents, which constitute 23% of the total publications, have been produced by researchers in the United States, who have rendered essential contributions.

Iranian researchers occupy the third place with 157 articles published to their credit; this constitutes 13% of the overall publication count. Being presented with an average of 120.7 citations as per document, American articles are acknowledged as having the highest scientific impact, outperforming United Kingdom publications in this arena.

Bibliometric mapping

International Collaboration

A significant amount of information concerning national trends in collaboration along with publication is provided by the VOSviewer software. The examination of international partnerships and collaborations was facilitated by this software, which ultimately resulted in the creation of a network visualization map (Fig. 2). As demonstrated in Figure 2A, the map resembles countries as spheres, along with the size associated with every sphere representing the quantity of publications that have been published. Figure 2B reveals, nonetheless, that citation counts in published works are greater for countries possessing larger spheres. It was determined that just 20 out of 75 countries that were reviewed matched the essential requirement of submitting not less than 15 articles from their respective countries. Each country was placed into one of four separate groupings, which served to showcase the high degree of coordination that exists between the countries that are classified into each category. Group 1, depicted in red, includes a total of seven countries. These countries are France, Germany, Spain, Poland, Italy, United Kingdom, and Singapore. Group 2, displayed in green, comprises six additional countries, including Egypt, Iran, Japan, Romania, Saudi Arabia, and Turkey. Brazil, Canada, China, and United States are the four countries that are a part of Group 3, represented in blue. Finally, group 4, shown in yellow, consisted of three countries; India, South Africa, and Taiwan. Subsequently, it has been observed that there is a high prevalence of collaborative publications that were produced by authors through the same group of countries. This is most likely due to shared interests in the scientific field. Typically, the visualization of international collaborations sheds light on patterns of worldwide cooperation and trends in publication.

Author keyword Analysis and Hotspot Forecasting

We carried out a keyword association analysis with the assistance of bibliometric tools, more notably Biblioshiny and VOSviewer, with the purpose of pinpointing the study domains that are currently being investigated in relation to the application of CNTs in cancer therapy. Author keywords were a focus of the analysis, with thesaurus file used for excluding synonyms as well at least occurrence requirement of 15 instances established.

The most frequently occurring author keywords, with each having a minimum of 15 occurrences out of 2542 author keywords, are represented in Figure 3. Figure 3A showcases a network visualization map of author keywords, featuring circular nodes that accentuate the most frequent keywords, with 15 or more occurrences. Similar-colored nodes are interconnected; as well the size of them is indicative of connections frequency.

Five distinguished clusters were created from author keywords that were identified. Single-walled carbon nanotubes, breast cancer, cytotoxicity, photothermal therapy, cancer therapy, apoptosis, and cisplatin are the seven terms collectively making Cluster 1, as denoted in red. Keywords related to multi- walled carbon nanotubes, doxorubicin, biosensor, chitosan, electrochemical sensor and gold nanoparticles are reflected in Cluster 2, as indicated in green.

Words involving carbon nanotubes, cancer, functionalization, toxicity and folic acid are featured in Cluster 3, as signified in blue. On the other hand, cluster 4, as highlighted in yellow, encompasses words that are linked to targeted drug delivery, controlled release and adsorption.

At last, Cluster 5, as illustrated in purple, features three words that are correlated with nanomedicine, nanotechnology, and lung cancer activity. Such clusters provide light on the key research subjects and areas that are pertained to the application of CNTs in cancer therapy, hence improving understanding of the predominant themes that are prevalent in this field. Thus, it should be emphasized that the results acquired from the two bibliometric softwares, Biblioshiny and VOSviewer, shown a notable similarity. The identified similarity points out that such clusters denote the primary study domains concerning the application of CNTs in cancer therapy.

Furthermore, as displayed in Figure 3B, a conceptual structural map was implemented for assessing author keywords clusters, and also biblioshiny was adopted to serve as bibliometric tool. It is intriguing that these clusters closely resemble the clusters that were previously identified, indicating that the interrelations across keywords have a significant impact on the research priorities of the field.

For a more thorough examination of the keywords that were collected, Biblioshiny was employed for constructing thematic map, as depicted in Figure 3C. In the field of bibliometrics, the use of thematic maps has become commonplace as a means of analyzing as well illustrating the diversity of subjects present in a selection of published works. The keywords that were identified were grouped into the following overarching thematic categories including, emerging, basic, niche, and motor themes. Immunosensor and gold nanoparticles are emerged prominent fields of research through niche themes. Research on these subjects was anticipated to have been particularly focused and devoted across the larger context of application of CNTs in cancer therapy. Consequently, the thematic analysis that was performed throughout this study sheds light on plenty of research topics and themes allied to this field of research.

A deeper comprehension of the authors' keyword analysis was achieved by the execution of two supplementary methods. One method was to generate a normalized overlay of the keyword clusters considering the average publication year; Figure 4A illuminates the result.

Clusters comprising the figure are color- coded pursuant to the publication dates of author keywords; keywords published recently are represented by yellow. A thorough overview of the development of multiple clusters of keywords is provided by this visualization. The second method, as illustrated in Figure 4B, utilizes the use of Biblioshiny to illustrate trending topics. In accordance to the findings of this analysis, the primary author keyword trends with regard to the field researched were electrical sensor, breast cancer, and adsorption. Through the analysis of trending topics, researchers have the ability to determine the growing preferences and goals in the application of CNTs for cancer therapy. The two methods produced results that were consistent, so underscoring the robustness of the data. The citations count displayed considerable diversity amongst different author keywords. Publishing date was utilized in order to normalize citations with the purpose to counteract the influence that the publication age has on the number of citations. This allowed for an equal comparison of various intervals of time for the author keywords that were being studied; the normalized mean number of citations is presented in Figure 4C. With the greatest normalized citation counts, the author keywords "electrical sensor," "breast cancer," along with "adsorption" demonstrated their considerable significance and impact within the scientific literature. These data furnish an in- depth comprehension of the topical foci, citation impacts, and temporal trends of author keywords in the field of CNTs applications in cancer therapy. These discoveries enrich the expanding body of knowledge while assist researchers in order to determine critical areas of interest in addition to potential directions during research in the future.

All Keywords Analysis

Correlations amongst all of the keyword words that were discovered across both the titles, and the abstracts of the scholarly articles also underwent testing in this study. The co-occurrences of these keywords are visualized using a cluster density map, as shown in Figure 4D, where each term requiring a minimum threshold of 100 occurrences to be included. Among 10,915 assessed words; merely 58 words fulfilled the requirement with 100 or more occurrences. Consequently, the cluster density map (Fig. 6) was used to illustrate these terms. There is a correlation between the intensity level among colors present on the map and occurrences frequency, whereas identical colored words suggest a noticeable association.

Figures

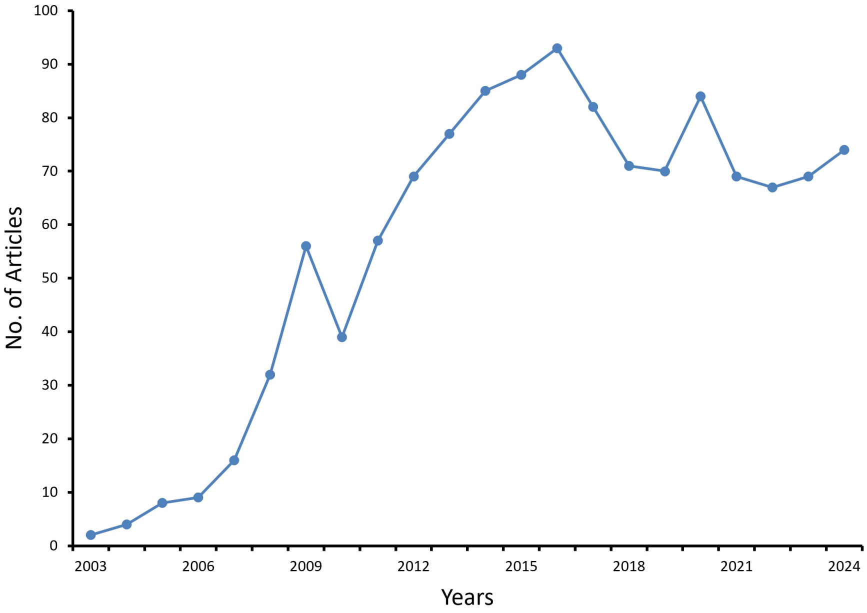


Figure 1: Annual scientific output in CNT- based cancer research. The figure illustrates the number of publications per year from 2003 to 2024 based on Scopus-indexed documents (n = 1221), highlighting the growth of research activity in CNT-related cancer studies over time.

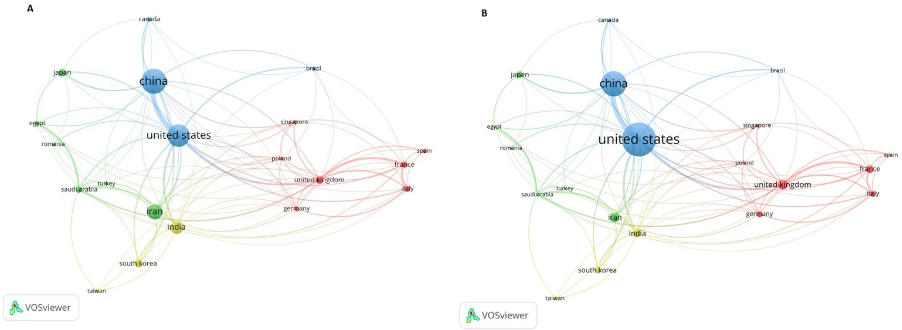


Figure 2A: Global collaboration network in CNT- based cancer research. Visualization of country-level collaborations generated using VOSviewer. Node size reflects either publication output or citation impact, and links indicate co-authorship relationships between countries. Colors denote clusters of closely collaborating nations. Panel (A) represents collaboration based on publication output, whereas panel (B) reflects citation impact. Figure 2B: Global collaboration network in CNT- based cancer research. Visualization of country-level collaborations generated using VOSviewer. Node size reflects either publication output or citation impact, and links indicate co-authorship relationships between countries. Colors denote clusters of closely collaborating nations. Panel (A) represents collaboration based on publication output, whereas panel (B) reflects citation impact.

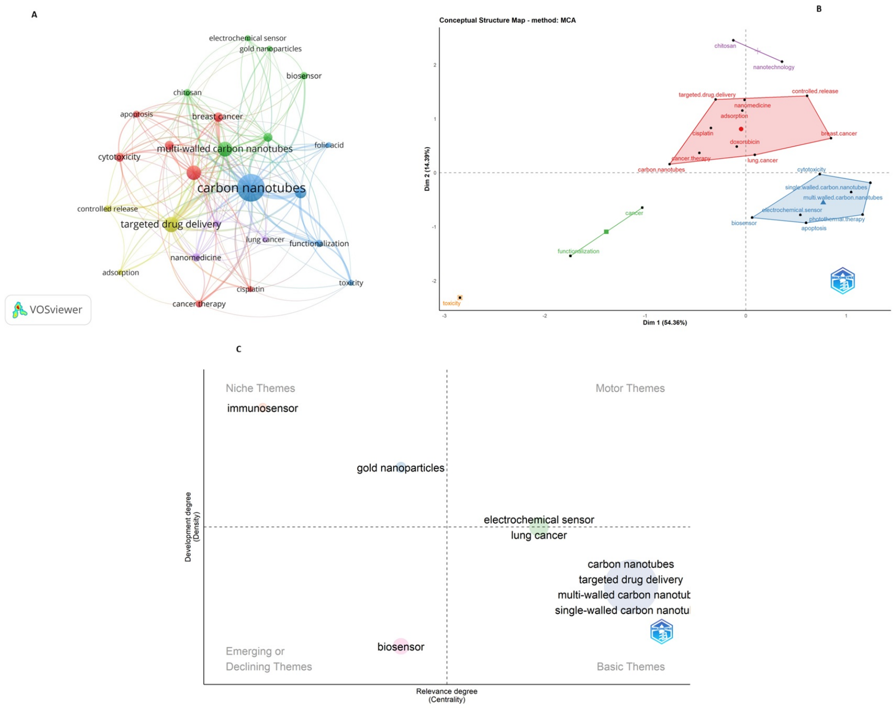


Figure 3A: Author keyword and thematic analysis in CNT- based cancer research. Keywords with a minimum occurrence of 15 were included. (A) Network visualization map generated using VOSviewer, illustrating co-occurrence relationships among keywords; node size reflects frequency, and colors indicate clusters. (B) Conceptual structure map derived from Biblioshiny, showing the relationships and grouping of research themes. (C) Thematic map generated using Biblioshiny, categorizing keywords into motor, basic, emerging, and niche themes based on their centrality and density. Figure 3B: Author keyword and thematic analysis in CNT- based cancer research. Keywords with a minimum occurrence of 15 were included. (A) Network visualization map generated using VOSviewer, illustrating co-occurrence relationships among keywords; node size reflects frequency, and colors indicate clusters. (B) Conceptual structure map derived from Biblioshiny, showing the relationships and grouping of research themes. (C) Thematic map generated using Biblioshiny, categorizing keywords into motor, basic, emerging, and niche themes based on their centrality and density. Figure 3C: Author keyword and thematic analysis in CNT- based cancer research. Keywords with a minimum occurrence of 15 were included. (A) Network visualization map generated using VOSviewer, illustrating co-occurrence relationships among keywords; node size reflects frequency, and colors indicate clusters. (B) Conceptual structure map derived from Biblioshiny, showing the relationships and grouping of research themes. (C) Thematic map generated using Biblioshiny, categorizing keywords into motor, basic, emerging, and niche themes based on their centrality and density.

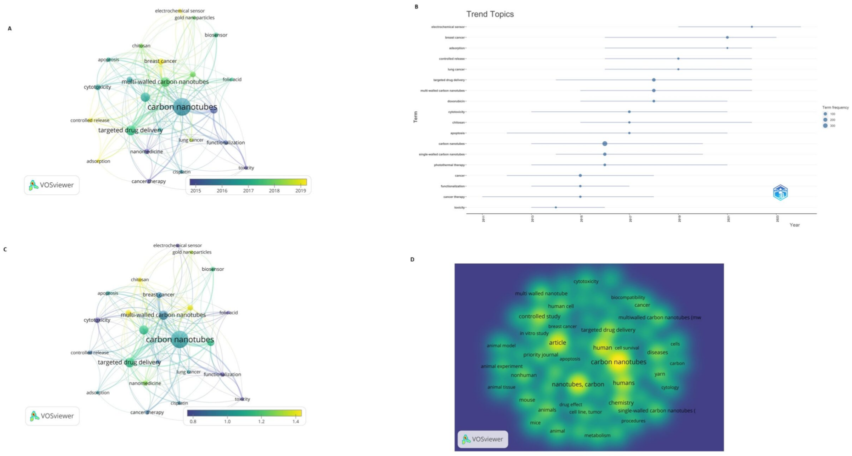
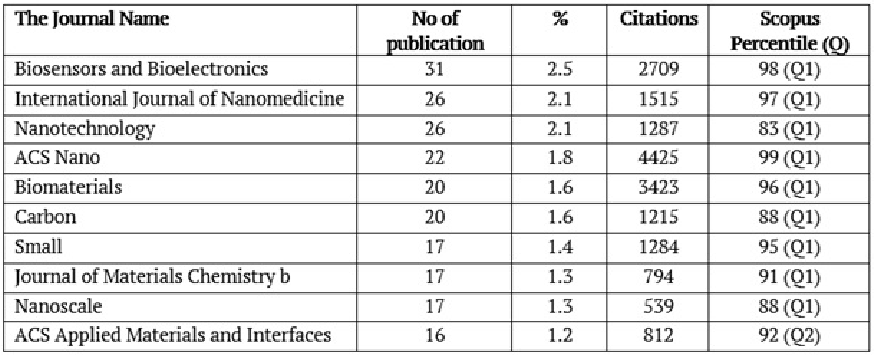


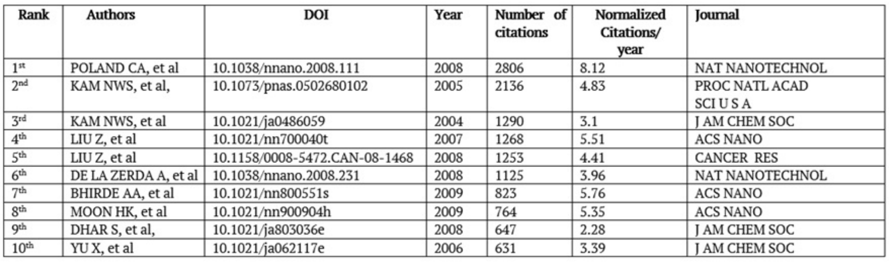
Figure 4A: Temporal trends and density analysis of keywords in CNT- based cancer research. (A) Overlay visualization map showing the co-occurrence of author keywords colored according to the average publication year, where more recent topics appear in yellow. (B) Trend analysis of author keywords illustrating the evolution of research focus over time. (C) Overlay visualization map of keywords based on average normalized citation scores, highlighting the relative impact of research topics. (D) Cluster density map of all keywords, where color intensity reflects the frequency of keyword occurrence and their interrelationships. Figure 4B: Temporal trends and density analysis of keywords in CNT- based cancer research. (A) Overlay *visualization map showing the co-occurrence of author keywords colored according to the average publication year, where more recent topics appear in yellow. (B) Trend analysis of author keywords illustrating the evolution of research focus over time. (C) Overlay visualization map of keywords based on average normalized citation scores, highlighting the relative impact of research topics. (D) Cluster density map of all keywords, where color intensity reflects the frequency of keyword occurrence and their interrelationships. Figure 4C: Temporal trends and density analysis of keywords in CNT- based cancer research. (A) Overlay visualization map showing the co-occurrence of author keywords colored according to the average publication year, where more recent topics appear in yellow. (B) Trend analysis of author keywords illustrating the evolution of research focus over time. (C) Overlay visualization map of keywords based on average normalized citation scores, highlighting the relative impact of research topics. (D) Cluster density map of all keywords, where color intensity reflects the frequency of keyword occurrence and their interrelationships. Figure 4D: Temporal trends and density analysis of keywords in CNT- based cancer research. (A) Overlay visualization map showing the co-occurrence of author keywords colored according to the average publication year, where more recent topics appear in yellow. (B) Trend analysis of author keywords illustrating the evolution of research focus over time. (C) Overlay visualization map of keywords based on average normalized citation scores, highlighting the relative impact of research topics. (D) Cluster density map of all keywords, where color intensity reflects the frequency of keyword occurrence and their interrelationships.*

Tables



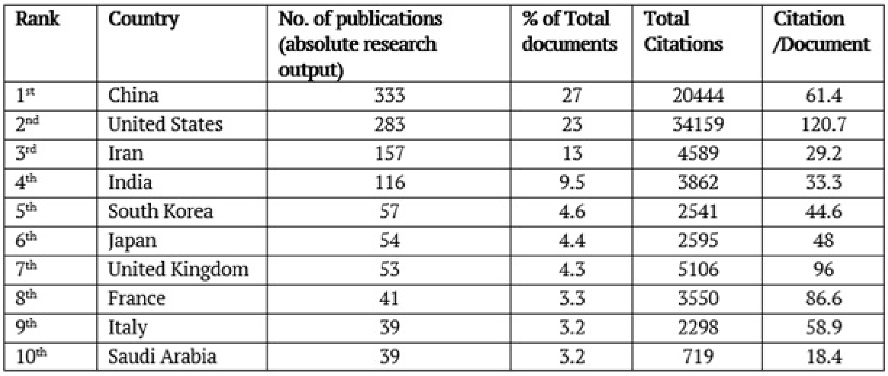
The Journal Name	No of publication	%	Citations	Scopus Percentile (Q)
Biosensors and Bioelectronics	31	2.5	2709	98 (Q1)
International Journal of Nanomedicine	26	2.1	1515	97 (Q1)
Nanotechnology	26	2.1	1287	83 (Q1)
ACS Nano	22	1.8	4425	99 (Q1)
Biomaterials	20	1.6	3423	96 (Q1)
Carbon	20	1.6	1215	88 (Q1)
Small	17	1.4	1284	95 (Q1)
Journal of Materials Chemistry b	17	1.3	794	91 (Q1)
Nanoscale	17	1.3	539	88 (Q1)
ACS Applied Materials and Interfaces	16	1.2	812	92 (Q2)

Table 1: Leading journals contributing to CNT- based cancer research. This table summarizes the ten foremost journals based on publication output, including the number of documents, percentage contribution, total citations, and Scopus percentile ranking (quartile classification). It highlights the most influential publication sources and their overall impact within CNT- based cancer research.



Rank	Authors	DOI	Year	Number of citations	Normalized Citations/ year	Journal
1st	POLAND CA, et al	10.1038/nnano.2008.111	2008	2806	8.12	NAT NANOTECHNOL
2nd	KAM NWS, et al,	10.1073/pnas.0502680102	2005	2136	4.83	PROC NATL ACAD SCI U S A
3rd	KAM NWS, et al	10.1021/ja0486059	2004	1290	3.1	J AM CHEM SOC
4th	LIU Z, et al	10.1021/nn700040t	2007	1268	5.51	ACS NANO
5th	LIU Z, et al	10.1158/0008-5472.CAN-08-1468	2008	1253	4.41	CANCER RES
6th	DE LA ZERDA A, et al	10.1038/nnano.2008.231	2008	1125	3.96	NAT NANOTECHNOL
7th	BHIRDE AA, et al	10.1021/nn800551s	2009	823	5.76	ACS NANO
8th	MOON HK, et al	10.1021/nn900904h	2009	764	5.35	ACS NANO
9th	DHAR S, et al,	10.1021/ja803036e	2008	647	2.28	J AM CHEM SOC
10th	YU X, et al	10.1021/ja062117e	2006	631	3.39	J AM CHEM SOC

Table 2: Most highly cited publications in CNT- based cancer research. The table summarizes the ten most cited articles identified through bibliometric analysis, including author details, publication source, digital object identifier (DOI), total citation count (TC), average citations per year, and normalized citation values, highlighting their contribution to the field.



Rank	Country	No. of publications (absolute research output)	% of Total documents	Total Citations	Citation /Document
1st	China	333	27	20444	61.4
2nd	United States	283	23	34159	120.7
3rd	Iran	157	13	4589	29.2
4th	India	116	9.5	3862	33.3
5th	South Korea	57	4.6	2541	44.6
6th	Japan	54	4.4	2595	48
7th	United Kingdom	53	4.3	5106	96
8th	France	41	3.3	3550	86.6
9th	Italy	39	3.2	2298	58.9
10th	Saudi Arabia	39	3.2	719	18.4

Table 3: Leading countries contributing to CNT- based cancer research. This table presents the top ten countries based on publication output, including the number of documents, total citations, percentage contribution to overall publications, and average citations per document. It highlights the global distribution of research activity and the relative scientific impact of each country in the field.

DISCUSSION

Carbon nanotubes utilization has gained significant attention for being a prospective approach for exploring a variety of biomedical applications, particularly in cancer therapy. These CNTs exhibit exceptional properties, including the ability to be modified for the purpose of targeted drug delivery by functionalizing them along with biocompatible molecules [59-61]. Furthermore, due to their unique electrical and optical properties, which enable their application in diagnostic imaging techniques such as near- infrared fluorescence and Raman spectroscopy, CNTs have demonstrated significant potential in cancer therapy [62,63]. However, while initial findings are promising, further in- depth studies are required to fully elucidate their therapeutic capabilities and to rigorously assess them in clinical settings for patient benefit in terms of efficacy and safety.

In scientific research, bibliometric analysis is essential since it permits a thorough examination and visual representation concerning enormous knowledge repositories [13]. The current research attempts to fill in the gaps that currently exist for our understanding through the provision of a quantitative assessment of global research on CNTs, with a focus on cancer therapy research. For attaining this goal, we gathered pertinent scientific literature sourced via the prestigious Scopus database, renowned for being the most comprehensive repository of peer- reviewed articles that encompasses abstracts along with citations. Accompanied by means of vast searching capabilities and analytical tools, Scopus assists with data extraction to support additional visualization as well as investigation. Scopus- indexed journals undergo rigorous evaluations and meticulous peer- review processes, strengthening their trustworthiness.

In addition, Scopus sorts these scientific journals by subject matter, thereby providing a thorough resource for those investigating CNTs application in cancer treatment research. Findings derived from the study we performed furnish crucial perspectives for guiding researchers and institutions in prioritization their attempts and directing forthcoming investigations into this burgeoning sector. The present study performed an intensive search to compile all the relevant literature from the last two decades that concerned the utilization of CNTs in cancer therapy. Solely reviews and papers written in English and subjected to a thorough peer review process were incorporated in this study.

Our findings indicated a notable increase in publications within this particular arena during the past five years, with almost 30% of the articles being released between the years 2020 and 2024, as shown in Figure 1. This growth reflects increasing global interest in nanotechnology-based cancer therapies and highlights the expanding role of CNTs in advanced biomedical applications. From 445 journals indexed in Scopus, a total of 1,221 papers were retrieved. Table 2 highlights that the most prolific top ten journals accounted for approximately 17% out of all published articles. The obtained documents produced 72,181 citations in total, having an average of 59.1 citations for each document. Moreover, the published publications had an *h*-index of 124, demonstrating a considerable degree of reader interest. The most citations have been received by the ACS Nano journal. As demonstrated in Table 2, the documents that were commonly referenced were disseminated between the years 2004 and 2009.

However, recently published publications failed to garner adequate citations to contend with the documents mentioned previously. Recent publications tend to have lower citation counts due to the limited time since publication, which restricts the accumulation of citations. Of all the documents that were retrieved, the scholarly publication by Poland C. *et al*., published in Nature Nanotechnology [64], garnered the greatest citation count. The essay examines that exposing the mesothelial lining of the body cavity of mice, as a surrogate for the mesothelial lining of the chest cavity, to long multiwalled carbon nanotubes results in asbestos-like, length-dependent, pathogenic behavior.

In accordance with the geographic distribution examination of the acquired papers, academics from China authored the highest count of publications, totaling 333 documents (27%). Consequently, researchers from USA released 283 documents, constituting 23% of the total.

The investigation of the scientific influence concerning these countries, as measured by the average number of citations per document, depicts that documents originating from United States showcase the highest total scientific impact, with 120.7 citations per document. Afterwards, with 96 citations per document, the United Kingdom is ranked second, and France occupies the third rank having 86.6 citations per document, as demonstrated in Table 3 and Figure 2.

Within the scope of this investigation, the acquired documents amassed 72,181 citations in total. The significant nature of this topic is underscored through the substantial number of citations, and further reinforced by articles in esteemed academic journals. This finding has been evidenced by the data displayed in Table 1, thereby implies that all of the leading 10 journals are listed into Q1 category. The investigation also evaluated international collaborations amongst countries associated with this scientific domain. The most prominent partnership was established between USA and China, as revealed by the network visualization of international research partnerships, depicted in Figure 2.

Research Hotspots and Trends

Through analyzing the co-occurrences of author keywords found within the gathered literature, which surpassed 15 incidences, Biblioshiny and VOSview were both employed to map hotspots. In consequence, five overlapping conceptual clusters comprising 24 primary keywords were discovered. These clusters emphasize the fields of focus along with study emphasis of the retrieved materials.

The five mentioned previous clusters, determined using VOSviewer and Biblioshiny, were utilized to infer the subsequently occurring hotspots, as shown in Figure 3C and Figure 4.

Cluster 1: Harnessing CNTs for Cancer Therapy (single-walled CNTs, breast cancer, cytotoxicity, photothermal therapy, cancer therapy, apoptosis, and cisplatin): Single- walled carbon nanotubes (SWCNTs) have gained significant attention in cancer therapy due to their unique physicochemical properties, including high surface area, biocompatibility, and the ability to easily functionalize for targeted drug delivery [65]. These nanotubes can serve as carriers for various therapeutic agents, including chemotherapy drugs, RNA molecules, and proteins, allowing for more precise targeting of cancer cells while minimizing damage to healthy tissues [66]. Additionally, SWCNTs have shown promise in photothermal therapy; where they can convert near- infrared light into heat to selectively destroy cancer cells [67]. CNTs offer a versatile platform in the treatment of breast cancer, particularly for enhancing the delivery and efficacy of chemotherapy. Their unique structure allows them to encapsulate hydrophobic drugs, improving solubility and stability in the bloodstream [18]. Moreover, CNTs can be conjugated with specific targeting agents, such as monoclonal antibodies, to improve selective accumulation at the tumor site. This targeted approach not only enhances the therapeutic effect but it additionally diminishes the side effects associated that are related to traditional chemotherapy [30]. CNTs can also be utilized for monitoring treatment response through imaging techniques, as they are capable of providing contrast in modalities like MRI [68].

On the other hand, CNTs have raised concerns regarding their cytotoxicity, which gets influenced by factors such as their surface charge, size, and functionalization. Studies have shown that CNTs can induce oxidative stress, inflammation, and cellular damage, leading to cytotoxic effects in various cell types [19]. However, the degree of toxicity varies significantly based on the physicochemical properties of the CNTs, with functionalization often mitigating harmful effects [69]. For example, surface modification with biocompatible molecules, such as polyethylene glycol (PEG), can reduce the inflammatory response and enhance their biocompatibility [70,71]. Additionally, CNTs' ability to penetrate cell membranes and interact with intracellular components has sparked interest in their potential use for drug delivery systems, although this also necessitates a careful evaluation of their long-term safety profile. As the body of research on CNTs' cytotoxicity grows, it is clear that balancing their therapeutic benefits with their potential toxic effects is crucial for their successful clinical application [72,73].

CNTs offer a promising approach in photothermal therapy (PTT) due to their ability to efficiently absorb and convert near-infrared light into heat. This makes them effective in targeted cancer treatment, where CNTs can be directed to tumor sites and activated by NIR light to induce localized thermal damage to cancer cells. Their unique structural properties, such as high surface area and conductivity, enable them to generate significant heat upon light exposure, making them ideal for enhancing the efficacy of PTT [74]. Functionalization with targeting agents, such as antibodies or peptides, allows for precise delivery to cancer cells, minimizing damage to healthy tissues. Despite their potential, careful consideration of heat management and biocompatibility is crucial to ensure that CNTs can be safely integrated into clinical practices for cancer treatment [75].

Carbon nanotubes (CNTs) have been shown to play a role in the induction of apoptosis, particularly in cancer cells, due to their ability to interact with cellular components and trigger cell death pathways. CNTs can facilitate the delivery of pro-apoptotic agents or induce oxidative stress, leading to mitochondrial dysfunction and the activation of apoptotic signaling. Their unique properties, including high surface area and ability to be functionalized with various biomolecules, enable precise targeting of tumor cells, where they can promote apoptosis without affecting healthy tissues [76,77]. Additionally, CNTs have been used in combination with chemotherapy agents to enhance their apoptotic effects, sensitizing cancer cells to treatment. However, the exact mechanisms by which CNTs influence apoptosis are still being studied, and concerns regarding their potential to induce unwanted toxicity or inflammation in normal cells must be addressed before their widespread clinical use [78,79].

Cisplatin, a potent chemotherapy agent, has been widely used in the treatment of various cancers; however, its clinical effectiveness is often limited by issues such as poor solubility, systemic toxicity, and the development of drug resistance [80-82]. Carbon nanotubes (CNTs) offer a promising solution to these challenges by serving as carriers for cisplatin, enhancing its solubility and targeted delivery to tumor sites. When functionalized with cisplatin, CNTs facilitate the controlled release of the drug, ensuring a higher concentration at the tumor while minimizing exposure to healthy tissues. Moreover, CNTs can enhance the uptake of cisplatin into cancer cells, overcoming resistance mechanisms and increasing its cytotoxic effects [83,84]. Despite the therapeutic potential, the safety profile of CNT- based cisplatin delivery systems needs further investigation to address concerns related to toxicity, biodegradability, and long- term biocompatibility [85]

Cluster 2: MWCNTs in Drug Delivery and Biosensing (multi- walled carbon nanotubes, doxorubicin, biosensor, chitosan, electrochemical sensor and gold nanoparticles): The unique properties of multi- walled carbon nanotubes (MWCNTs), including their high surface area, mechanical strength, and ease of functionalization, have positioned them as a promising tool in nanomedicine [86,87]. In cancer therapy, MWCNTs are increasingly employed as carriers for the delivery of chemotherapeutic agents, such as doxorubicin, a potent anti- cancer drug. By attaching doxorubicin to the surface of MWCNTs, researchers have been able to boost the solubility, stability, and targeted delivery of the drug, which enhances its therapeutic efficacy while minimizing systemic side effects [88-90]. Furthermore, MWCNTs' ability to penetrate cell membranes allows for efficient intracellular delivery, making them particularly valuable in overcoming drug resistance mechanisms observed in many cancer types. To enhance their biocompatibility and prevent premature drug release, MWCNTs are often combined with biopolymers like chitosan, which not only stabilizes the drug- nanotube complex but also improves the uptake and distribution of the drug within tumor cells. This combination ensures that doxorubicin remains active in its therapeutic role without causing excessive toxicity to healthy tissues [91,92]. Beyond their application in drug delivery, MWCNTs have also been explored in the development of highly sensitive biosensors [93-95]. When integrated with gold nanoparticles, MWCNTs create hybrid nanocomposites with exceptional electrical conductivity and surface area, making them ideal candidates for electrochemical biosensing. These sensors have shown remarkable sensitivity in detecting cancer biomarkers, enabling early diagnosis and real- time monitoring of treatment progress [96,97]. The synergy between MWCNTs, gold nanoparticles, and chitosan further enhances the performance of electrochemical sensors, leading to increased specificity and detection limits, which are critical in the early detection of cancer and other diseases [98]. The combination of these technologies for both therapeutic and diagnostic purposes holds significant promise for advancing personalized medicine and improving patient outcomes.

Cluster 3: Exploring CNT functionalization and cancer treatment (Carbon Nanotubes, Cancer, Functionalization, Toxicity, Folic Acid): Recent advancements in nanomedicine have positioned carbon nanotubes (CNTs) as highly promising candidates for cancer therapy, offering precise drug delivery and enhanced therapeutic efficiency [99]. However, their biomedical applications are often hindered by concerns related to cytotoxicity and potential long-term accumulation in tissues. To address these challenges, extensive research has focused on functionalization techniques that modify the surface of CNTs, improving their solubility, reducing toxicity, and increasing their specificity for cancer cells [100]. One of the most effective approaches involves conjugating CNTs with folic acid, leveraging the overexpression of folate receptors on many cancer cells to enable selective targeting. This functionalization strategy enhances the cellular uptake of CNT- based therapeutics, ensuring higher drug concentrations at tumor sites while minimizing adverse effects on healthy tissues [101-103]. Additionally, folic acid- functionalized CNTs serve as efficient carriers for chemotherapeutic agents, allowing for controlled drug release and prolonged retention within malignant cells. Functionalization not only optimizes therapeutic outcomes but also mitigates oxidative stress and inflammatory responses often associated with unmodified CNTs, making them more suitable for clinical applications [104]. Beyond drug delivery, folic acid- modified CNTs have demonstrated potential in cancer diagnostics, where they can improve imaging contrast and biomarker detection [105-107]. Despite these promising developments, further research is essential to fine- tune functionalization methods, ensuring that CNT-based platforms achieve maximum efficacy with minimal toxicity. Long-term in vivo studies will be critical to evaluating their pharmacokinetics, clearance mechanisms, and overall safety before transitioning to widespread clinical use [47,108]. As functionalization strategies continue to evolve, CNTs hold immense potential for revolutionizing cancer treatment by providing highly efficient, targeted, and minimally invasive therapeutic solutions [109,110].

Cluster 4: Advancing Drug Delivery with CNTs (Targeted Drug Delivery, Controlled Release, Adsorption): The effectiveness of cancer therapy depends not only on the potency of the drug but also on its ability to reach the tumor site in a controlled and sustained manner. Carbon nanotubes (CNTs) have emerged as highly efficient nanocarriers due to their ability to adsorb therapeutic molecules and release them in a targeted fashion [101,111]. Their large surface area allows for strong interactions with a wide range of drugs through physical adsorption and chemical attachment, ensuring high drug-loading capacity [112,113]. Functionalized CNTs can be engineered to respond to specific biological stimuli, such as pH changes in the tumor microenvironment, to trigger controlled drug release precisely where it is needed. This approach prevents premature drug degradation, reduces systemic toxicity, and enhances therapeutic efficiency [3,27,114]. Additionally, the adsorption properties of CNTs enable them to carry multiple therapeutic agents simultaneously, opening possibilities for combination therapies that attack cancer through different mechanisms [14]. While promising, further research is required to optimize CNT-based drug carriers for improved stability, reduced unintended interactions with healthy cells, and enhanced biodegradability to facilitate their safe transition into clinical applications [43,115].

Cluster 5: CNTs in nanomedicine for lung cancer (nanomedicine, nanotechnology, lung cancer): Nanomedicine, empowered by advancements in nanotechnology, holds immense potential for revolutionizing lung cancer treatment. Carbon nanotubes (CNTs), as key components of nanomedicine, offer a highly versatile platform for targeted drug delivery, enhancing the precision and efficacy of cancer therapies [19,67,104]. In the context of lung cancer, CNTs can be functionalized with specific ligands to target tumor cells selectively, overcoming challenges related to conventional chemotherapy, such as low drug bioavailability and non-specific toxicity. Moreover, their unique structural properties allow CNTs to interact with and penetrate cancerous tissues, delivering therapeutic agents directly to the site of the tumor [74,93,116].

Nanotechnology-driven innovations, such as the use of CNTs for controlled drug release and real-time monitoring, have significantly improved the potential for personalized cancer therapies [1,117,118]. As research progresses, CNT-based nanomedicines are being designed to tackle the complexities of lung cancer, with promising results in preclinical models showing enhanced treatment outcomes [119]. However, the successful translation of CNT-based therapies into clinical settings requires further studies to assess long-term safety, biocompatibility, and the potential for overcoming drug resistance in lung cancer cells.

Study limitations

Considering our study purely utilized Scopus database for document retrieval, it is of the utmost importance to recognize that relevant research on CNTs and cancer may be released by journals that are not indexed by Scopus. Furthermore, only restricted assortment of 2024 publications may not have been incorporated into Scopus during our investigation, presumably leading to their omission from the investigation we conduct. Furthermore, we excluded items which remained in "in press" phase. Therefore, it is plausible that these circumstances have resulted in the neglect of particularly relevant research articles or review papers on the subject that were published into the late 2024. The fact that we merely utilized papers produced in English is a further limitation of our investigation. Scholars may gain significant insights about the application CNTs in cancer therapy from research accomplished in other languages. At long last, it is essential to remark that the findings of the study could be impacted by even slight discrepancies in the affiliations or names of the authors.

Conclusions

Encompassing a wide range of scientific fields, our extensive bibliometric study reveals the immense prospects of application of CNTs in cancer therapy. The revolutionary significance of CNTs is highlighted by our investigation of the present status of the field and potential avenues for future research. Significant attention has been directed towards the potential integration of CNTs in cancer diagnostics and treatment, as they hold the promise for improving patient outcomes along with fewer adverse effects. Moreover, CNTs utilization in cancer therapy aligns with the growing focus on sustainable nanotechnology, offering a promising and responsible method for developing targeted treatments with enhanced therapeutic efficacy.

Our bibliometric analysis, in essence, accentuates the significance of ongoing research, cooperation align with the translation to clinical applications in addition to highlighting the recent advancements in the use of CNTs in cancer therapy.

CONFLICT OF INTEREST

The authors declare that they have no known financial or personal relationships with any individuals or organizations that could have influenced the work reported in this manuscript. There are no professional, financial, or personal interests of any kind related to any product, service, or company that could be perceived as affecting the content, analysis, or conclusions presented in this manuscript.

AUTHOR CONTRIBUTIONS

Islam Hamad: Conceptualization, methodology, writing – original draft.

Amani Harb: Data curation, formal analysis.

Shrouq Twal: Visualization, software.

Adi I Arida: Investigation.

Amal Mayyas: Validation.

Rula Amr: Writing – review & editing.

Nour Bustanji: Supervision.

Mona Al Olabi: Resources.

Yasser Bustanji: Project administration, final approval.

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