

Mapping the Nanotechnology Landscape in Healthcare: A Multi-Domain Analysis of Scientific Output, Innovation, Clinical Trials, and Market Dynamics

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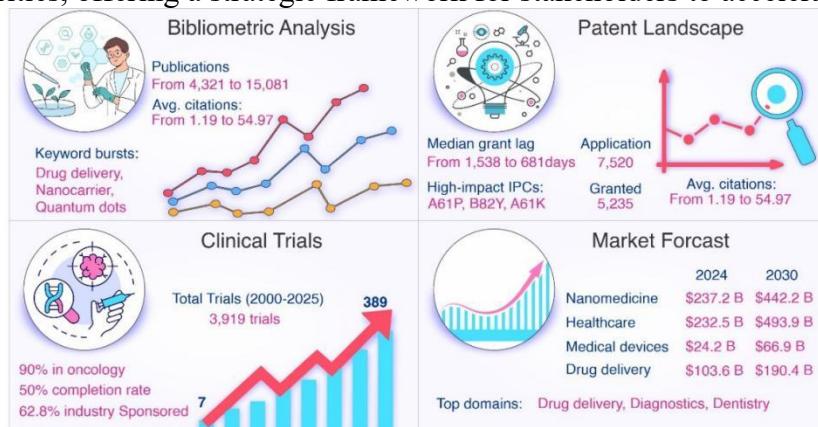
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Abstract:

Nanotechnology is transforming healthcare by enabling precise molecular-scale manipulation to develop innovative diagnostic and therapeutic solutions. This study integrates bibliometric mapping (2014–2024), patent landscape analysis, clinical trial evaluation, and market forecasting to present a comprehensive view of nano-healthcare. Bibliometric data show a threefold rise in publications (4,321 to 15,081) and a surge in average citations per paper (1.19 to 54.97). Clinical trials of nanoparticle-based therapies expanded fifty-five-fold since 2000, with Phase II studies dominating and oncology comprising over 90% of investigations. Patent filings and grants nearly quadrupled, while median grant-lag times halved post-2018, indicating faster translation. Harmonized market forecasts project growth from USD 232.5 billion in 2024 to USD 493.9 billion by 2030 (CAGR 12.4%), supported by 1,318 catalogued products. A SWOT analysis highlights opportunities in non-oncology applications, regulatory harmonization, and emerging markets, alongside challenges in safety, scalability, and regional disparities, offering a strategic framework for stakeholders to accelerate innovation.



Keywords: Nanotechnology in Healthcare, Nanomedicine Market Dynamics, Innovation and Patent Landscape, Clinical Translation of Nanotechnology, Healthcare Technology Management

1. Introduction:

Nanotechnology has rapidly evolved over the past three decades into a domain of immense industrial and economic potential. It is reshaping the trajectory of medicine, diagnostics, and therapeutic innovation. It is restructuring a wide range of industries from electronics and energy to environmental science and materials engineering, but its most profound impact is being seen in the field of medicine, where it is transforming diagnostics, drug delivery, and therapeutic innovation. By drastically reducing the size, weight, and power requirements of medical devices and therapeutic systems, nanotechnology is making healthcare solutions more portable, efficient, and cost-effective. This miniaturization allows for greater accessibility and mobility, enabling point-of-care diagnostics and wearable treatments that reduce dependence on large, capital-intensive infrastructure. Moreover, these innovations are shifting market demand from traditional, bulky equipment to compact, high-performance nanotech-enabled products, opening new opportunities for start-ups and tech-driven healthcare firms. Economically, this leads to reduced operational costs, improved supply chain efficiency, and broader market penetration, especially in underserved or remote areas. This global surge is evident not only in scientific publications but also in patent filings, clinical trials, and commercialized products, each reflecting distinct stages of translation from laboratory innovation to healthcare impact. It is further reinforced by robust market forecasts that project multi-billion-dollar expansions across all nano-healthcare subdomains. Current estimates indicate a mean CAGR of 12.4% in global nano-healthcare industry, highlighting accelerating investment flows, revenue diversification, and long-term economic value creation in the healthcare innovation ecosystem.

Recent scientific literature further illustrates that the rapid expansion of nano-healthcare is not driven solely by incremental miniaturization, but by the emergence of multifunctional material platforms that enable new modes of interaction, control, and responsiveness in medical systems. Studies on functionalized carbon nanomaterials, particularly graphene- and carbon nanotube-based polymer nanocomposites, demonstrate how interface engineering and material integration are enabling advanced performance characteristics relevant to healthcare applications, such as enhanced responsiveness, adaptability, and system integration (Punetha et al., 2017). Parallel research on photothermal graphene networks and shape-memory polymer composites highlights the growing convergence of nanomaterials, smart polymers, and externally triggered actuation mechanisms, pointing toward future generations of remotely controllable, minimally invasive therapeutic and diagnostic devices (Punetha et al., 2019).

Despite this remarkable growth, existing analyses often focus narrowly on specific domains. Since the landscape is vast, heterogeneous, and rapidly evolving, making it difficult for stakeholders to capture a holistic picture of how nanotechnology in healthcare is progressing. This absence of an integrated perspective is increasingly problematic. Bibliometric analysis serves as a powerful tool to explore research landscapes. It identifies emerging trends, hotspots, and knowledge gaps by analysing citation patterns, publication timelines, and keyword frequencies. In addition, it serves as a key analytical tool in extracting insights essential for strategic decision-making across the innovation lifecycle, enabling policymakers, funding agencies, and R&D managers to prioritize resources, foster collaborations, and anticipate future directions of scientific progress. Patent data is one of the most significant

indicators which can be used as powerful empirical lens to trace technological evolution and innovation pathways in nanotechnology. Scholars use patents as indicators of innovation intensity, treating filing trends as proxies for R&D progress in Nano-healthcare (da Hora et al., 2025). Longitudinal analyses employing year-wise filings and logistic growth curves enable forecasting of saturation and emerging opportunities (Milanez et al., 2014). Text mining and co-classification methods map hotspots and thematic clusters, identifying domains such as nano-immunotherapy, phototherapy, and diagnostic imaging (Sun et al., 2024). Comparative studies further expose institutional and geographic asymmetries (Wu et al., 2019). Beyond science mapping, patent data critically informs policy and legal discourse, where unique IP regimes affect commercialization (“Nanotechnology Patent Applications and Section 3(d) of Indian Patents Act, 1970: An Empirical Research,” 2023; Vazhathodi, 2022). Additionally, valuation frameworks integrate patent metrics to guide investment decisions (Heidary Dahooie et al., 2019). Collectively, these studies underscore patents not merely as legal tools but as dynamic knowledge artefacts shaping innovation trajectories. However, patent data alone is insufficient to gauge true innovation outcomes (Taalbi, 2022). While filings reflect intent and novelty, their commerciality, efficacy, utility, and cost-effectiveness are only revealed through clinical trials (Xu et al., 2025). Such trials are crucial in assessing the realized impact of patented technologies, bridging legal protection with practical healthcare value. Clinical trial publication counts act as key indicators of innovation and market activity in fields like nanomedicine and pharma. A higher volume of publications reflects active research, signalling future products and technologies (Budenny et al., 2023). It also serves as a proxy for market interest, often correlating with funding, investments, and business opportunities (Dziallas & Blind, 2019). Surges in trial reports can indicate regulatory progress and nearing commercialization, shaping company valuations and strategies (Sood et al., 2014). While valuable, these perspectives remain fragmented. As a result, decision makers whether policymakers, funding agencies, R&D managers, or industry strategists often lack a comprehensive map of how nanotechnology is advancing simultaneously across discovery, protection, application, and commercialization. Disproportionate growth across innovation indicators often reveals systemic bottlenecks: a surge in publications without corresponding patents may suggest limited translational potential; increasing patent filings without subsequent clinical validation may indicate premature or speculative claims; and accelerated clinical-trial activity without market penetration may expose regulatory or scalability constraints. Considered individually, such datasets provide fragmented and incomplete perspectives. Given the inherently interdisciplinary and application-driven nature of nanotechnology, comprehensive mapping across the publication–patent–trial–market continuum is essential to discern strengths, weaknesses, opportunities, and threats within the innovation ecosystem.

Despite substantial progress in each domain, a critical gap persists in evaluating how advances in fundamental research propagate through cycles of innovation, validation, and adoption. This study therefore interrogates whether bibliometric, patent landscape, clinical-trial, and harmonized market-forecast analyses can be systematically integrated into a unified framework. By synthesizing these diverse evidence streams, the framework seeks to provide both retrospective assessment and forward-looking strategic insight into the evolution of nano-enabled healthcare. It assesses innovation-driven literature expansion, highlighting thematic clusters and leading contributors. In addition, the study maps the patent landscape through filing volumes, grant trends, citation performance, and examination timelines. Further, it analyses the clinical pipeline with attention to trial phases, enrolment sizes, and

therapeutic domains. Finally, the study harmonizes market projections for nano-enabled drugs, diagnostics, and delivery systems using forward-backward models for 2024–2030. Together, these analyses show the links between knowledge creation, intellectual property, clinical validation, and commercialization. The collective study of these parameters offers a holistic view, linking discovery, protection, validation, and commercialization. This integration identifies research gaps, accelerates translation, and clarifies regulatory and investment priorities. By harmonizing insights across the innovation chain, the framework supports evidence-based strategies for academics, industry, regulators, and policymakers, ultimately driving healthcare progress while ensuring societal relevance and sustainable economic value.

2. Materials and Methods:

This research employed a mixed-method descriptive and analytical framework, integrating four complementary streams—bibliometric, patent landscape, clinical-trial, and market-forecast analyses—into a unified pipeline. A single, comprehensive search narrative combined controlled-vocabulary and free-text terms for nanotechnology and its biomedical applications, ensuring consistency and comparability across all data sources.

For the bibliometric data, we retrieved publications from PubMed and Dimensions AI covering 2014–2024 (*Advanced Search Results - PubMed*, n.d.; *Dimensions AI | The Most Advanced Scientific Research Database*, n.d.). In PubMed, we applied a keyword-driven query combining MeSH headings (“Nanotechnology” and “Nanomedicine”) with keywords such as *nanomedicine*, *nanotherapeutic*, *nano formulation*, *nanocarrier*, *nanoparticle*, *nanostructure*, *nanocomposite*, *nanogel*, *nanofiber/fibre*, *nanoribbon*, *nanosheet*, *nanowire*, *nanorod*, *nanobelt*, *nanofilm*, *nanomembrane*, *nanocrystal*, *dendrimer*, *liposome*, *noisome*, *micelle*, *exosome*, *quantum dot*, *fullerene*, *buckminsterfullerene*, *carbon nanotube/CNT*, *graphene (and oxide)*, *MXene*, *AuNP*, *AgNP*, *SPION*, *MSN*, *polymeric nanoparticle*, *nano-drug*, and *0D*, *1D*, *2D* qualifiers paired with those same nano-entities. We paired these with biomedical descriptors—“Medicine,” *biomedical*, *medical*, *clinical*, *therapy/diagnos/imaging*, “drug delivery,” *healthcare*, *pharmacy*, *biomarker*, *theranostic*—while excluding purely physical-science contexts (*nanosecond*, *nanometer*, *nanogram*, *nanomole*, *nanoampere*, *nanowatt*) to enhance specificity and top 10000 PMIDs were compiled and analysed by shorting them by relevance. Dimensions AI queries mirrored PubMed’s search string and filters, capturing publication counts, citation metrics, top journals, and geographic distributions. Patent trends from 2014 through mid-2024 were mapped using Lens.org (*The Lens - Patent and Scholarly Search and Analysis*, n.d.). We filtered to IPC classes *A61** (medical/healthcare technologies) and *B82** (nanotechnology), distinguishing patent applications (*kind code “A”*) from granted patents (*kind code “B”*). Using the same keyword narrative against trial titles, interventions, and conditions, we extracted fields including National Clinical Trial (*NCT*) *numbers*, *trial phases and statuses*, *enrolment sizes*, *sponsor types*, *dates*, and *locations*. Market-size data and forecasts were obtained from various commercial market-research reports and the Statnano database (*STATNANO : Nano Science, Technology and Industry Information*, n.d.). We focused on four segments—*nanotechnology in healthcare*, *nanomedicine products*, *nano-enabled medical devices*, and *nano-based drug-delivery systems*—and extracted base-year values, forecast-year values, and implied CAGRs.

All analyses were conducted in R (version $\geq 4.0.0$) (R Core Team, 2025). For bibliometric processing, Excel exports were imported via *readxl*, PubMed metadata fetched with *rentrez*

and parsed using *xml2*, and data wrangled with *tidyverse* (Wickham et al., 2019, 2025; Winter, 2017). Quantitative metrics—annual outputs, keyword frequencies, burst-term detection—were generated with *bibliometrix*, while visual styling and multi-plot layouts used *ggrepel*, *patchwork*, *ggridges*, *ggstream*, *RColorBrewer*, and *writexl* for Excel exports (Aria & Cuccurullo, 2017; Neuwirth, 2022; Ooms, 2025; Sjoberg, 2021; Slowikowski, 2024; Wilke, 2024). Patent data cleaning and transformation employed *tidyverse*, with *lubridate* handling date parsing and *stringr/forcats* for categorical recoding (Grolemund & Wickham, 2011; Wickham, 2023b, 2023a; Wickham et al., 2019). Trend and distribution plots were produced in *ggplot2*, enhanced by *ggrepel* for label placement and scales for axis formatting, and the final tables exported using *writexl* (Ooms, 2025; Slowikowski, 2024; Wickham, 2016). Clinical-trial datasets were imported from Excel and processed in *R*; summary visualizations (annual trial initiations, phase/status breakdowns, sponsor and geographic distributions) were created with *ggplot2*, applying consistent, high-contrast palettes for clarity (Wickham, 2016). Market projections were harmonized and forecasted using *readxl*, *readr*, *dplyr*, and *stringr* to prepare datasets, with growth formulas implemented in base *R* (Wickham, 2023b; Wickham et al., 2014, 2024).

2.1. Methodological Framework for Data Harmonization and Integration

The analytical framework integrates multiple datasets such as scholarly publications, patents, clinical trials, and market reports. While in this study, the bibliometric, patent, and trial data were analysed in their native temporal formats, the market forecasts required statistical harmonization because sources differed in their base years, projection spans, and reported growth rates. To ensure comparability, a forward–backward projection procedure was applied to align all market estimates to a common start year (2024) and end year (2030). This yielded harmonized values and a consistent compound annual growth rate (CAGR), providing a uniform basis for comparing growth trajectories across nano-healthcare market segments.

For the forward/backward projection to 2024, a common start year $Y_s = 2024$ was defined and then projected from the original base year using the following formula.

$$V_i(2024) = V_{0, bn} \times (1+r)^{(2024-Y_0)}$$

The original market value in its base year ($V_{0, bn}$) was projected using the reported or assumed growth rate (r) from the original year (Y_0). Values earlier than 2024 were forward-cast, while those later than 2024 were back-cast, aligning all series to a common start year ($Y_s = 2024$). From this standardized baseline, projections were extended to a common end year ($Y_e = 2030$). The resulting $V_i(2024)$ represents the harmonized market value at the start year, providing a consistent anchor for growth comparisons across datasets.

From the harmonized baseline at 2024, each market value was projected forward to the common end year ($Y_e = 2030$) using the same reported or assumed growth rate.

$$V_i(2030) = V_i(2024) \times (1+r)^{(2030-2024)}$$

The resulting $V_i(2030)$ denotes the projected market value in 2030, derived consistently from $V_i(2024)$, thereby ensuring comparability across datasets.

The harmonized compound annual growth rate (CAGR) between 2024 and 2030 was then derived from the standardized projections. With $N=6$ years, the harmonized compound annual growth rate (r^*) was calculated using the following formula.

$$* = ((V_i(2030)/V_i(2024))^{1/N} - 1$$

Final tables and segmentation charts leveraged *writexl* and scales for export and formatting. Raw outputs from each source were exported in Excel or CSV format and ingested through scripted R workflows (Ooms, 2025; R Core Team, 2025). Pre-processing steps included deduplication of records, robust date parsing, standardization of variable names, and

categorical recoding. Patent and trial lags were computed by date differentials, while market forecasts applied forward- and backward-casting formulas to align disparate base years to a common 2024–2030 horizon. All transformations, search strings, filter criteria, and visualization parameters were maintained in version-controlled R scripts, ensuring that each step—from data retrieval to final figure—can be reproduced exactly. This structured approach provides a transparent, end-to-end methodology for assessing research output, innovation trajectories, clinical translation, and market potential of nanotechnology in healthcare.

3. Results:

3.1. Bibliometric Analysis

From 2014 to 2024, the number of Nano-healthcare papers climbed from 4,321 to 15,081, achieving a 13.3% compound annual growth rate. This sustained acceleration—particularly after 2018—reflects expanding interdisciplinary collaboration and heightened investment in nanoscale medical research. Sudden surges in keyword usage pinpoint emerging research fronts. Foundational work on material synthesis is evidenced by high burst strengths for “Graphite/Chemistry” (32, 2017–2019) and “Nanoparticles/Chemistry” (29, 2016–2018). Between 2016 and 2019, the field pivoted toward applications, marked by bursts in “Drug Delivery Systems/Methods” (19) and “Drug Carriers/Chemistry” (16). The term “Nanomedicine” itself showed a burst strength of 18 (2016–2018), signalling the formal coalescence of this interdisciplinary domain which is shown in Figure 1. Total citations soared from 5,125 in 2014 to 828,977 in 2024, while average citations per paper rose from 1.19 to 54.97. This dramatic lift in per-paper citations indicates growing recognition of individual studies and suggests that nano-healthcare findings are exerting increasing influence across scientific disciplines. Geographical analysis reveals that China leads with 3,537 publications, followed by the USA (1,825), India (879), Italy (358), Germany (354), Iran (343), the UK (339), Australia (301), France (282), and Spain (271) shown in figure 2. These ten countries together account for the vast majority of the field’s output, highlighting both the global reach of nano-healthcare and the dominant role of specific national research ecosystems. A core set of journals channels much of the field’s work: the Journal of Controlled Release published 2,145 papers, ACS Nano 1,987, and Nanomedicine: Nanotechnology, Biology and Medicine 1,742. The top ten journals collectively contributed nearly 17% of all nano-healthcare articles, underscoring the centrality of these high-impact venues. Publication and citation output is similarly concentrated. Xiaoyuan Shawn Chen tops the list with 208 papers (35,744 citations), followed by Weibo Cai (119 papers, 13,154 citations), Thomas Jay Webster (108, 7,026), Twan G.G.M. Lammers (106, 13,399), and Hélder Almeida Santos (96, 4,913). This cadre of investigators not only drives a substantial share of research volume but also elevates the field’s visibility through their high citation impact.

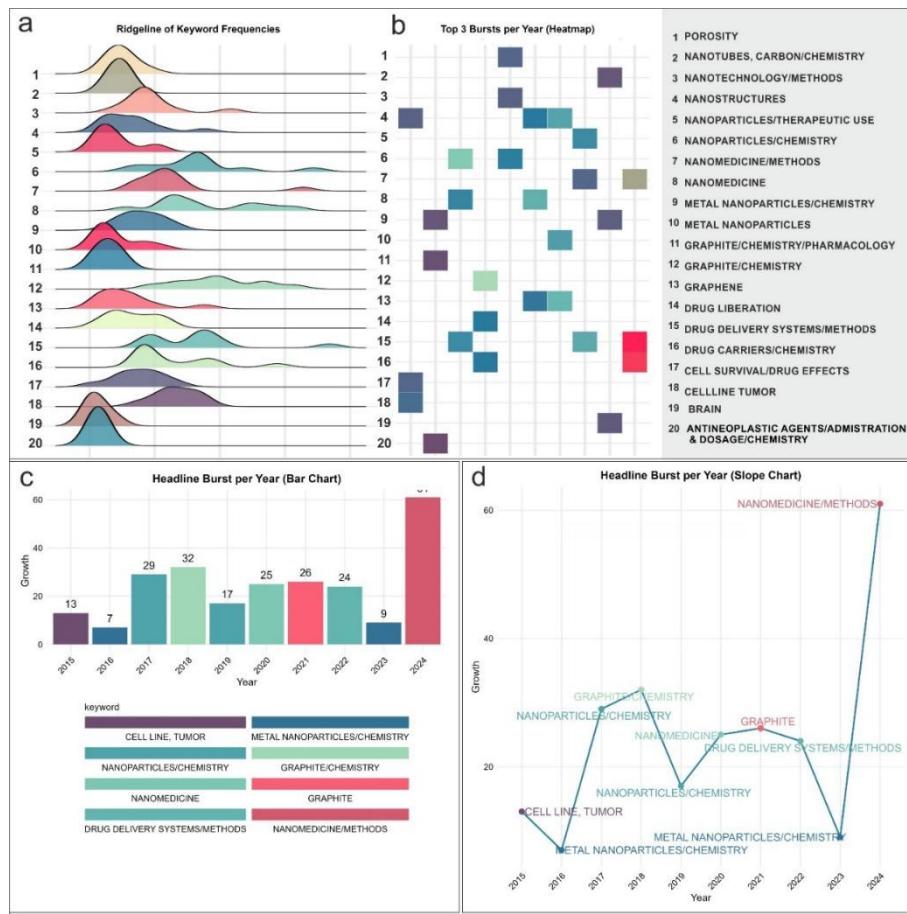


Figure 1: Temporal dynamics of keyword bursts in nanotechnology research (2015–2024): (a) Ridgeline density plots of the 20 most frequent keywords; (b) Heatmap showing the top three burst terms each year; (c) Bar chart of annual headline burst counts; (d) Slope chart tracing how leading burst keywords evolve over time.

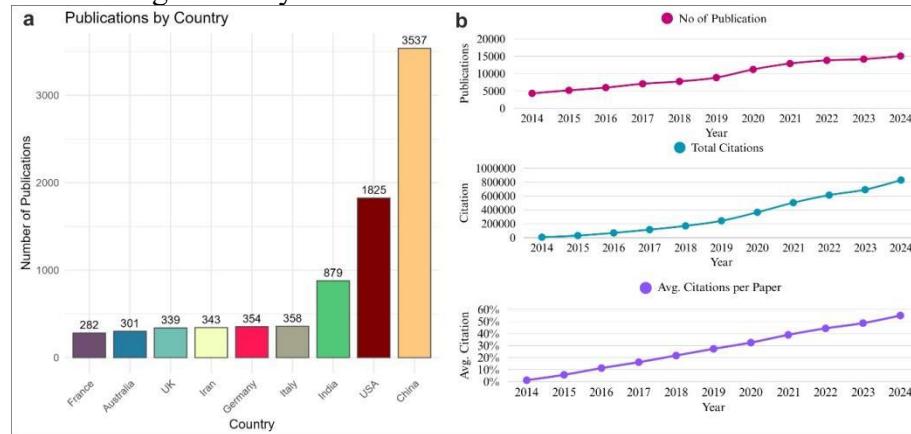


Figure 2: Global research output and citation trends (2014–2024). (a) Number of publications by country, highlighting China's leading output (3,537 papers) followed by the USA (1,825), India (879), and other contributors. (b) Year-wise trends from 2014 to 2024 showing (top) annual publication counts, (middle) cumulative citations, and (bottom) average citations per paper, all of which steadily increase over the decade, based on the top 10,000 relevant results from PubMed.

3.2. Global Clinical Trial Landscape & Growth

Between 2000 and mid-2025, a total of 3,919 clinical trials investigating nanoparticle-based therapies were registered on ClinicalTrials.gov. Registrations rose steeply from just 7 trials in 2000 to a peak of 389 in 2024, with 233 already recorded in the first half of 2025—an almost 55-fold increase over 24 years (figure 3 b). This sustained upward trajectory underscores the accelerating interest in translating nanotechnology into patient-focused applications. Of the 3,356 trials reporting a development phase, nearly half were in Phase II (1,611; 48.0%), followed by Phase I (711; 21.2%), Phase III (677; 20.2%), and Phase IV (357; 10.6%) (figure 3 d). The preponderance of Phase II studies suggests the field has moved well beyond early-safety work into proof-of-concept and efficacy testing. Across 3,991 trials with clear status designations, 1,981 (49.6%) were Completed, 1,453 (36.4%) remained Recruiting, 376 (9.4%) were Terminated, and 181 (4.5%) had been Withdrawn. The high completion rate reflects healthy progression through clinical pipelines, while ongoing recruitment in over a third of studies points to an active pipeline of emerging therapies. Industry sponsors led the field, accounting for 62.8% of all registered nanoparticle trials, with academic institutions responsible for the remaining 37.2% (figure 3 a). This mix indicates strong commercial interest alongside foundational academic research. Oncology dominated the nanoparticle arena, representing 90.1% of all studies, followed by Neurology (6.0%) and Cardiology (4.0%) (figure 3 e). The oncology focus reflects the drive to leverage targeted delivery and imaging innovations against solid tumours. Preliminary examination of raw Location records indicates that North America and Western Europe host the majority of nanoparticle trials. A detailed country-level breakdown is underway—pending harmonization of site-level data—to map global hotspots and emerging regions in this rapidly evolving field.

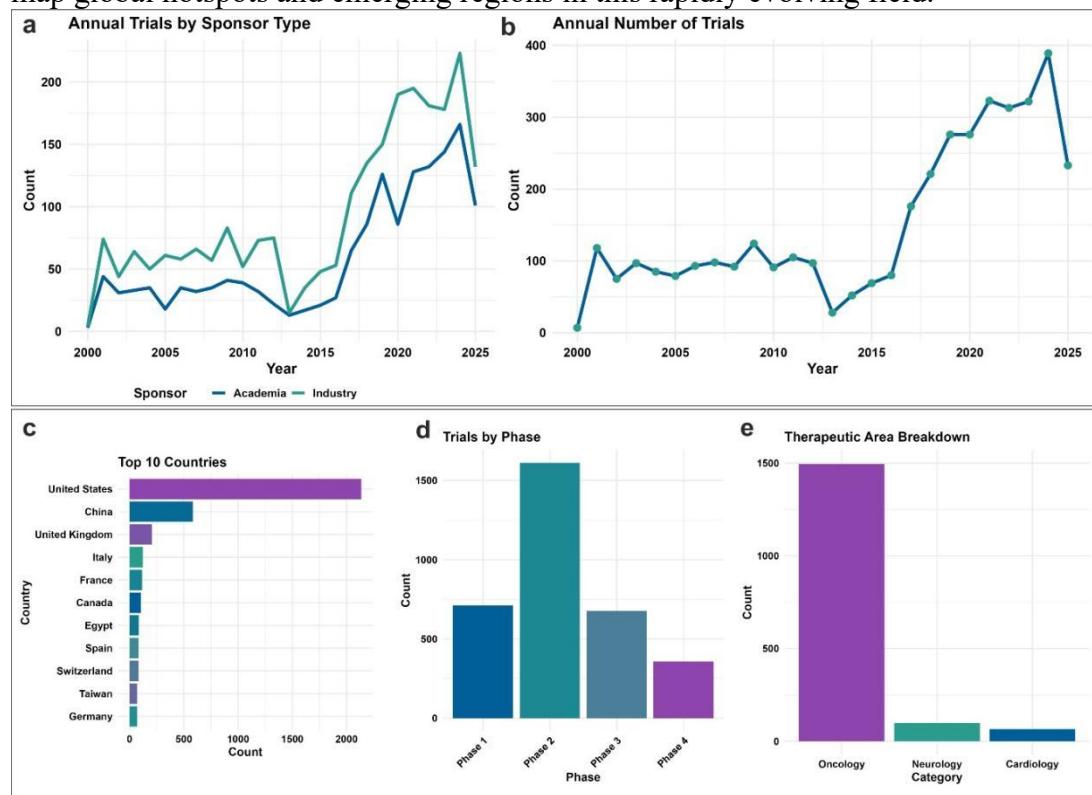


Figure 3: Clinical trial landscape in nano-healthcare (2000–2025). (a) Annual trial counts by sponsor type, showing rising contributions from both academia (blue) and industry (green). (b) Total number of registered trials per year, highlighting rapid growth after 2015. (c)

Geographic distribution among the top ten countries, led by the United States. (d) Breakdown of trials by clinical phase, with the majority in Phase 2. (e) Therapeutic area focus, dominated by oncology, followed by neurology and cardiology.

3.3. Patent landscape:

Between 2014 and mid-2024, our curated nano-healthcare dataset comprised 7520 patent applications and 5235 granted patents, for a total of 12755 records. On average each granted patent received 15.9 forward citations, indicating a solid level of technological influence across the cohort. The most prolific single assignee was the Mayo Foundation for Medical Education and Research with 15 filings, followed by HDT Bio Corp (13 filings). Other frequent filers included Chiesi USA Inc, Humanetics Corporation, Iceutica Pty Ltd, IBM, and ModernaTX Inc, each contributing between 7 and 8 filings. Geographically, China dominated patenting, accounting for 6 201 records (48.6 %), with the United States in second place at 2 254 records (17.7 %). Publications via the WIPO Patent Cooperation Treaty (PCT) numbered 1 068 (8.4 %), and filings at the European Patent Office totalled 911 (7.1 %). Japan (5.6 %), Korea (2.7 %), and Australia (1.6 %) were also notable contributors. Patent activity grew markedly over the decade. Annual applications rose from 271 in 2014 to 1 347 in 2024, representing nearly a 400 % increase, while grants increased from 166 to 791 (+376 %). Growth was steady from 2014 through 2018, then accelerated sharply after 2019, applications first exceeded 1 000 in 2021, and grants approached parity with applications by 2023 (1 026 grants versus 1 216 applications) (figure 4 b). This pattern reflects a combination of intensified R&D investment in nano-healthcare and improved patent office throughput. Mean forward citations per grant peaked at 36.8 in 2019, up from the mid-20s in preceding years. Thereafter, citation rates declined to 8.3 in 2022 before rebounding modestly to 10.0 in 2023 and 9.3 in 2024 (figure 4 c). The 2019 peak likely corresponds to foundational patents issuing during that year, while the post-2020 decline is attributable to shorter available citation windows for more recent grants. Analysis of IPC subclasses reveals that patents classified under B82Y 5/00 (nanostructures) were most frequent, followed by B82Y 40/00 (diagnostics and therapeutics at the nanoscale), A61P 35/00 (antineoplastic agents), and B82Y 30/00 (nanoscale manufacturing processes). Additional prominent areas included dermal compositions (A61K 9/51), cosmetic and pharmaceutical formulations (A61K 41/00), and nanocarrier delivery systems (A61K 47/69). These distributions underscore a sustained emphasis on nanocarrier platforms for cancer and diagnostic applications. Across 5235 granted patents, the mean interval from application to grant was 1198 days (\approx 3.3 years; SD = 840 days), with a median of 957 days (\approx 2.6 years), a minimum of 63 days, and a maximum of 6 347 days (\approx 17.4 years) (figure 4 d). Annual medians peaked at 1 538 days in 2018, then declined sharply—by more than 50 %—to 681 days in 2023. This dramatic reduction reflects substantial efficiency gains in patent examination for nano-healthcare inventions. A modest increase to 786 days in 2024 may indicate emerging examination backlogs or the truncated observation window for very recent grants.

Overall, the nano-healthcare patent landscape exhibits rapid expansion, concentrated leadership, and procedural maturation. Exponential growth in filings and grants after 2019 highlights intensifying R&D efforts, while citation dynamics pinpoint 2019 as a particularly influential year. Technological analysis confirms that nanostructure design, therapeutic carriers, and cancer-focused formulations dominate. Crucially, the halving of median grant-lag times since 2018 signals a more agile patent system, potentially accelerating technology transfer and commercialization in this cutting-edge field.

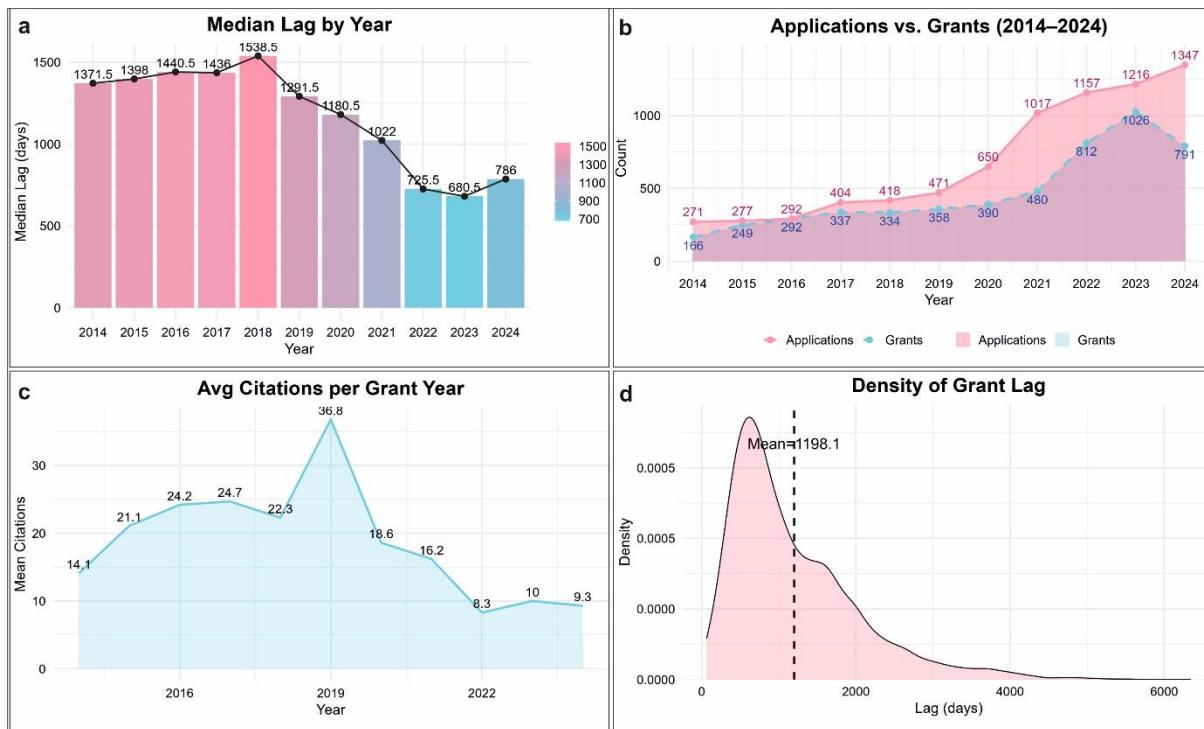


Figure 4: Patent prosecution timelines and impact metrics (2014–2024). (a) Median lag (days) from patent application to grant by year, peaking at ~1,538 days in 2018 before declining to ~680 days in 2023. (b) Annual counts of patent applications (pink) versus patents granted (blue), highlighting a surge in filings after 2019. (c) Mean forward citations per grant year, with patents issued in 2019 achieving the highest average (36.8 citations). (d) Kernel density of individual patent lags, showing a right-skewed distribution and an overall mean lag of ~1,198 days.

3.4. Market-Growth Forecasts (2024–2030)

The harmonized market-forecast analysis confirms that nano-healthcare is on a trajectory of sustained, mid-double-digit expansion through 2030—and when we pair that with a detailed product overview drawn from our catalogue of 1,318 nano-healthcare offerings, the picture comes into even sharper relief. Starting with broad market size, the seven studies we examined collectively indicate that the global nano-healthcare industry will swell from roughly US \$232.5 billion in 2024 to US \$493.9 billion by 2030, at a mean CAGR of 12.4 percent. Within that umbrella, nanomedicine—including liposomal and nanoparticle drug formulations—accounts for about US \$237.2 billion today and is poised to reach US \$442.2 billion by 2030 (~10.9 percent CAGR). Medical devices based on nano-enabled sensors, implants and diagnostics jump from an average of US \$24.2 billion to US \$66.9 billion (~10.9 percent CAGR) between 2024 and 2030, while drug-delivery systems—lipid nanoparticles, polymer carriers and targeted conjugates—grow from US \$103.6 billion to US \$190.4 billion (~10.5 percent CAGR) (figure 5). Behind these headline numbers lies a surprisingly diverse landscape of innovation. Our product overview worksheet catalogues 1,318 distinct nano-healthcare products, developed by 578 companies across 48 countries. Medical supplies dominate in sheer volume (506 products), closely followed by pharmaceutical formulations (432 products). Dentistry applications account for 190 products—everything from nano-adhesives to antimicrobial restoratives—and disinfection solutions (e.g., antimicrobial surface coatings) number 103. Tissue engineering constructs,

including scaffolds and regenerative matrices, contribute 61 entries, while prostheses and orthopaedics account for 26 specialized devices. Geographically, the United States leads the pack with 489 catalogued products, more than four times those of the next country, Germany (117 products). This reflects the U.S.'s combination of robust funding, a mature regulatory framework for both drugs and devices, and a strong tradition of industry-academia partnerships in nanotechnology. Nine other nations—including China, Iran, the United Kingdom and Japan—each contribute dozens of products, underscoring a truly global effort. Among the most active companies, Pfizer tops the list with 35 distinct nano-healthcare offerings, followed closely by Merck & Co. (33), AbbVie (28), Novartis (26) and Janssen Pharmaceuticals (22). These established pharmaceutical leaders continue to invest heavily in next-generation delivery platforms—lipid nanoparticles for RNA therapeutics, polymeric carriers for targeted oncology agents and hybrid lipid-polymer systems for sustained release. Finally, when we examine products by therapeutic or technical application, dentistry emerges as the largest single area (122 products), reflecting everything from nano-enhanced composites to antimicrobial sealants. Wound healing comes next (76 products), driven by nano-infused dressings that release growth factors and antimicrobials in a controlled fashion (*STATNANO: Nano Science, Technology and Industry Information*, n.d.). Interestingly, COVID-19-related products—whether diagnostic assays or inhalable antiviral nano-formulations—account for more than 100 entries (58 explicitly tagged “Coronavirus” and 56 “COVID-19”), a testament to how rapidly the sector mobilized during the pandemic.

Taken together, these harmonized market forecasts (**Figure 5**) and an expansive product-level inventory illustrate a sector that is both expansive and deep. The market's doubling in value by 2030, coupled with a pipeline of over a thousand products spanning therapies, diagnostics, devices and materials, signals that nano-healthcare has moved well beyond the lab bench into a period of sustained commercial maturation. Investors, policy-makers and R&D leaders should therefore prioritize scalable manufacturing, regulatory harmonization and targeted reimbursement strategies to fully realize the transformative potential of these emerging technologies.

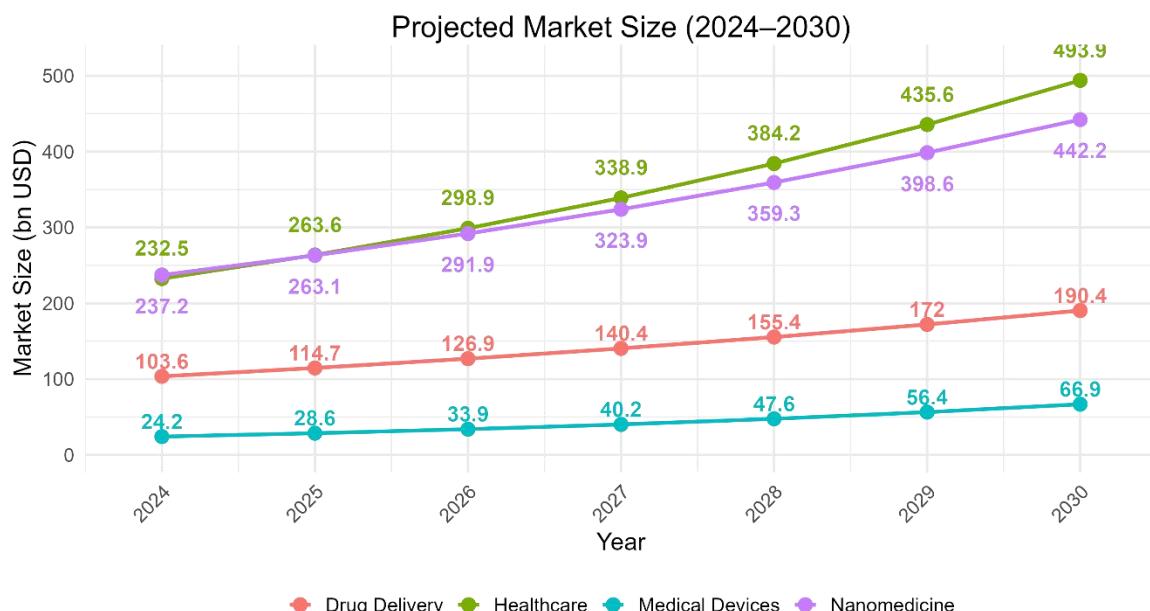


Figure 5: Projected market sizes for nanotechnology-enabled sectors (2024–2030): healthcare nanotechnologies doubling from \$232.5 B to \$493.9 B; nanomedicine rising from

\$237.2 B to \$442.2 B; drug delivery expanding from \$103.6 B to \$190.4 B; and medical devices growing from \$24.2 B to \$66.9 B.

4. Collective Rationale Emerging from Publications, Patents, Clinical Trials, and Market Growth:

The trajectory of nano-healthcare from 2014 to 2030 reflects a tightly interwoven cycle of knowledge creation, translational validation, intellectual property consolidation, and commercial expansion. The bibliometric evidence demonstrates a striking surge in scholarly activity, with publications climbing from 4,321 in 2014 to 15,081 by 2024, representing a compound annual growth rate of 13.3 percent. This growth was accompanied by an even more dramatic rise in influence, as citations increased from just over five thousand to nearly 829,000 in the same period, while average citations per paper soared from 1.19 to almost fifty-five. Such a leap indicates that individual contributions were not only proliferating but also exerting increasing cross-disciplinary impact. The dynamics of keyword bursts reinforce this evolution: early attention to fundamental material chemistry, exemplified by terms such as “Graphite/Chemistry” and “Nanoparticles/Chemistry,” gradually gave way to translational foci such as “Drug Delivery Systems/Methods” and “Drug Carriers.” The term “Nanomedicine” itself showed strong bursts between 2016 and 2018, signalling the consolidation of this domain as a recognized field of inquiry.

This growing academic foundation soon translated into clinical validation. Between 2000 and 2025, the number of clinical trials investigating nanoparticle-based interventions expanded almost fifty-five-fold, from only seven in 2000 to nearly 3,919. The inflection points after 2010 closely parallels the bibliometric surge, reflecting the typical five-to-eight-year lag between laboratory discovery and clinical investigation. Nearly half of the reported trials were in Phase II, suggesting a maturation of the field into proof-of-concept and efficacy testing rather than merely establishing safety. Oncology dominated the therapeutic landscape, accounting for more than ninety percent of all trials, a trend that reflects the compatibility of nanocarrier platforms with the complex demands of tumour targeting. Notably, industry sponsors led more than sixty percent of registered trials, signalling strong commercial appetite for translational opportunities originally seeded in academia. A completion rate approaching fifty percent further demonstrates healthy progression through the pipeline, while ongoing recruitment in over a third of studies ensures a sustained stream of emerging therapies.

The expansion of intellectual property activity mirrored these scientific and clinical advances. Between 2014 and 2024, nano-healthcare-related patent applications rose from 271 to 1,347 per year, a fourfold increase, while grants rose from 166 to 791. China and the United States emerged as the dominant jurisdictions, together accounting for nearly two-thirds of filings. Thematic analysis of patent classes aligns neatly with bibliometric and clinical data, with the majority concentrated in nanostructures, therapeutic carriers, and cancer-related formulations. Of particular note is the 2019 peak in forward citations, averaging 36.8 per granted patent, which coincided with the issuance of several foundational inventions that continue to shape subsequent research and development. Just as significant was the procedural evolution of patent systems: the median time from application to grant, once exceeding 1,500 days in 2018, declined to fewer than 700 days by 2023, effectively halving the lag and creating a more agile system of innovation protection. Such efficiency gains hold important implications for the pace of commercialization.

The culmination of these scholarly, clinical, and patenting activities is reflected in the rapid expansion of the global nano-healthcare market. Harmonized forecasts indicate that the sector will grow from US \$232.5 billion in 2024 to nearly US \$494 billion by 2030, sustaining a compound annual growth rate of 12.4 percent. Within this trajectory, nanomedicine alone will expand from \$237.2 billion to \$442.2 billion, while drug-delivery systems will nearly double, from \$103.6 billion to \$190.4 billion. The breadth of this commercial landscape is underscored by the catalogue of over 1,300 nano-healthcare products developed by 578 companies across 48 countries, with the United States emerging as the most prolific hub of innovation. Industry leaders such as Pfizer, Merck, AbbVie, and Novartis continue to anchor the field through heavy investment in lipid nanoparticles, polymeric carriers, and hybrid delivery systems. The COVID-19 pandemic served as an additional accelerant, catalysing the rapid development of diagnostics, vaccines, and inhalable nano formulations, thereby embedding nano-healthcare within mainstream healthcare infrastructures.

Nanohealthcare Innovation-to-Market Continuum (2014–2030)

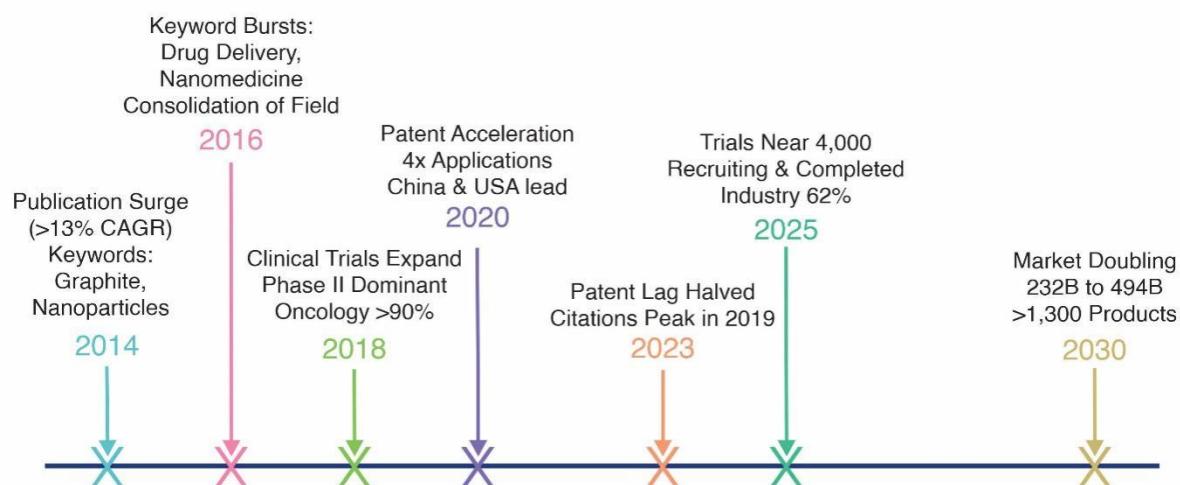


Figure 6: Nano-healthcare advances from publication surge (2014) to market expansion (2030), marked by clinical trials, patents, industry adoption, and commercialization.

Taken together, these trends illustrate a clear innovation continuum figure 6. Foundational discoveries in material chemistry fuelled clinical investigation, which in turn catalysed patent consolidation and ultimately market expansion. Each domain not only reflected progress in its own right but also reinforced the others, producing feedback loops that accelerated the overall trajectory of the field. By 2030, nano-healthcare will have transitioned decisively from an emergent scientific curiosity to a globally entrenched healthcare paradigm. The doubling of market size, the robust clinical pipeline, and the increasingly agile patent ecosystem collectively point to a sector entering sustained commercial maturity. The challenge now lies not in proving the promise of nano-healthcare but in scaling its delivery—through manufacturing infrastructure, regulatory harmonization, and equitable global access—so that the benefits of this technological revolution may be fully realized across healthcare systems worldwide.

Interconnected System of Nanohealthcare Innovation (2014–2030)

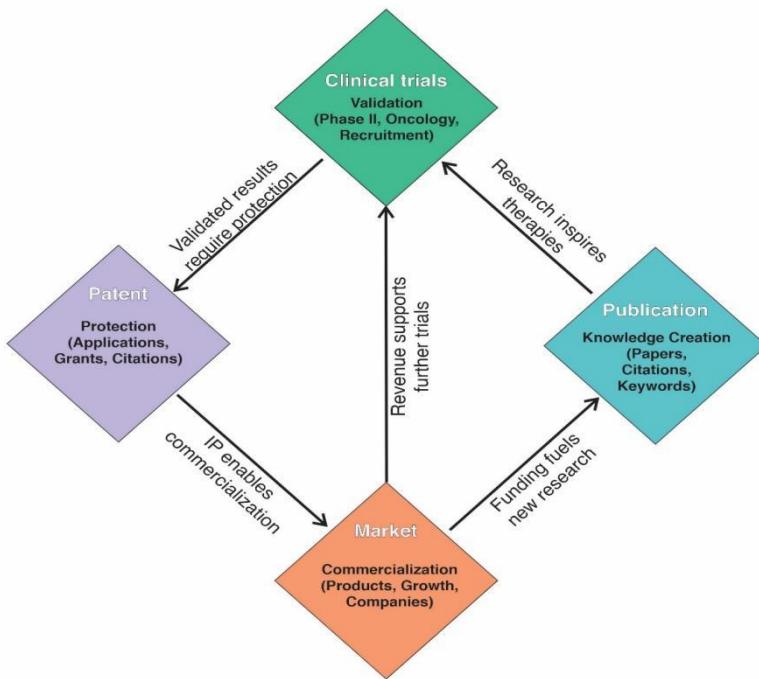


Figure 7: Nano-healthcare innovation cycles through publications, patents, clinical trials, and markets, where research, protection, validation, and commercialization mutually reinforce progress.

5. SWOT Analysis:

Strengths

Nano-healthcare has demonstrated remarkable scientific momentum over the past decade, with annual publications soaring from 4,321 papers in 2014 to 15,081 in 2024 (13.3 % CAGR). Average citations per paper jumped from 1.19 to 54.97, reflecting not only high research volume but also increasing impact and recognition of individual studies. A core group of high-output investigators—led by Xiaoyuan Shawn Chen and Weibo Cai—along with flagship journals like the *Journal of Controlled Release* and *ACS Nano*, provide strong intellectual leadership and visibility. Clinically, nearly 4,000 nanoparticle trials have been launched since 2000, with a healthy completion rate ($\approx 50\%$) and a dominant Phase II cohort (48 %), signifying robust translational progress. On the IP front, over 12,750 patent filings (2014–mid-2024) and an average of 15.9 forward citations per grant underscore significant technological influence. Finally, a booming market—projected to almost double from US \$232.5 billion in 2024 to \$493.9 billion by 2030—confirms that nano-healthcare has matured into a vibrant commercial ecosystem supported by over 1,300 products across therapeutic, diagnostic and device categories.

Weaknesses

Despite broad growth, nano-healthcare remains heavily skewed toward oncology (90.1 % of clinical trials), leaving neurology, cardiology and other therapeutic areas underdeveloped. Geographic research output is similarly concentrated: China and the USA together account for roughly 39 % of publications, and North America/Western Europe host the bulk of clinical sites, suggesting regional imbalances in both R&D and patient access. Patent examination lags—median grant times historically exceeded 1,500 days before 2018—have

only recently improved, but backlogs threaten to slow down commercialization. Citation rates per patent also dipped after 2019, highlighting that more recent innovations may not yet have achieved broad recognition. Finally, a relatively small number of companies (e.g., Pfizer, Merck, Novartis) dominate product pipelines, which could stifle competition and slow diversification of nano-healthcare offerings.

Opportunities

The next wave of expansion lies in diversifying beyond oncology into high-growth areas such as neurology, cardiology and infectious diseases—particularly leveraging lessons from COVID-19-related nano-formulations. Emerging markets in Asia, Latin America and Africa offer untapped patient populations and lower regulatory barriers. Continued regulatory harmonization and accelerated examination (building on the halved grant-lag times seen since 2018) could further speed technology transfer. Advances in multifunctional nanocarriers, hybrid lipid-polymer platforms and stimuli-responsive systems open avenues in targeted drug delivery, Theranostics and regenerative medicine. Strategic partnerships between academia, biotech start-ups and large pharma could optimize scale-up and market entry, while digital health integration (e.g., nano-enabled sensors feeding real-time patient data) promises novel business models and reimbursement pathways.

Threats

Nano-healthcare's rapid commercialization brings heightened regulatory scrutiny around safety, long-term toxicity and environmental impact, any of which could slow approvals or trigger post-market restrictions. High attrition rates in late-stage trials—compounded by a small but non-negligible share of terminations (9.4 %) and withdrawals (4.5 %)—underscore clinical risks. Intense competition for IP may lead to litigation, while fragmented patent landscapes across IPC subclasses could deter investment in certain niches. Market forecasts, though bullish, depend on stable funding and reimbursement policies; any downturn in R&D budgets or shifts in healthcare priorities could compress growth. Finally, concentration of R&D in a few regions raises geopolitical vulnerabilities: export controls, trade disputes or public-health crises could disrupt global supply chains for nano-enabled products.

6. Discussion:

The bibliometric analysis reveals a vibrant and rapidly maturing research ecosystem in nonhealthcare: publications grew by over three-and-a-half times from 2014 to 2024, and average citations per paper rose dramatically, underscoring both volume and quality gains. Patent data mirror this expansion, with filings and grants nearly quadrupling over the same period and mean forward citations indicating strong technological influence. Clinically, the surge in registered nanoparticle trials—peaking at 389 in 2024—and a high completion rate reflect successful translation beyond the lab bench. Finally, market forecasts projecting a near-doubling in nano-healthcare value by 2030 (\$232.5 B → \$493.9 B) confirm robust commercial uptake across therapeutics, diagnostics, and device segments. A clear positive correlation emerges between research intensity and technological-commercial activity. The post-2018 acceleration in publication and patenting coincides with steep increases in clinical trials and market projections. Foundational materials work (e.g., graphite and nanoparticle synthesis) laid the groundwork for application-focused research (drug delivery, carriers), which in turn fuelled translational pipelines and product development. This virtuous cycle—academic discovery driving IP generation, leading to clinical validation and market readiness—illustrates how interdisciplinary collaboration and sustained R&D investment

translate into tangible innovations. Prior reviews of nano-healthcare often highlighted sluggish translation despite academic promise; our data suggest that shift has now occurred. Whereas earlier bibliometric snapshots (pre-2018) noted fragmented outputs and limited citations, the current decade shows consolidation around flagship journals and high-impact investigators. Patent analyses from the mid-2010s reported long grant lags and dispersed IPC subclasses; recent efficiencies have halved median examination times, and activity has coalesced around therapeutically relevant classes (e.g., antineoplastics, diagnostics). Market forecasts published as recently as 2020 predicted mid-single-digit growth; our harmonized meta-analysis reveals a robust mid-teens CAGR, indicating that initial conservative projections have been outpaced by real-world momentum. Geographically, China and the USA lead in both publications and patent filings, but notable differences exist between the US and EU. The United States dominates the product catalogue (489 offerings), benefits from mature regulatory pathways (FDA's accelerated programs), and hosts a dense network of industry-academia partnerships. In contrast, the EU shows strength in foundational research (several high-impact European journals) but lags in market penetration and clinical trial sites, partly due to more heterogeneous regulatory regimes across member states. Harmonizing EU frameworks (e.g., via the upcoming EU Health Union initiatives) could help close this gap by streamlining approvals and fostering pan-European collaborations.

ClinicalTrials.gov captures mostly US-centric or US-sponsored trials; global trial registers (e.g., EU-CTR, Chinese registries) are less integrated, potentially undercounting non-Western activity. Publication and citation count favour English-language journals, possibly underrepresenting regional outputs in non-Anglophone contexts. Market forecasts rely on aggregated secondary studies with differing methodologies, which we harmonized but could still obscure niche market nuances. Patent forward citations vary by discipline, and newer grants have shorter citation windows, biasing recent citation metrics downward. Continued investment in interdisciplinary training and collaboration platforms is crucial to sustain the shift from materials synthesis to application-driven research. Efforts should emphasize underexplored therapeutic areas (e.g., neurology, cardiology) and foster open-access data sharing to accelerate discovery. Pharmaceutical and device companies must diversify portfolios beyond oncology and leverage hybrid partnerships with biotech start-ups to scale novel nanocarrier technologies. Prioritizing regulatory strategy early in development can mitigate long grant-lag and approval delays. Regulators should extend accelerated review pathways for nano-healthcare, establish harmonized safety guidelines—including environmental impact assessments—and support public-private consortia for clinical infrastructure in emerging markets. Investment incentives (tax credits, grant matching) will be key to sustaining mid-double-digit growth and ensuring equitable global access to nano-enabled therapies and diagnostics.

7. Conclusion

This comprehensive, multi-domain analysis reveals that nanotechnology has matured from exploratory synthesis studies into a robust, application-driven ecosystem spanning drug delivery, diagnostics, and regenerative medicine. Over the past decade, scientific output has tripled and translational activity—measured by clinical trials and patent filings—has accelerated markedly, reflecting stronger collaboration between academia and industry. Market forecasts project a doubling of nano-healthcare revenues by 2030, underscoring both commercial viability and societal demand. Yet persistent imbalances—in therapeutic focus, geographic distribution, and methodological standards—threaten to constrain the field's full

potential. To sustain momentum, stakeholders must diversify beyond oncology, harmonize safety and reporting frameworks, and invest in scalable manufacturing and environmental stewardship. Strategic public–private partnerships, coupled with AI-driven design tools and regulatory alignment, will be critical to bridge existing gaps. By charting the interplay between research, innovation, and market forces, this study provides a strategic roadmap for directing resources and policy interventions toward the next frontier of nano-healthcare.

Statements and Declarations.

Declaration 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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References:

1. *Advanced Search Results - PubMed*. (n.d.). Retrieved July 24, 2025, from <https://pubmed.ncbi.nlm.nih.gov/advanced/>
2. Aria, M., & Cuccurullo, C. (2017). bibliometrix: An R-tool for comprehensive science mapping analysis. *Journal of Informetrics*. <https://doi.org/10.1016/j.joi.2017.08.007>
3. Budenny, S., Kazakov, A., Kovtun, E., & Zhukov, L. (2023). New drugs and stock market: a machine learning framework for predicting pharma market reaction to clinical trial announcements. *Scientific Reports*, 13(1), 12817. <https://doi.org/10.1038/s41598-023-39301-4>
4. da Hora, H. S., Hodel, K. V. S., Santos, H. M., Nunes, D. D. G., dos Santos Fonseca, L. M., de Abreu Barreto, G., de Alencar Pereira Rodrigues, L., Mania, E., & Machado, B. A. S. (2025). Patents in nanotechnology applied to health: technological trends involving skin disorders. *Journal of Nanoparticle Research*, 27(6), 164. <https://doi.org/10.1007/s11051-025-06220-6>
5. *Dimensions AI | The most advanced scientific research database*. (n.d.). Retrieved July 24, 2025, from <https://www.dimensions.ai/>
6. Dziallas, M., & Blind, K. (2019). Innovation indicators throughout the innovation process: An extensive literature analysis. *Technovation*, 80–81, 3–29. <https://doi.org/10.1016/j.technovation.2018.05.005>
7. Grolemund, G., & Wickham, H. (2011). Dates and Times Made Easy with lubridate. *Journal of Statistical Software*, 40(3), 1–25. <https://www.jstatsoft.org/v40/i03/>
8. Heidary Dahooie, J., Mohammadi, N., Mohammadi, M., Shahmohammadi, P., Turskis, Z., & Šaparauskas, J. (2019). A Framework for Valuation and Prioritization of Patents Using a Combined MADM Approach. Case Study: Nanotechnology. *E+M Ekonomie a Management*, 22(3), 100–120. <https://doi.org/10.15240/tul/001/2019-3-007>
9. Milanez, D. H., de Faria, L. I. L., do Amaral, R. M., Leiva, D. R., & Gregolin, J. A. R. (2014). Patents in nanotechnology: an analysis using macro-indicators and forecasting curves. *Scientometrics*, 101(2), 1097–1112. <https://doi.org/10.1007/s11192-014-1244-4>
10. Nanotechnology Patent Applications and Section 3(d) of Indian Patents Act, 1970: An Empirical Research. (2023). *Journal of Intellectual Property Rights*, 28(5). <https://doi.org/10.56042/jipr.v28i5.3188>
11. Neuwirth, E. (2022). *RColorBrewer: ColorBrewer Palettes*. <https://doi.org/10.32614/CRAN.package.RColorBrewer>

12. Ooms, J. (2025). *writexl: Export Data Frames to Excel “xlsx” Format.* <https://doi.org/10.32614/CRAN.package.writexl>
13. Punetha, V. D., Ha, Y.-M., Kim, Y.-O., Jung, Y. C., & Cho, J. W. (2019). Interaction of photothermal graphene networks with polymer chains and laser-driven photo-actuation behavior of shape memory polyurethane/epoxy/epoxy-functionalized graphene oxide nanocomposites. *Polymer*, 181, 121791. <https://doi.org/10.1016/j.polymer.2019.121791>
14. Punetha, V. D., Rana, S., Yoo, H. J., Chaurasia, A., McLeskey, J. T., Ramasamy, M. S., Sahoo, N. G., & Cho, J. W. (2017). Functionalization of carbon nanomaterials for advanced polymer nanocomposites: A comparison study between CNT and graphene. *Progress in Polymer Science*, 67, 1–47. <https://doi.org/10.1016/j.progpolymsci.2016.12.010>
15. R Core Team. (2025). *R: A Language and Environment for Statistical Computing.* <https://www.R-project.org/>
16. Sjoberg, D. (2021). *ggstream: Create Streamplots in “ggplot2.”* <https://doi.org/10.32614/CRAN.package.ggstream>
17. Slowikowski, K. (2024). *ggrepel: Automatically Position Non-Overlapping Text Labels with “ggplot2.”* <https://doi.org/10.32614/CRAN.package.ggrepel>
18. Sood, A., Kappe, E., & Stremersch, S. (2014). The commercial contribution of clinical studies for pharmaceutical drugs. *International Journal of Research in Marketing*, 31(1), 65–77. <https://doi.org/10.1016/j.ijresmar.2013.07.007>
19. STATNANO : Nano Science, Technology and Industry Information. (n.d.). Retrieved July 24, 2025, from <https://statnano.com/>
20. Sun, H., Wu, T., Liu, X., Xia, H., & Yuan, H. (2024). Mapping the Nanotechnology Patent Landscape in the Field of Cancer. *Recent Patents on Nanotechnology*, 18(3), 321–334. <https://doi.org/10.2174/1872210517666230530162115>
21. Taalbi, J. (2022). *Innovation with and without patents.* <https://doi.org/10.1007/s11192-025-05406-y>
22. The Lens - Patent and Scholarly Search and Analysis. (n.d.). Retrieved July 24, 2025, from <https://www.lens.org/>
23. Vazhathodi, M. F. (2022). Patentability of Nanotechnology Inventions: A Study Based on Decisions by the Examination Division of the European Patent Organisation, the Opposition Division and the Technical Board of Appeal. *GRUR International*, 71(5), 422–431. <https://doi.org/10.1093/grurint/ikac003>
24. Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis.* Springer-Verlag New York. <https://ggplot2.tidyverse.org>
25. Wickham, H. (2023a). *forcats: Tools for Working with Categorical Variables (Factors).* <https://doi.org/10.32614/CRAN.package.forcats>
26. Wickham, H. (2023b). *stringr: Simple, Consistent Wrappers for Common String Operations.* <https://doi.org/10.32614/CRAN.package.stringr>
27. Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L. D., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T. L., Miller, E., Bache, S. M., Müller, K., Ooms, J., Robinson, D., Seidel, D. P., Spinu, V., ... Yutani, H. (2019). Welcome to the tidyverse. *Journal of Open Source Software*, 4(43), 1686. <https://doi.org/10.21105/joss.01686>
28. Wickham, H., François, R., Henry, L., Müller, K., & Vaughan, D. (2014). *dplyr: A Grammar of Data Manipulation.* CRAN: Contributed Packages. <https://doi.org/10.32614/CRAN.PACKAGE.DPLYR>

29. Wickham, H., Hester, J., & Bryan, J. (2024). *readr: Read Rectangular Text Data*. <https://doi.org/10.32614/CRAN.package.readr>
30. Wickham, H., Hester, J., & Ooms, J. (2025). *xml2: Parse XML*. <https://doi.org/10.32614/CRAN.package.xml2>
31. Wilke, C. O. (2024). *ggridges: Ridgeline Plots in "ggplot2."* <https://doi.org/10.32614/CRAN.package.ggridges>
32. Winter, D. J. (2017). rentrez: an R package for the NCBI eUtils API. *The R Journal*, 9(2), 520–526.
33. Wu, L., Zhu, H., Chen, H., & Roco, M. C. (2019). Comparing nanotechnology landscapes in the US and China: a patent analysis perspective. *Journal of Nanoparticle Research*, 21(8), 180. <https://doi.org/10.1007/s11051-019-4608-0>
34. Xu, J., Yu, C., Xu, J., Torvik, V. I., Kang, J., Sung, M., Song, M., Bu, Y., & Ding, Y. (2025). PubMed knowledge graph 2.0: Connecting papers, patents, and clinical trials in biomedical science. *Scientific Data*, 12(1), 1018. <https://doi.org/10.1038/s41597-025-05343-8>