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# Fluorescent Nano-sensors at the Nano–Bio Interface: Mechanistic Convergence of FRET, Nanomaterials and AI-Enabled Diagnostics

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## Authors Contributions:

**Sunil Kumar:** Writing-original draft, formal analysis, and data curation.

**Sushma Singh:** Writing-review and editing, formal analysis, and conceptualization.

**Abhishek Chakraborty:** Writing – original draft, review and editing, visualization, validation, project administration and conceptualization.

**Data Availability Statement:** The bibliometric dataset used in this study was retrieved from the Scopus database using a defined search query and inclusion criteria (2002–2026). While direct sharing of raw Scopus records is restricted by licensing agreements, all relevant methodological details, including the search string and screening process are provided to enable reproducibility. Processed data may be made available by the corresponding author upon reasonable request.

## Abstract

Fluorescent nano-sensors at the nano–bio interface has undergone a mechanistic convergence in which fluorescence resonance energy transfer (FRET) based transduction, nanomaterial enabled signal control and artificial intelligence driven analytics are increasingly integrated to enable intelligent diagnostic applications. This study provides a comprehensive bibliometric synthesis that clarifies how fluorescent nano-sensor research has structurally evolved over the past two decades with particular emphasis on translational relevance. By integrating temporal growth analysis, intellectual structure mapping, collaboration networks and thematic evolution the study demonstrates increasing shift from early mechanism-driven FRET systems toward mature application-oriented platforms increasingly augmented by artificial intelligence. The results reveal strong thematic convergence between fluorescence mechanisms, nanomaterials and AI-assisted analytics supported by globally networked yet institutionally concentrated collaboration hubs. Importantly, this work identifies emerging diagnostic trajectories characterized by automated signal interpretation enhanced sensitivity and adaptive analytical performance. These insights provide strategic evidence base for guiding methodological standardization, interdisciplinary collaboration and validation-focused research. Finally, the findings support the accelerated development and real-world translation of intelligent fluorescent nano-sensors for clinical diagnostics, environmental monitoring and point-of-care applications.

**Keywords:** *Fluorescent nano-sensors, Nano–bio interface, Fluorescence resonance energy transfer (FRET), Nanomaterials, Artificial intelligence enabled diagnostics, Machine learning in biosensing.*

## Introduction

Fluorescent nano-sensors have emerged as a keystone of modern nano–bio research by enabling highly sensitive detection, imaging and quantification of biological, chemical and environmental targets as previously reported (1). By integrating fluorescence mechanisms with nanoscale materials these sensors offer unique advantages such as high signal-to-noise ratios, spatial temporal resolution and adaptability for real-time analysis (2). Among these mechanisms the fluorescence resonance energy transfer (FRET) has played a pivotal role providing a robust platform for molecular recognition and signal transduction in biosensing applications as reported (3). (4,5) Demonstrated that over the past two decades the rapid advances in nanomaterial engineering including quantum dots, carbon dots, graphene-based systems and hybrid nanostructures which have substantially expanded the functional scope of fluorescent nano-sensors. These developments have enabled applications ranging from

bioimaging and disease diagnostics to food safety and environmental monitoring (6). Concurrently, increasing research complexity associated with multiplexed sensing and high-throughput imaging has driven the incorporation of machine learning and artificial intelligence (AI) based analytical approaches thus marking a paradigm shift from mechanism-centric sensing toward AI and data-driven diagnostic systems as observed in some earlier studies (7,8). Despite this rapid growth the fluorescent nano-sensor literature remains highly fragmented across disciplines, materials platforms, analytical methodologies and application domains (9). While numerous experimental and review studies have addressed specific sensing strategies or materials, comprehensive and system-level understanding of the field's evolutionary growth, intellectual structure, collaboration dynamics and thematic convergence is still lacking (10). Such an understanding is essential for identifying dominant research trajectories, emerging methodological shifts and translational bottlenecks that influence the deployment of fluorescent nano-sensors in real-world scenario (11).

In this study a comprehensive bibliometric analysis of Scopus-indexed fluorescent nano-sensor research published between 2002 and 2026 is conducted to systematically examine: (i) the temporal growth and maturation of the field (RQ1) (ii) shifts in its intellectual and analytical foundations (RQ2) (iii) global collaboration and knowledge diffusion patterns (RQ3) and (iv) the extent of thematic convergence between fluorescence mechanisms, nanomaterial platforms and AI-integrated analytics (RQ4).

By integrating performance indicators, network analysis and thematic evolution mapping, this work provides a consolidated knowledge base and strategic perspective on the development of fluorescent nano-sensors (12). The findings aim to inform future research directions, support methodological standardization and accelerate the translation of intelligent fluorescent nano-sensing technologies toward diagnostic, biomedical and environmental applications.

## **2. Research Questions and Analytical Framework**

### **RQ1 (Evolutionary Growth).**

*How has fluorescent nano-sensor research evolved temporally between 2002 and 2026 and what distinct growth phases characterize its progression toward a mature research domain?*

**Methodological linkage:** RQ1 is addressed using longitudinal performance analysis of annual publications and citations from Scopus (2002–2026). Publication–citation trends, life-cycle modeling and cumulative growth curves were applied to identify exploratory, expansion and consolidation phases and to assess structural maturation (13).

### **RQ2 (Intellectual Restructuring).**

*How has the intellectual structure of fluorescent nano-sensor research shifted from mechanism-centric fluorescence and FRET-based systems toward data-driven and AI-integrated analytical frameworks?*

**Methodological linkage:** RQ2 is examined through keyword frequency, centrality and co-citation analyses. VOSviewer-based keyword co-occurrence networks were used to evaluate the persistence of FRET and the growing integration of machine learning and artificial intelligence within the intellectual structure (14).

**RQ3 (Collaboration Intensification).**

*What are the dominant global collaboration patterns and knowledge diffusion pathways shaping fluorescent nano-sensor research and how do institutional and author-level networks influence research consolidation?*

**Methodological linkage:** RQ3 is investigated using country, institution and author-level collaboration networks and productivity distributions. Co-authorship mapping and Lotka-type patterns were employed to characterize global knowledge diffusion and institutional concentration (15).

**RQ4 (Thematic Convergence).**

*To what extent does thematic convergence occur among fluorescence mechanisms, nanomaterial platforms, AI-enabled analytics and how does this convergence support the emergence of intelligent diagnostic nano-sensing systems?*

**Methodological linkage:** RQ4 is addressed through thematic evolution (Sankey analysis), strategic thematic mapping and citation dynamics, enabling assessment of convergence among fluorescence mechanisms, nanomaterials and AI-enabled analytics over time (16).

### **3. Methodology**

#### **3.1 Data Source and Search Strategy**

The bibliometric dataset for this study was obtained exclusively from the Scopus database, selected for its extensive multidisciplinary coverage, standardized citation indexing and strong representation of peer-reviewed journals in nanoscience, biosensing and artificial intelligence (17). Scopus is widely recognized as a robust and reliable source for bibliometric and science-mapping analyses and is particularly suitable for studies examining interdisciplinary research domains (18). Data retrieval was conducted on 16 January 2026, ensuring consistency and minimizing potential bias due to continuous database updates. The focused search strategy deliberately targeted the precise intersection of fluorescent nano sensors, nanomaterial-enabled fluorescence mechanisms including FRET and explicit incorporation of artificial intelligence or machine learning approaches for diagnostics (19). This intentional narrow scope yields a

smaller but high-quality dataset of 4273 records, ensuring methodological rigor, relevance and depth rather than breadth, while capturing the emerging core of AI-integrated fluorescent nano sensing research.

A comprehensive and systematically constructed search strategy was employed to capture literature at the intersection of fluorescent nano sensors, FRET-based fluorescence mechanisms, nanomaterial-enabled sensing platforms and AI-driven diagnostic analytics (20). The search period covered publications from 2002 to January 16, 2026, encompassing both the foundational phase of fluorescence-based nano sensing and its recent convergence with AI-assisted analytical approaches frameworks. To ensure methodological rigor and data quality, Conference papers, book chapters and other non-article document types were retained in the initial dataset but excluded from conceptual, thematic and citation-based interpretations (20). Only peer-reviewed journal articles and review papers published in English were retained. Search string: *TITLE-ABS-KEY (fluorescent nano " OR "fluorescence nano " OR "FRET OR "Fluorescence resonance energy transfer" AND "artificial intelligence" OR "machine learning" OR "deeplearning" OR "AI" OR "ML" AND "sensor" OR "nano-sensor" OR "biosensor" OR "diagnostic")*

After applying the inclusion and exclusion criteria, a total of 4273 valid records was identified. The complete bibliographic information including cited references, was exported in CSV and plain-text formats and served as the final dataset for subsequent performance analysis and science-mapping procedures using Biblioshiny and VOSviewer (20).

### **3.2 Inclusion and Exclusion Criteria**

To ensure relevance and methodological consistency, the analysis included English-language peer-reviewed journal articles and review papers indexed in Scopus between 2002 and January 2026 that focus on fluorescent nano sensors or fluorescence-based biosensing, involve nanomaterial-enabled fluorescence mechanisms including FRET and incorporate artificial intelligence or data-driven analytical approaches for diagnostics (21). Excluded were editorials, letters, book chapters, short surveys, retracted or duplicate records, non-fluorescent sensing studies and AI-related works lacking direct relevance to fluorescent nano sensing (22). This screening process ensured focused and high-quality dataset aligned with the bibliometric objectives (23). Bradford zones were identified by ranking sources according to publication output and cumulative citations followed by classification into core and successive zones based on source scattering patterns (24).

## **4. Results**

### **4.1 Evolution of Scientific Production (RQ1)**

The document type distribution which is summarised in Table 1 reveals predominance of review articles which accounts to 52% of total 4,273 publications, followed by original research articles which is 37% (1,600 publications) indicating research landscape of the specified field, characterized by strong thematic consolidation and continued experimental activity. The high proportion of reviews reflects the interdisciplinary nature of fluorescent nano-sensor research where advances of nano-bio interface require frequent synthesis of concepts spanning materials science, fluorescence mechanisms and biological applications which is in agreement with the observations (9,25).

*Table 1: Distribution of document types*

<b>Document Type</b>	<b>Publications (TP)</b>	<b>Percentage (%)</b>
Review	2,212	52%
Article	1,600	37%
Book chapter	340	8%
Book	121	3%
<b>Grand Total</b>	<b>4,273</b>	<b>100.0</b>

At the same time the substantial share of original articles highlights ongoing methodological and experimental development, which is in line with (26). Contributions of book chapters and books in the specified field, remain limited accounting to only 11% of the total publications, suggesting that knowledge dissemination in this field is primarily driven by peer-reviewed journals which is consistent with the swift evolution and dynamic scope of nanoscience-based biosensing research (27).

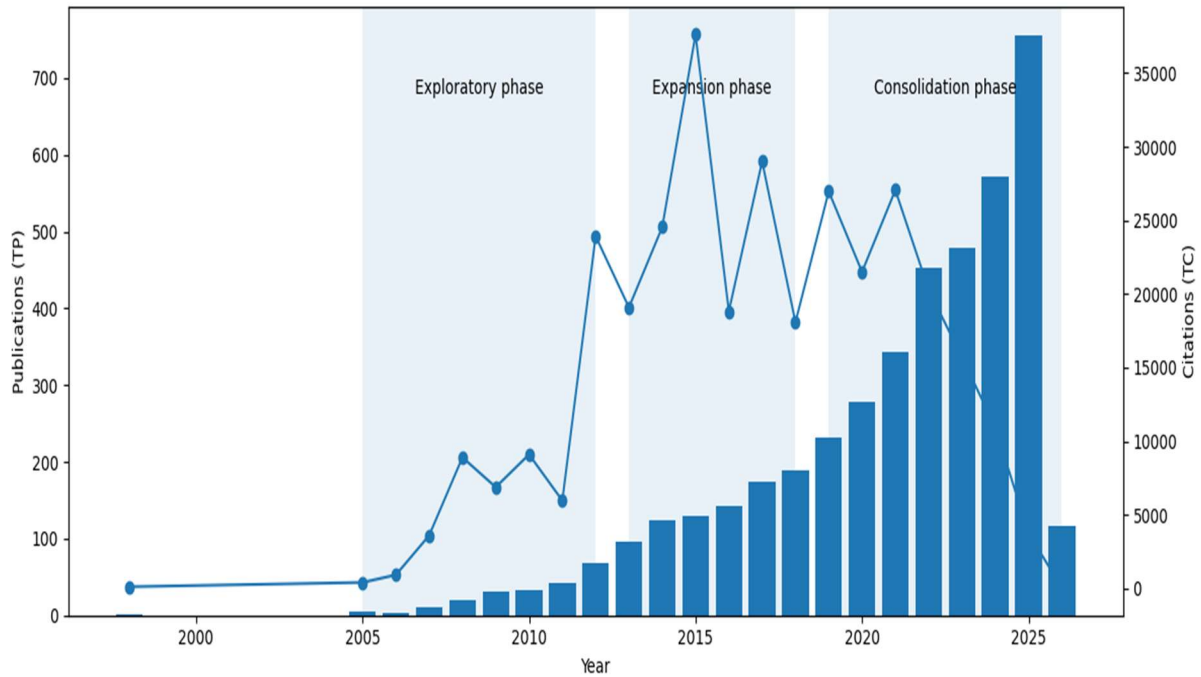


Figure 1: Annual publication output and citation trends in fluorescent nano sensor research

The Figure 1 reveals three-phase evolutionary trajectory which is suggested by (27). The exploratory phase from 2005 to 2012 is characterized by sporadic publication and unstable citation patterns, reflecting early conceptual development. The expansion phase from 2013 to 2018 with steady growth in publications as well as citations, indicating thematic diversification and broader adoption of fluorescence-based nano sensing approaches. The consolidation phase from 2019 to 2026 onwards, demonstrates rapid publication growth and strong citation impact, confirming structural maturation of the field. The decline in citation post-2024 is attributable to shorter citation windows thereby supporting RQ1.

The life-cycle analysis presented in Figure 2 of annual publication output based on a logistic growth model, complementing the phase-based temporal trends shown in Figure 1. The fitted curve with  $R^2$  of 0.78 indicates an initial period of slow growth followed by rapid acceleration which is consistent with the exploratory and expansion phases similar findings were observed in the field of “*life sciences*” (29). The estimated peak in publication activity around 2023-24 corresponds to consolidation phase, suggesting transition from rapid expansion toward more stabilized publication similar findings were observed in the field of “*environmental design*” (30). While short-term fluctuations are evident in the observed data the logistic fit captures the overall maturation trajectory of the field which is in agreement with the observation in the area of “*mine thermal environment*” (31). Notably, the forecasted trend should be interpreted as descriptive indicator of structural evolution rather than deterministic prediction thus reflecting

typical life-cycle behavior in maturing nano–bio research domains which is in line with RQ1 and is supported by the similar findings in “life sciences” (29).

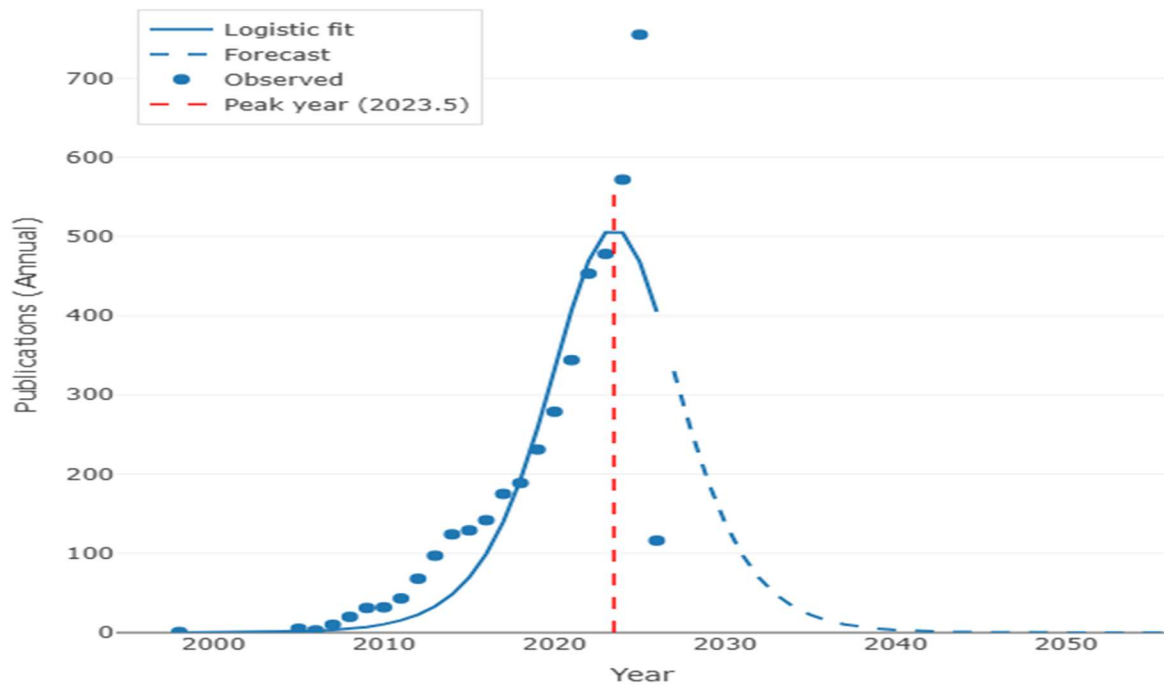


Figure 2: Life-cycle dynamics of annual publications in fluorescent nano sensor research

The cumulative growth curve in Figure 3 exhibits saturation tendency is further reflected in the document-type distribution where the high proportion of review articles indicates increased efforts toward knowledge synthesis and consolidation a pattern commonly observed as research fields transition from rapid expansion to structural maturity which is in agreement with (32,33).

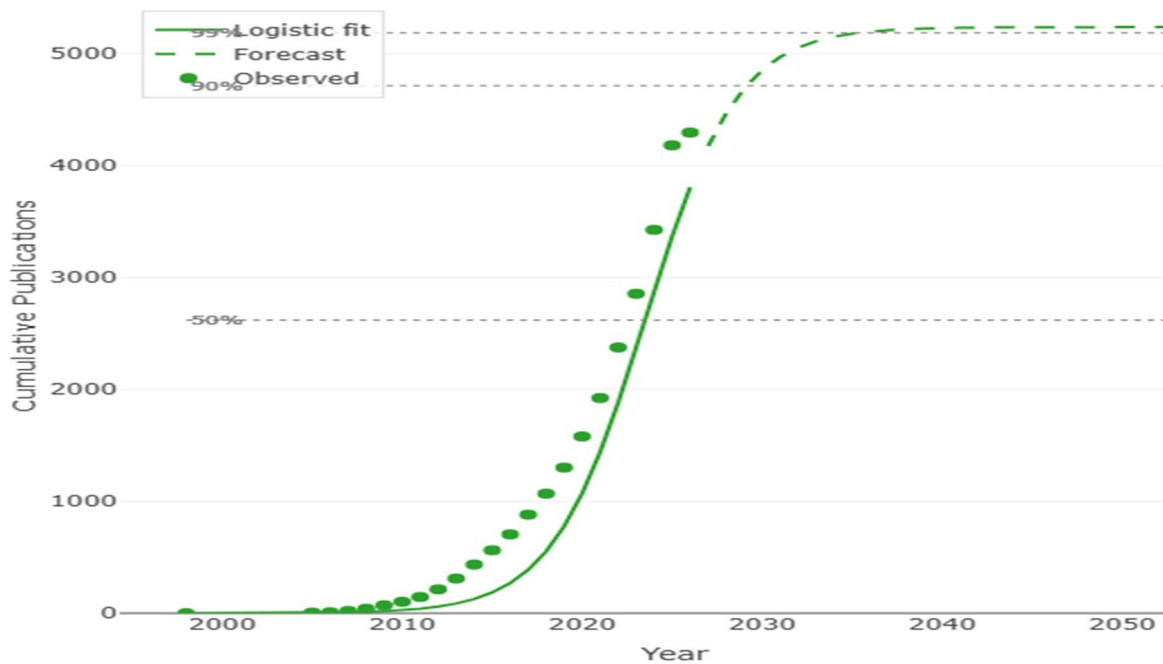


Figure 3: Cumulative publication growth curve for fluorescent nano-sensor research (2002–2026)

Collectively, the integrated performance, structural and thematic analyses demonstrate that fluorescent nano sensor research has evolved from mechanism-centric experimentation into a globally networked, AI-assisted analytical approaches domain characterized by thematic convergence, institutional concentration and accelerating scientific influence (34,35). This transition mirrors broader patterns observed in maturing scientific fields where early experimental exploration is followed by consolidation interdisciplinary integration and the emergence of dominant analytical frameworks (36,37). Recent studies further indicate that the incorporation of artificial intelligence has enhanced signal interpretation, scalability and robustness in fluorescence-based biosensing systems (38).

#### **4.2 Conceptual and Thematic Structure**

Based on the VOSviewer keyword co-occurrence analysis Figure 4 the Scopus-indexed literature on fluorescent nano-sensors is structured into four major thematic clusters providing empirical support for thematic convergence (RQ4). The red cluster (Cluster 1) represents the core fluorescence-based nano-sensing domain, dominated by *fluorescence*, *biosensors*, *nanoparticles*, *carbon dots* and *photoluminescence*, corresponding primarily to the exploratory phase identified in the Sankey analysis. The green cluster (Cluster 2) encompasses biomedical and translational themes such as *bioimaging*, *diagnosis*, *theranostics* and *drug delivery*, which emerge and expand during the expansion phase. The blue cluster (Cluster 3) reflects advanced optical and analytical methodologies including *fluorescence imaging* and *live-cell imaging* which align with late expansion to consolidation phases. The yellow cluster (Cluster 4) includes the environmental and electrochemical sensing applications that exists across all the phases. The strong interlinkages among these clusters indicate progressive thematic integration which confirms the convergence towards mature multidisciplinary nano-sensing framework thus substantiating RQ4 which is supported by the observations by (39).



The Figure 5 compares temporal evolution of “*FRET*” and “*AI*” related keyword occurrences across the research phases. Keywords related to “*FRET*” exhibit early emergence and sustained presence throughout the exploratory and expansion phases thus confirms their foundational role in fluorescent nano-sensor research. In contrast the keywords related to “*AI*” remain largely missing during the exploratory phase and begin to appear only after 2018 thus coincides with the expansion phase. A distinct rise in “*AI*” and related keyword frequency is observed during the consolidation phase thus reflecting accelerated adoption of data-driven analytical approaches. The continued importance of “*FRET*” and related terms alongside rising *AI* activity indicates integration rather than replacement of fluorescence mechanisms. The figure provides quantitative evidence of progressive convergence between established FRET-based sensing and emerging AI-assisted analysis thus reinforcing the thematic integration identified in earlier results.

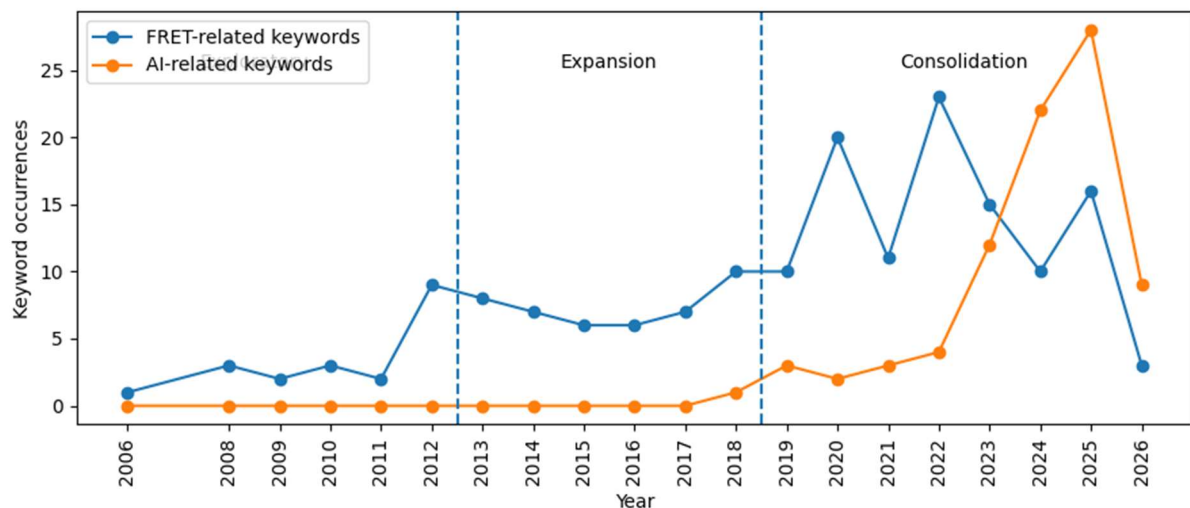


Figure 5: Timeline Plot Showing FRET vs AI Emergence

In Figure 5 vertical dashed lines indicate phase boundaries separating exploratory before 2012, expansion between 2013 to 2018 and consolidation after 2019 periods. FRET-related keywords are present throughout the study period while AI-related terms emerge primarily during the consolidation phase.

### Thematic Evolution

The thematic evolution analysis Figure 6 traces the longitudinal progression of research themes and provides convergent evidence for RQ4-thematic convergence, when interpreted alongside the keyword statistics Table 2 and life-cycle analyses Figure 2 and Figure 3. During the 2002 to 2012 exploratory phase the themes such as *fluorescence*, *quantum dots*, *graphene* and *biosensors* dominate and consistent with the early emergence and high centrality of *FRET* reported. The 2013 to 2019 expansion phase shows thematic reorganization around

*nanoparticles* and *biosensors*, corresponding to the accelerated growth in annual publications observed in the life-cycle curve Figure 2. From 2020 onward the emergence of *carbon dots*, *nanomaterials* and application-oriented themes aligns with the rise of *machine learning* and *artificial intelligence* keywords and the transition into the consolidation phase identified in both annual and cumulative growth analyses. Collectively, the Sankey flow demonstrate thematic continuity with progressive integration thus reinforcing the interpretation that fluorescent nano-sensor research has evolved toward mature data-augmented and application-driven framework.

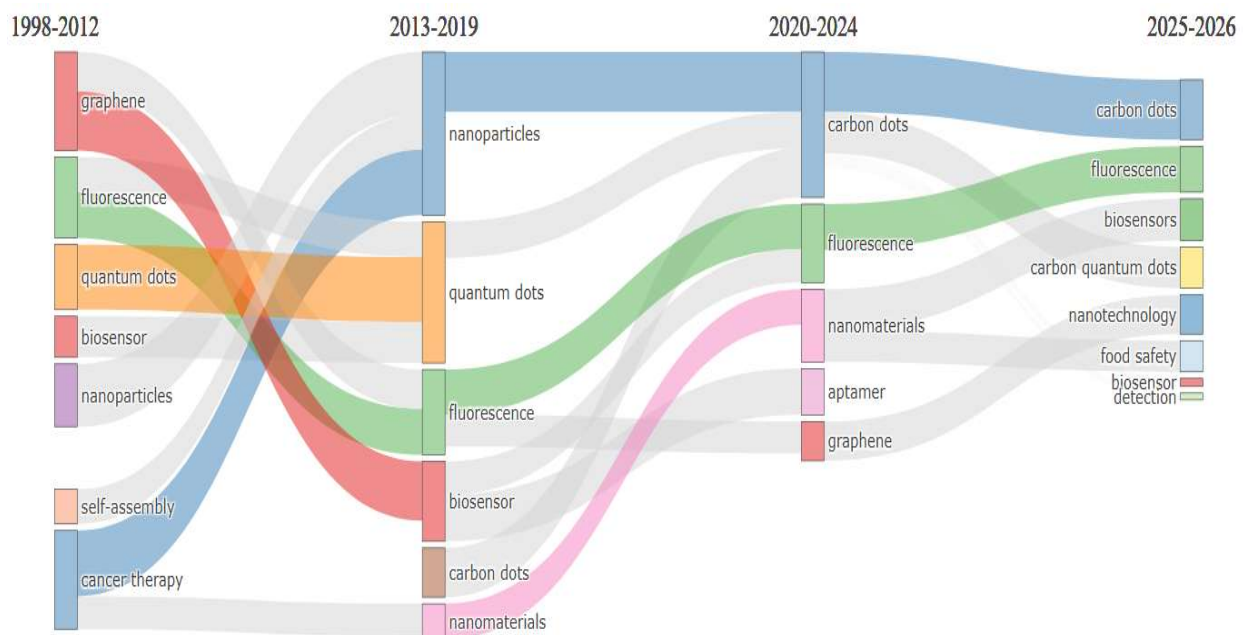


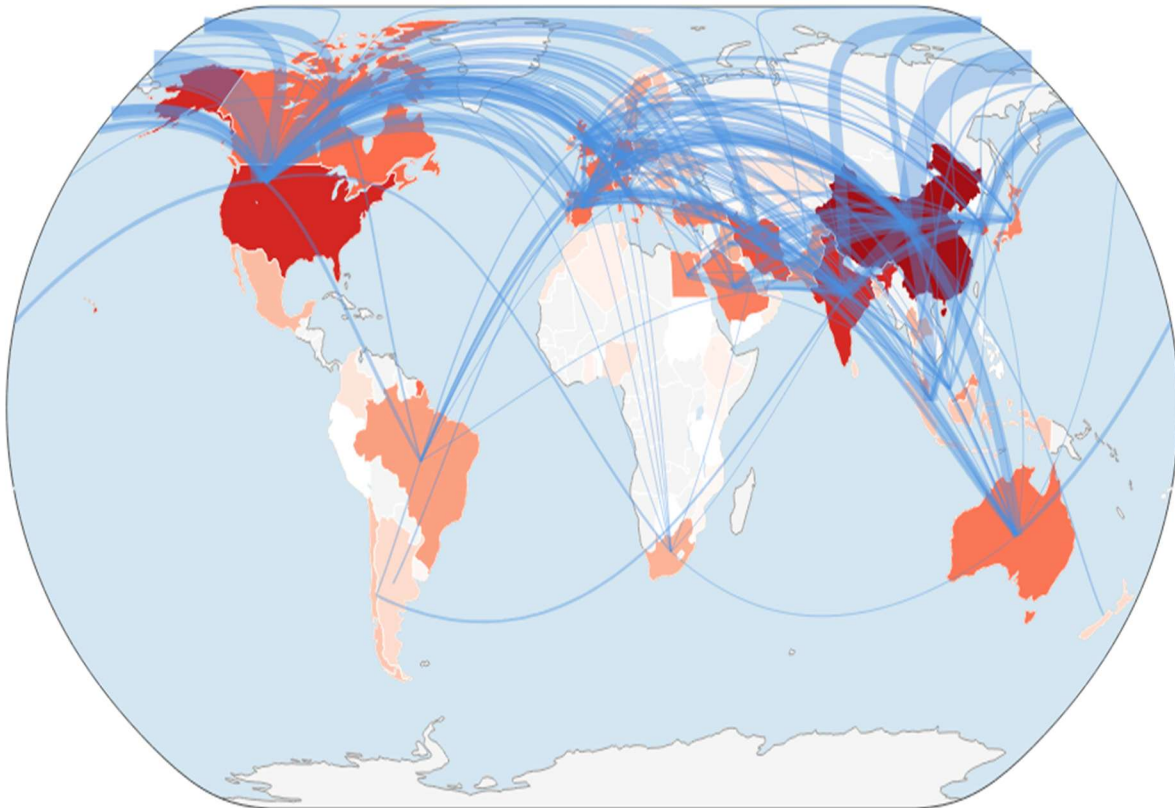
Figure 6: Thematic evolution of fluorescent nano sensor research over successive time periods (2002–2026)

This evolution empirically supports RQ4-Thematic Convergence demonstrating the integration of traditional FRET-based fluorescence mechanisms into data-driven AI frameworks marking the field's transition toward intelligent, autonomous diagnostic systems.

#### 4.3 Collaboration and Knowledge Diffusion

The Figure 7 illustrates global collaboration and information diffusion patterns in fluorescent nano-sensor research which complements the thematic evolution and convergence results. The dense intercontinental linkages highlight highly internationalized research landscape with major hubs in US, China and Europe. Strong connections between Asia, North America and Europe facilitates the cross-regional knowledge exchange and hence supports the integration of foundational fluorescence mechanisms with emerging analytical approaches (42,43). The collaboration pattern aligns with the consolidation phase identified in the life-cycle analysis

indicating that thematic convergence in fluorescent nano-sensor research is reinforced by sustained international cooperation and global diffusion of expertise (44).



*Figure 7: Country-level co-authorship network with international collaboration patterns in fluorescent nano sensor research*

The institutional research indicators further substantiate the global collaboration patterns as observed in Table 3. Leading contributions concentrated in China, Singapore and US which is consistent with their roles as major international collaboration hubs. The institutions in China dominate in research reflecting strong publication capacity and network centrality while Singapore institutions exhibit exceptionally high average citations per publication which indicates high-impact and efficiency-driven contributions. US institutions show balanced productivity and sustained influence. Thus, the distribution of institutional productivity and impact supports the interpretation that thematic convergence and knowledge diffusion in fluorescent nano-sensor research are driven by a small number of globally connected research hubs operating within mature international networks consistent with RQ3 (44,42,43).

*Table 3: Leading institutions contributing to fluorescent nano sensor research integrating AI-driven approaches.*

Rank	Institution	Country	TP	TC	ACP	h-index
1	University of Chinese Academy of Sciences	China	66	10,549	159.83	31
2	Jiangsu University	China	31	4,602	148.45	12

3	National University of Singapore (Chemistry)	Singapore	25	9,974	398.96	21
4	School of Chemistry & Chemical Engineering (Singapore)	Singapore	24	2,540	105.83	19
5	State Key Laboratory of Electroanalytical Chemistry	China	24	4,064	169.33	15
6	City University of Hong Kong	Hong Kong	22	3,822	173.73	16
7	Grainger College of Engineering, University of Illinois	United States	21	834	39.71	18
8	Academy of Scientific and Innovative Research (AcSIR)	India	21	353	16.81	9
9	National Center for Nanoscience and Technology	China	20	3,590	179.50	14
10	State Key Laboratory of Chemo/Biosensing & Chemometrics	China	19	894	47.05	14

#### 4.4 Sources and Authors of Influence

Bradford's law analysis reveals highly concentrated source distribution within fluorescent nano-sensor research as summarised in Table 4. The small core group journals including Chemical Reviews, Chemical Society Reviews, Coordination Chemistry Reviews and Biosensors accounts for disproportionate share of total citations thus reflecting their central role in consolidating and disseminating high-impact knowledge. Zone-1 journals such as "Sensors and Actuators B: Chemical", "TrAC Trends in Analytical Chemistry" and "Talanta" display balanced productivity and citation impact thus serves as primary outlets for experimental and methodological advances. While the Zone-2 journals demonstrate lower citation efficiency but contribute to thematic diversification and applied dissemination which is consistent with Bradford's predicted source scattering pattern.

Table 4: Core and Peripheral Publication Sources Based on Bradford's Law and Impact Indicators

S. N.	Source	TP	TC	ACP	Source h-index	Bradford Zone	Publisher
1	Chemical Reviews	69	29,644	429.6	55	Core	American Chemical Society
2	Chemical Society Reviews	68	23,733	349.5	49	Core	Royal Society of Chemistry
3	Coordination Chemistry Reviews	127	6,354	50.0	38	Core	Elsevier B.V.
4	Biosensors and Bioelectronics	99	6,343	64.1	41	Core	Elsevier Ltd
5	Sensors and Actuators B: Chemical	77	3,104	40.3	34	Zone 1	Elsevier B.V.
6	TrAC – Trends in Analytical Chemistry	79	3,387	42.9	36	Zone 1	Elsevier B.V.
7	Talanta	80	3,130	39.1	32	Zone 1	Elsevier B.V.

<b>8</b>	Analyst	45	1,262	28.0	24	Zone 2	Royal Society of Chemistry
<b>9</b>	Microchemical Journal	56	485	8.7	14	Zone 2	Elsevier Inc.
<b>10</b>	Biosensors	45	436	9.7	13	Zone 2	MDPI

Author-level analysis reveals geographically diverse but institutionally concentrated research landscape as in Table 5. The leading contributors are primarily affiliated with institutions in China, Singapore and Europe reflecting the globalized nature of fluorescent nano-sensor research. While several authors exhibit high publication output the others demonstrate substantially greater citation efficiency indicated by elevated average citations per publication. This pattern is consistent with mature research domain characterized by both prolific contributors and highly influential researchers (45,46).

*Table 5: Author productivity distribution and bibliometric indicators.*

<b>S. N</b>	<b>Author</b>	<b>Institution (Primary)</b>	<b>Country</b>	<b>TP</b>	<b>TC</b>	<b>ACP</b>	<b>h-index</b>
<b>1</b>	Su, X.	Dept. of Analytical Chemistry, Jilin University	China	13	410	31.54	11
<b>2</b>	Roghani-Mamaqani, H.	Faculty of Polymer Engineering, Sahand University of Technology	Iran	8	653	81.63	6
<b>3</b>	Wolfbeis, O. S.	Institute of Analytical Chemistry, Chemo- & Biosensors	Germany	7	1,324	189.14	7
<b>4</b>	Tang, B.	Chemical Engineering & Materials Science, MIIT	China	7	354	50.57	6
<b>5</b>	Adam, V.	Dept. of Chemistry & Biochemistry, Mendel University	Czech Republic	7	202	28.86	6
<b>6</b>	Hosseini, M.	Dept. of Life Science Engineering, University of Tehran	Iran	7	172	24.57	6
<b>7</b>	Liu, X.	Dept. of Chemistry, National University of Singapore	Singapore	6	2,479	413.17	6
<b>8</b>	Xiong, Y.	State Key Lab of Food Science & Technology	China	6	447	74.50	5
<b>9</b>	Wang, K.	College of Chemistry & Chemical Engineering	China	6	411	68.50	6
<b>10</b>	Demchenko, A. P.	Palladin Institute of Biochemistry, NAS	Ukraine	6	373	62.17	6

*Bibliometric indicators were computed based on citation data within the analyzed Scopus dataset and do not represent global Scopus author metrics.*

Author productivity as shown in Figure 8 follows power-law distribution and follows Lotka's law. Log-log regression analysis generated Lotka exponent with  $\beta$  value 1.82 and high

goodness of fit having  $R^2$  value 0.89 indicating skewed authorship pattern dominated by limited number of prolific contributors (45). Kolmogorov-Smirnov (K-S) test revealed significant deviation at the distribution tail with D value 0.42,  $p < 0.001$  reflecting expected empirical variation in large-scale bibliometric datasets. The high  $R^2$  value indicates that author productivity follows strong inverse power-law relationship consistent with Lotka’s law (47).

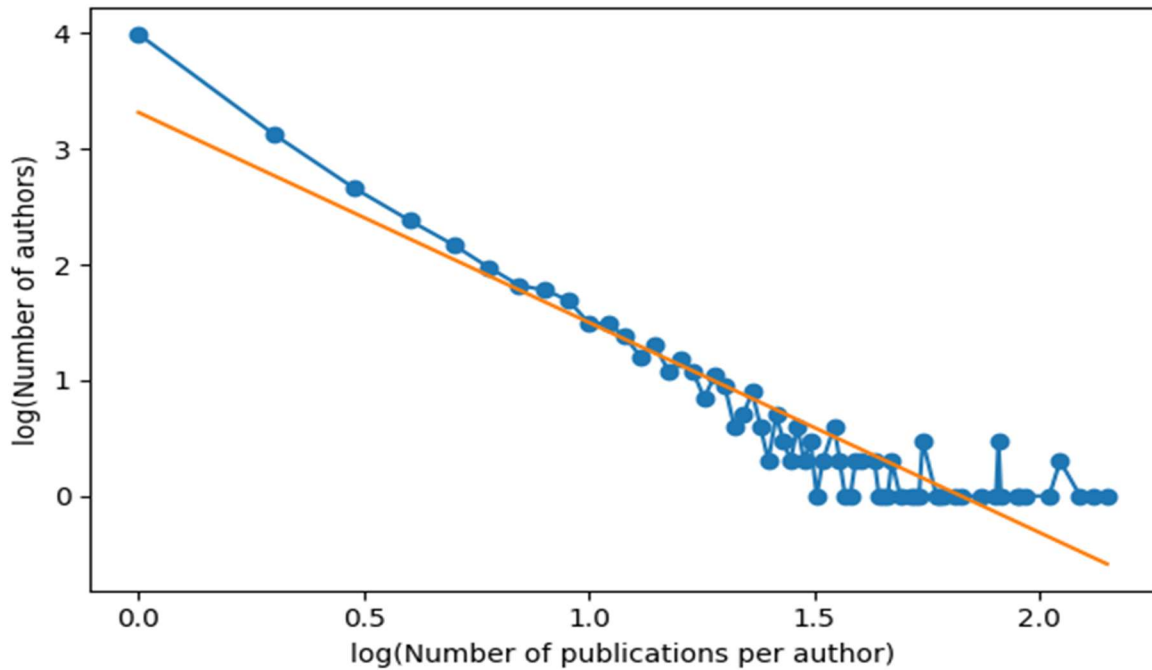


Figure 8: Strategic thematic map based on centrality and density measures.

#### 4.5 Intellectual Foundations and Research Fronts

Table 6 demonstrates the intellectual influence in the field arising from both foundational and emerging contributions (48). Recent studies in the core “*FRET*” biosensing and nanomaterials exhibit strong citation bursts and high citations per year identifying active research fronts. While the earlier methodological and biological studies show high normalized centrality but limited burst behavior thus indicating their role as stable intellectual foundations (49). This dual structure highlights the field that is simultaneously consolidating foundational knowledge and rapidly advancing toward AI-integrated diagnostic applications substantiating similar findings in use of big data analytics in health systems (50).

Table 6: Highly cited publications and research fronts in fluorescent nano sensor research.

Article	Institution	Country	Thematic Cluster	Year	TC	Burst	NC
Aggregation-Induced Emission: Together We Shine	Hong Kong Univ. of Science & Technology	China	Foundational Fluorescence Mechanisms	2015	7,363	Strong burst	1.0

Carbon Quantum Dots and Their Applications	National University of Singapore	Singapore	Nanomaterials	2015	4,500	Strong burst	0.6
Gold Nanoparticles in Chemical and Biological Sensing	Univ. of Massachusetts Amherst	USA	Nanomaterials Biosensing	2012	4,363	Strong burst	0.5
Graphene Oxide: Preparation, Functionalization and Applications	Tsinghua University	China	Nanomaterials	2012	3,385	Strong burst	0.4
Lanthanide Luminescence for Functional Materials	EPFL	Switzerland	Optical & Luminescent Materials	2010	3,339	Strong burst	0.3
Aggregation-Induced Emission: The Whole Is More Than the Sum	Hong Kong Univ. of Science & Technology	China	Foundational Fluorescence	2014	3,119	Strong burst	0.4
Photothermal Therapy and Photoacoustic Imaging	NIH	USA	Biomedical Nanotechnology	2019	2,623	Strong burst	0.5
The Photoluminescence Mechanism in Carbon Dots	Chinese Academy of Sciences	China	Nanomaterials	2015	2,604	Strong burst	0.4
Upconversion Nanoparticles: Design and Applications	Harbin Institute of Technology	China	Advanced Optical Nanomaterials	2014	2,484	Strong burst	0.3
Synthetic Molecular Motors and Mechanical Machines	University of Edinburgh	UK	Molecular & Chemical Foundations	2007	2,426	Strong burst	0.2

*Total Citations (TC); Citations per Year (CPY); NC: Normalised Centrality (i)Leading institution and country were assigned only where clearly identifiable from the Scopus affiliation data; otherwise, articles were classified as multinational or multicentre to avoid attribution bias. (ii)Burst interpretation is based on normalized citations per year (CPY), used as a Scopus-based proxy for citation acceleration in the absence of full CiteSpace burst-strength outputs. (iii)Normalized centrality reflects relative co-citation importance within the dataset (maximum = 1.00).*

### **Thematic Map Interpretation**

The thematic map in Figure 9 synthesizes the field by positioning themes according to relevance i.e centrality and development though density, integrating the preceding analyses (51). Motor themes *nanoparticles*, *drug delivery* and *theranostics* are both highly developed and central aligning with the consolidation phase identified in the life-cycle analysis and dominant publication sources (44). Basic themes including *carbon dots*, *carbon quantum dots*, *bioimaging* and *biosensing* exhibit high centrality but lower density reflecting foundational relevance consistent with persistent FRET dominance. Niche themes like *aptamer*, *graphene*, *aptasensor* show high internal development but limited connectivity indicating specialized trajectories (49). Emerging themes such as *machine learning* and *food safety* occupy low-

density positions, corroborating their recent appearance and low centrality in the keyword statistics and temporal evolution analyses (52). Overall, the map confirms thematic convergence with RQ4 across mechanisms, materials and applications (53).

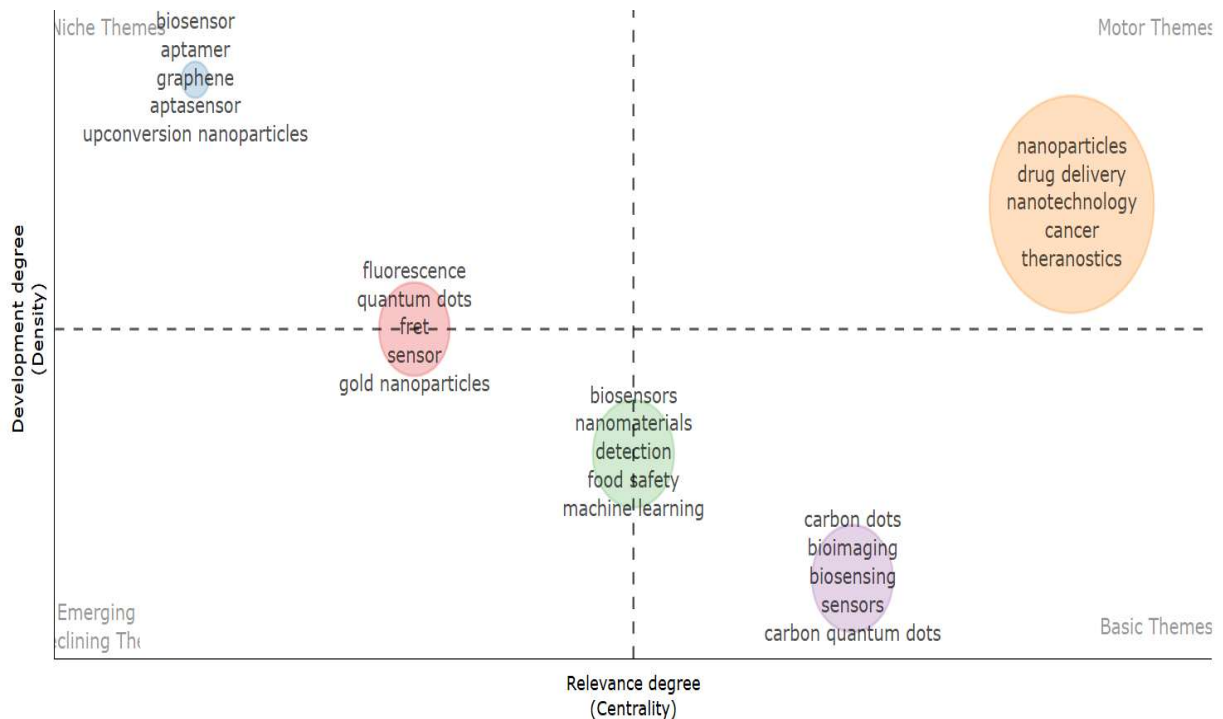


Figure 9 "Strategic thematic map by centrality (relevance, x-axis) and density (development, y-axis). Motor themes (upper-right) highlight machine learning dominance; basic/niche themes include FRET-related terms

## 5. Discussion

The preceding analyses collectively reveal the field that has evolved from mechanism-centric fluorescence research toward an integrated nano to bio to AI diagnostic paradigm. To move beyond descriptive trends the discussion synthesizes these results by linking temporal growth, intellectual restructuring, collaboration dynamics and thematic convergence to underlying nano-bio mechanisms and translational implications. This bibliometric synthesis maps the evolution, intellectual structure, collaboration patterns and thematic convergence of Scopus indexed fluorescent nano-sensor research from 2002 to 2026. By combining longitudinal metrics, science-mapping and citation diagnostics we address RQ1 to RQ4 and document the field's transition from mechanism-centric FRET systems to AI-augmented analytical frameworks.

### 5.1 Evolutionary growth and field maturation (RQ1)

Temporal analyses identify three stages: exploratory from 2002 to 2013, expansion phase from 2014 to 2018 and consolidation phase from 2019 onwards. The consolidation phase shows sustained increase in publications and citations and is consistent with structural maturation rather than cyclic growth. The post-2019 inflection aligns with uptake of AI-assisted analyses and indicates a move toward application-focused system-level research, similar findings were observed in the field of “gene editing and crop breeding” by (54)

### **5.2 Intellectual restructuring toward data-driven nano-sensing (RQ2)**

Network and co-citation analyses indicate that FRET and fluorescence remain central while becoming embedded within AI-enabled analytical layers. Rising prominence of machine learning, artificial intelligence and, more recently, deep learning signals a shift toward automated signal processing, pattern recognition and decision support. Heterogeneity in algorithm reporting and validation motivates community adoption of standardized benchmarks and reporting protocols to support reproducibility and comparative evaluation which is in agreement with findings with (55,56).

### **5.3 Intensification of collaboration and knowledge diffusion (RQ3)**

Collaboration networks reveal globally connected yet institutionally concentrated ecosystem with US and China acting as principal hubs and Europe and the Asia-Pacific region serving as key intermediaries. Author and institutional indicators reflect a hub and core structure and a Lotka-type productivity distribution typical of mature fields. While such concentration accelerates knowledge diffusion it may also influence research priorities, underscoring the need for inclusive international collaboration frameworks (57).

### **5.4 Thematic convergence and emergence of data-driven nano-sensing (RQ4)**

Triangulating keyword, Sankey and thematic-map analyses it is observed that the convergence among fluorescence mechanisms, nanomaterials engineering and AI-integrated analytics. Highly cited and burst-active publications increasingly occupy this intersection indicating research trajectories toward intelligent sensing systems capable of adaptive analysis and predictive interpretation. Translation to real-world diagnostics remains limited by scarce multi-centre validation regulatory requirements and the need for explainable AI systems which is in line with findings by (58,59).

### **5.5 Nano–Bio–AI Mechanistic Framework**

To contextualize the bibliometrically observed convergence of fluorescence mechanisms, nanomaterial platforms and artificial intelligence the trends is synthesised into a unified nano–bio–AI mechanistic framework Figure 10.

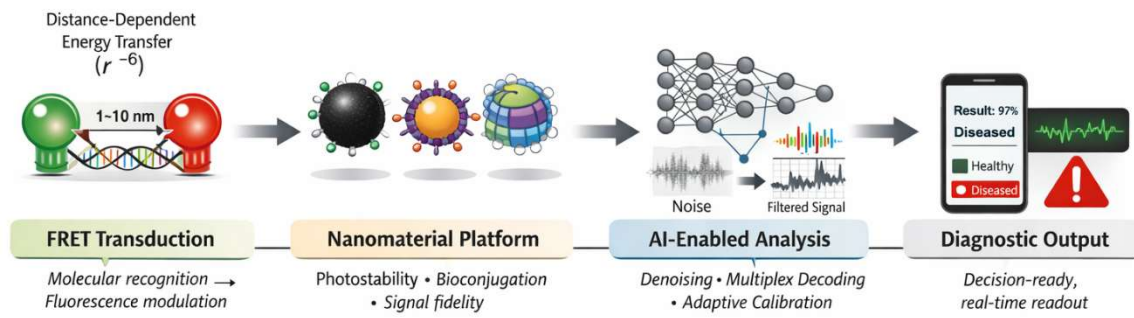


Figure 10: Integrated FRET–Nanomaterial–AI pipeline for intelligent fluorescent nano-sensing

Figure 10 schematically summarizes the mechanistic integration underlying the bibliometrically observed convergence of FRET, nanomaterials and artificial intelligence. Distance-dependent FRET transduction converts biomolecular recognition events into fluorescence modulation, while nanomaterial platforms stabilize and amplify the signal under physiological conditions (60). AI-enabled analytical layers subsequently extract, denoise and decode multidimensional fluorescence data to generate robust decision-ready diagnostic outputs thus explaining the sustained dominance of FRET-based architectures alongside the recent rise of data-driven analytical approaches (61).

### 5.6 Implications and future directions

Conceptually, this field would benefit from integrative frameworks that unify optical physics, nanomaterials and artificial intelligence within reproducible sensing architectures. From an application perspective the priorities include open benchmark datasets, standardized AI reporting and large-scale validation studies to bridge laboratory demonstrations and real-world deployment. Limitations include use of single-database coverage, English-language bias and proxy-based burst measures are acknowledged; these do not undermine the robust structural patterns reported. Thus, the findings point to substantial potential for AI-enhanced fluorescent nano-sensors in multiplexed, real-time point-of-care diagnostics thus aligning with emerging needs in personalized and precision healthcare. Taken together these findings comprehensively address RQ1–RQ4 by demonstrating how fluorescent nano-sensor research has matured structurally thus converged thematically and transitioned mechanistically toward intelligent diagnostic systems.

## 6. Conclusions

This study presents comprehensive bibliometric synthesis of Scopus-indexed research on fluorescent nano-sensors spanning from 2002 to 2026 integrating temporal growth analysis, intellectual structure mapping, collaboration networks and thematic evolution. The results

demonstrate clear progression from exploratory, mechanism-driven fluorescence research towards consolidated and application-oriented domain increasingly shaped by data-driven analytical approaches. Across multiple analytical layers the fluorescence resonance energy transfer (FRET) and related optical mechanisms remain the foundational core of the field while machine learning and artificial intelligence (AI) have emerged as complementary analytical frameworks that enhance signal processing, interpretation and system-level performance. Collaboration patterns reveal globally connected but institutionally concentrated research ecosystem with sustained knowledge diffusion driven by limited number of international hubs. The integrated FRET nanomaterial AI framework in Figure 10 provides a mechanistic and translational blueprint for the rational design of next-generation intelligent fluorescent nano-sensors. Thematic mapping further confirms convergence among fluorescence mechanisms, nanomaterial engineering and AI-enabled analytics thus indicating maturation rather than fragmentation.

Finally these findings position fluorescent nano-sensor research as structurally mature and interdisciplinary field with strong potential for intelligent and real-time diagnostic applications. The study provides consolidated knowledge base and strategic reference point to guide future methodological standardization, collaborative research and translational development of next-generation fluorescent nano-sensing technologies. Future progress will depend on designing fluorescent nano-sensors in which FRET-based biophysical transduction, nanomaterial-enabled signal stability and explainable AI analytics are developed as a unified system rather than independent components.

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