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ACADEMIC FOUNDATIONS TO COMMERCIAL TRANSLATION: MAPPING THE EVOLVING LANDSCAPE OF GRAPHENE OPTICAL RESEARCH THROUGH KEYWORD ANALYSIS

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Abstract: Graphene, a two-dimensional allotrope of carbon composed of a single atomic layer arranged in a hexagonal honeycomb lattice, exhibits exceptional electronic and optical properties arising from its linear energy dispersion and massless Dirac fermions. Since its experimental isolation, graphene has attracted intense research interest due to its broadband optical absorption, ultrafast carrier dynamics, high optical conductivity, and strong nonlinear optical response. The rapid and multidisciplinary growth of literature on the optical properties of graphene has resulted in a large, heterogeneous knowledge base, making it increasingly difficult to systematically identify dominant research themes, emerging trends, and knowledge structures. To address this gap, the present study performs a comprehensive keyword-based scientometric analysis of research on the optical properties of graphene. A total of 1,196 documents indexed in the Web of Science (WoS) database from January 2004 to March 2025 were analysed employing three different approaches of keyword analyses viz. keyword co-occurrence analysis, cluster analysis of thematic map and factorial analysis. Visualization and mapping were carried out using VOSviewer, while thematic evolution was examined using the Bibliometrix R package. The analysis reveals the conceptual organization of the field, highlights core and emerging research clusters, and traces the intellectual evolution of graphene optics research.

The findings underscore the central role of graphene's optical properties in enabling applications such as photodetectors, optical modulators, saturable absorbers for ultrafast lasers, transparent electrodes, plasmonic and optoelectronic devices, and broadband optical sensors. This study provides a structured overview of the research landscape and offers valuable insights for researchers and academicians aiming to guide future developments in graphene-based optical and photonic technologies. Furthermore, the dominant keyword clusters are mapped to real-world graphene-enabled products, illustrating the translational progression of fundamental research toward commercial technologies.

Keywords: Optical properties, graphene, keyword analysis, cluster analysis, thematic map, factorial analysis, Vosviewer, bibliometrix.

1. Introduction:

Graphene has attracted significant scientific and technological interest since its experimental isolation in 2004 due to its exceptional physical properties(1–3) and wide application potential(4–6). In graphene each carbon atom forms three in-plane σ bonds, while the remaining out-of-plane π orbital gives rise to π and π^* bands, which dominate graphene's electronic and optical behaviour. This unique band structure is directly responsible for graphene's remarkable linear and nonlinear optical responses under electromagnetic excitation, making it a promising material for optoelectronic and photonic applications.

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Graphene provides a bridge between condensed matter physics and quantum electrodynamics and opens new perspectives for carbon-based electronic(2,7) and optoelectronic devices(8,9). Graphene exhibits ultrahigh electron mobility on the order of 10^5 cm^2 V^{-1} s^{-1}, a large specific surface area of approximately 2600 m^2 g^{-1}, and exceptional thermal conductivity in the range of 3000-5000 W m^{-1} K^{-1} (10,11). These attributes, combined with its mechanical flexibility, chemical stability, and robustness, position graphene as a versatile platform for next-generation photonic, electronic and optoelectronic technologies.

From an optical perspective, graphene is distinguished by its nearly wavelength-independent optical response and high transparency of ~97% per monolayer, arising from its universal optical conductivity(12,13). Monolayer graphene simultaneously offers relatively low sheet resistance (~450 Ω sq^{-1}) and high optical transmittance, making it a strong candidate for transparent conducting electrodes in optoelectronic devices. In organic light-emitting diodes (OLEDs) wafer-scale graphene anodes replaces indium tin oxide (ITO), offering comparable optical transparency and electrical performance while overcoming the brittleness and material scarcity associated with ITO(14). Beyond conventional optoelectronics, the optical transparency of few-layer graphene (~85%) has enabled emerging applications in flexible and bio-integrated photonics, including transparent, wafer-thin, self-adhesive, unobtrusive, and non-invasive continuous blood-pressure monitoring tattoos(15).

A substantial body of literature has explored both the linear and nonlinear (16)optical properties of graphene. Linear optical parameters such as optical absorption, optical conductivity, refractive index, dielectric function, and reflectivity have been shown to depend on layer thickness, substrate interactions, and external modulation(13,17). In parallel, graphene exhibits prominent nonlinear optical responses, including reverse saturable absorption(18), optical limiting(14,19), frequency mixing(19), two-photon absorption(20), and frequency multiplication(19,21). These nonlinear effects originate from graphene's gapless band structure and ultrafast carrier dynamics, where strong optical excitation leads to Pauli blocking and saturable absorption, suppressing further photon absorption(21). As a result, graphene has found widespread use in ultrafast lasers(22), mode-locked and Q-switched laser(23,24) systems, optical sensors(25), and nonlinear integrated photonics(19,26).

Despite the extensive experimental and theoretical research on graphene's optical properties, the rapid growth and diversification of this literature present challenges in identifying dominant research themes, influential publications, and emerging trends. Bibliometric/scientometric analyses provide powerful quantitative tools to address these challenges by systematically mapping the intellectual structure of a research field through keyword co-occurrence and thematic evolution. Such analyses enable the identification of seminal works, research clusters, and knowledge gaps, while also revealing how foundational studies translate into application-driven research over time(27).

Although several bibliometric studies have examined graphene research at a general level or within specific application domains-such as transparent conductive electrodes(28,29), sensors(30) and electronic components(31–33), focused scientometric investigations dedicated explicitly to the optical properties of graphene remain limited. In particular, there is a lack of comprehensive keyword analysis that capture both linear and nonlinear optical research and their associated technological applications.

The present work addresses this gap through a comprehensive keyword-based analysis of the literature on graphene's optical properties. It maps major research themes associated with optical behaviour and tracks the temporal evolution of key research topics. This bibliometric study offers a quantitative and holistic perspective on how graphene's optical properties have shaped-and continue to drive-technological advances in optoelectronics, photonics, and biomedicine. The resulting insights are expected to support future research planning, foster interdisciplinary collaboration, and guide the strategic development of graphene-based optical technologies. The rationale of this study are to

1. examine the temporal progression of scholarly publications and citation impact related to the optical properties of graphene.
2. identify dominant research themes and their interrelationships through author-assigned keyword co-occurrences and cluster analysis.
3. employ thematic map analysis to access the maturity, relevance, and developmental status of research themes across different developmental stages.
4. uncover latent thematic structures and their evolution using factorial analysis.
5. analyse the temporal evolution of prominent keywords to reveal shifting research trends, emerging optical phenomena, and application-driven trends.
6. locate the most significant and frequently used keywords in graphene's optical properties-based research and map the associated applications in various domains. It is also desired to further investigate the application based well researched products and the associated companies.

2. Materials and Method:

The WoS database represents a comprehensive, publisher-independent, and globally recognized repository of high-quality, peer-reviewed scholarly literature, widely acknowledged for its reliability and coverage. In addition, WoS data can be exported in multiple formats that are compatible with bibliometric analysis tools such as VOSviewer(34,35) Bibliometrix(36) and several other software. Bibliometric data for the present study were retrieved from the Web of Science (WoS) Core Collection covering the period from January 2004 to March 2025. Publications written in English were included. All relevant metadata fields including titles and keywords were extracted and utilized for bibliometric analysis. The search query was framed using the Boolean operators in the title field of the WoS data collection. The query resulted in a total of 1,194 documents.

3. Results and discussion:

The temporal distribution of published literature on the optical properties of graphene as a function of publication year is presented in Figure 1. The figure exhibits several distinct peaks corresponding to periods of heightened research activity. The highest publication output was recorded in the year 2018, with 110 documents, followed by 102 and 101 publications in year 2020 and 2022, respectively. The year-wise average citations per year, normalized with respect to preceding years, are shown in Figure 2. Two prominent citation peaks are observed in 2009 and 2007, with average citation rates of 15.66 and 12.65 per year, respectively. These peaks reflect the strong and sustained impact of early seminal contributions to the field.

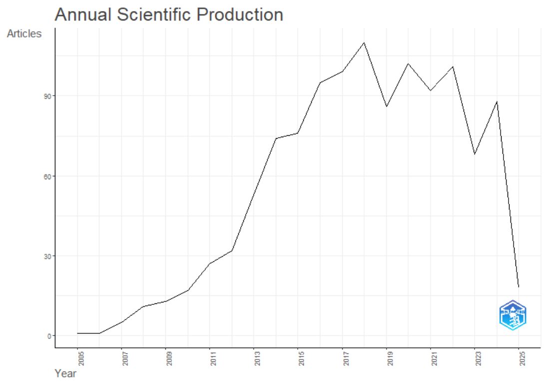

Figure 1: Number of documents as a function of year.

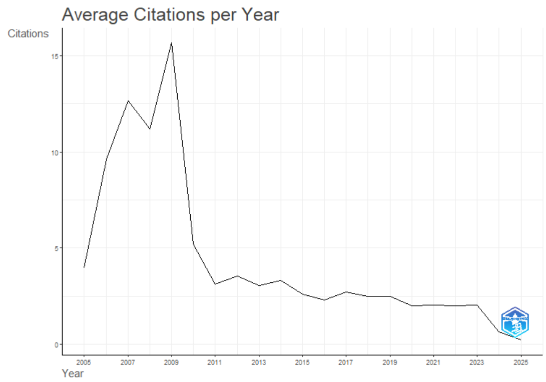

Figure 2: Average citations as a function of time.

3.1 Keyword Co-occurrence Analysis:

Keyword co-occurrences analysis finds the frequency of the specific keywords that appear together and is particularly effective for identifying research fronts and thematic linkages. Keyword co-occurrence analysis was carried out using author keywords through VOSviewer software and the visualization map is shown in figure 3. A total of 1,874 author keywords were identified in the present metadata. To reduce complexity, the minimum keyword occurrence threshold was set to four, resulting in 87 keywords, which were grouped into three distinct clusters. The cluster titles, constituent keywords, their mapped applications and associated references are summarized in Table 1.

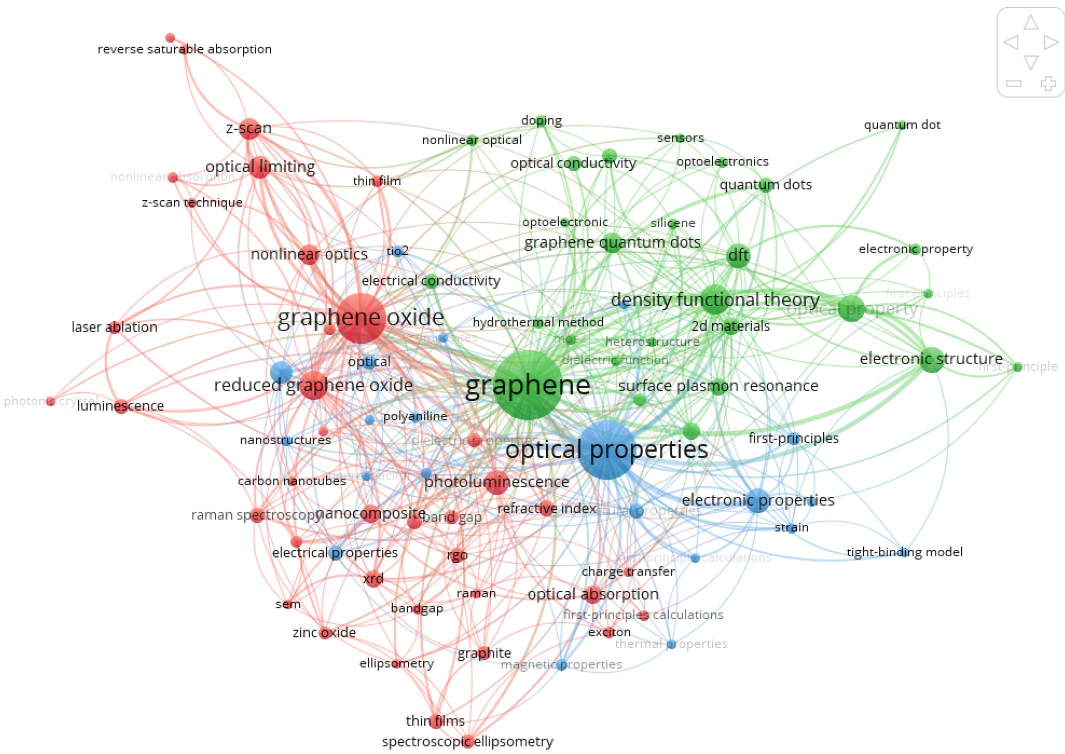

Figure 3: Keyword co-occurrence map on the optical properties of graphene.

Table 1: Cluster 1 (represented by red colour) : Optical and Nonlinear Optical Properties of Graphene-Based Nanomaterials and their Photonic and Optoelectronic Applications			
Sub Cluster's Title	**Keywords present in the cluster**	**Mapped applications**	**References**
Graphene-Based Materials and Nanocomposites	graphene oxide, reduced graphene oxide, graphite, carbon nanotubes, nanocomposite, composite, thin films, zinc oxide, ZnO	Flexible optoelectronics, hybrid photonic devices, transparent electrodes	Singh et. al.(37) Vollmer et. al. (29)
Optical Absorption and Emission, Nonlinear Optical Properties	Absorption, refractive index, transmittance, optical absorption, nonlinear absorption, nonlinear optics, saturable absorption, reverse saturable absorption, optical limiting, photoluminescence, luminescence,	Optical limiters, ultrafast photonics, eye and sensor protection, all-optical switching Photodetectors, light-emitting devices, optical sensors, solar energy harvesting	sun et. al.(38) Bonaccors et. al. (39) Eda et. al.(40)

Electronic Structure & Charge Dynamics	bandgap, charge transfer, exciton, dielectric properties	Bandgap engineering, high-speed optoelectronic devices, photovoltaics	Wang et al. (2012); Liu et al. (2016)
Structural and Spectroscopic Characterization Techniques	Raman spectroscopy, ellipsometry, spectroscopic ellipsometry, SEM, XRD, Z-scan, Z-scan technique	Material quality assessment, thin-film diagnostics, device optimization	Ferrari, Basko et. al. (41), Zhang et. al. (42)
Theoretical and Computational Studies	first-principles calculation, density functional theory	Predictive material design, understanding light-matter interaction mechanisms	Yazyev, Chen et. al.(43)
Photonic & Laser-Based Processing	photonic crystal, laser ablation	integrated photonic circuits, micro/nanofabrication, optical modulation	Malinauskas et al. (44)

Table 2: Cluster 2 (represented by green colour): Study of Electronic, Optical, and Optoelectronic Properties of Two-Dimensional (2D) Materials

Sub Cluster's Title	**Keywords present in the cluster**	**Mapped applications**	**References**
2D Materials & Quantum Structures	graphene, bilayer graphene, quantum dots, MoS_2, heterostructure, silicene	Nanoelectronics, van der Waals devices, flexible electronics	Geim, Grigorieva et. al.(45) , Novoselov et al. (46)
Electronic Structure and transport	band structure, electronic structure, electrical conductivity, doping, surface plasmon resonance	High-speed transistors, conductive layers, plasmonic devices	Castro Neto et al. (47) Low, Avouris (48)
Optical and Nonlinear Optical Properties	absorption coefficient, optical conductivity, dielectric function, nonlinear optical	Photodetectors, optical modulators, nonlinear optical devices	Mak et al. (49), Koppens et al. (50)
First-Principles Modeling and device optimization	DFT, density functional theory, first principles	Predictive material design, band engineering, device optimization	

Optoelectronic Functionality	optoelectronics, optical property	LEDs, solar cells, integrated photonic circuits	Qiaoliang Bao, Kian Ping Loh(51)
Sensing Applications	sensors, surface plasmon resonance	Gas sensors, biosensors, environmental monitoring.	Eric Singh et.al. (37), Chakraborthy et. al.(52), Maurizio Donarelli et. al.(53)

The keyword co-occurrence cluster analysis highlights a material's optics applications continuum, where graphene and other 2D materials are studied using advanced spectroscopic and theoretical tools to understand the electronic structure, charge dynamics and nonlinear optical phenomenon. These studies can further be exploited in photonic technologies, particularly in ultrafast optics, optical limiting and next-generation optoelectronic devices.

Cluster 2 reflects a theory-driven exploration of two-dimensional (2D) materials, where density functional theory and first-principles calculations establish links between electronic structure and optical/optoelectronic performance. The presence of quantum dots, van der Waals heterostructures, and plasmonic effects highlights ongoing efforts toward nanoscale optoelectronic and sensing devices.

Cluster 3 corresponds to a functionality-driven materials research direction, in which theoretical modeling combined with controlled synthesis strategies is employed to tailor the multi-physical properties of graphene-based nanostructures. Compared with Clusters 1 and 2, this cluster shows a stronger application orientation toward energy storage, photocatalysis, and multifunctional electronic devices.

Table 3: Cluster 3 (represented by blue colour): Multifunctional Properties and First-Principles Design of Graphene-Based Nanostructured Composites for Energy and Catalytic Applications

Sub Cluster's Title	Keywords present in the cluster	Mapped applications	References
Graphene-Based Nanostructures and Composites	graphene nanoribbons, composites, polyaniline, nanocomposites, nanostructures, TiO_2	Hybrid functional materials, flexible electronics, smart coatings	Stankovich et al. (54)
First-Principles and Theoretical Modelling	DFT calculations, tight-binding model, first principle calculations	Property prediction, material optimization, strain engineering	Castro Neto et al. (55), Yazyev (56)

Optical, Electronic & Magnetic and Thermal Properties	optical properties, electrical properties, magnetic properties, thermal properties	nano-electronic devices, strain-tunable electronics, Spintronics, Optoelectronic devices, thermal management materials.	Balandin et al.(10)
Structural Engineering & Synthesis controlled materials	hydrothermal, structural properties	Scalable synthesis of nanomaterials, morphology-controlled materials	Dreyer et al. (57)
Energy Storage & Photocatalysis	supercapacitor, photocatalysis	Energy storage systems, hydrogen generation, environmental remediation	Zhu et al.(58) Kamat (59)

3.2 Most Relevant Keywords:

The most relevant keywords, categorized based on their co-occurrence frequencies, are presented in Figure 4(a). ‘Graphene’ emerges as the most prominent keyword, with 221 occurrences, followed by ‘optical properties’ and ‘graphene oxide’ which exhibit 156 and 113 co-occurrences, respectively. The remaining keywords, arranged in decreasing order of co-occurrence frequency, can be identified directly from the figure. Figure 4(b) presents a tree map illustrating the percentage contribution of keyword co-occurrences. ‘Graphene’, ‘optical properties’ and ‘graphene oxide’ account for 22%, 16%, and 11% of the total co-occurrences, respectively. The temporal evolution of keyword usage is shown in Figure 4(c). The keywords ‘graphene’, ‘optical properties’ and ‘graphene oxide’ exhibit a rapid and sustained increase in usage over time, reflecting their growing importance in the field. In contrast, the remaining keywords display comparatively slower variations in frequency, indicating more stable or specialized research interest.

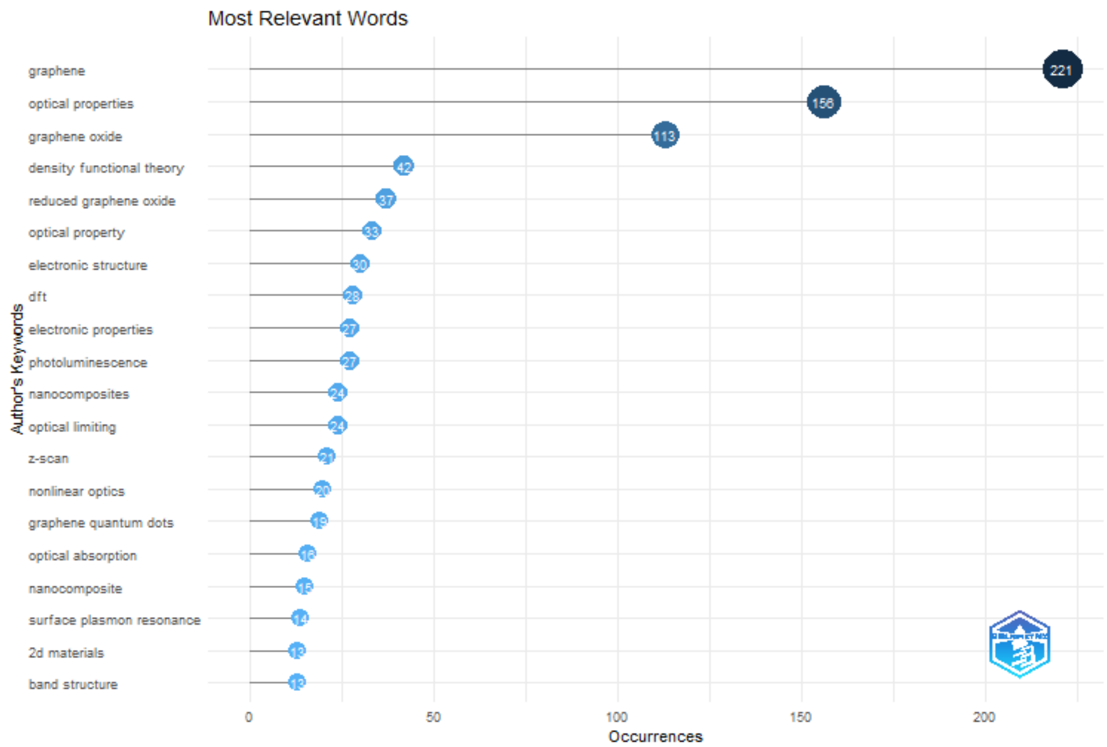

Figure 4(a): Most relevant keywords as a function of co-occurrences.

Figure 4(d) illustrates the temporal evolution of keywords and their corresponding frequencies from 2009 to 2025. The size of the blue circles represents term frequency, ranging from 50 to 200, with smaller and larger circles indicating lower and higher frequencies, respectively. The early period prior to 2015 is characterized by relatively low keyword frequencies (50-100), reflecting the formative stage of research in this field. During this phase, studies predominantly focused on fundamental concepts and precursor materials, such as graphite oxide, graphene oxide films, and nanostructured materials, as well as basic properties including electrical properties and electronic band structure. Additional emerging topics during this period included photonic crystals, photocurrents, and polymeric materials such as polypyrrole.

Between 2014 and 2019, a marked increase in research activity is observed, particularly in studies related to optical properties. This surge is evident from the high to very high frequencies of keywords such as optical properties, optical limiting, Z-scan, absorption, electronic properties, electrical properties, and density functional theory. These terms are closely associated with both the experimental characterization and theoretical evaluation

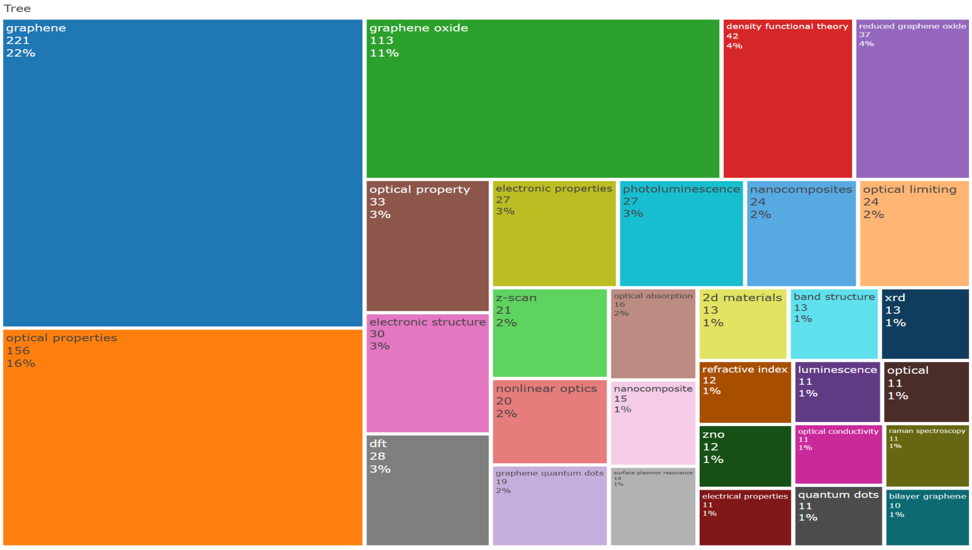

Figure 4(b): Tree map revealing percentage occurrences of keywords.

In the most recent period, spanning 2020 to 2025, research trends reflect sustained but more specialized interest, with keyword frequencies ranging from moderate to low. This phase is characterized by the emergence of specific two-dimensional material systems, such as bilayer graphene and silicene, alongside continued investigations into optical, dielectric, electronic, mechanical, and magnetic properties. Advanced characterization techniques, including X-ray diffraction are also prominently featured. Keywords such as DC conductivity and refractive index

of the optical behaviour of graphene and its derivatives, indicating a phase of rapid expansion and consolidation of optical research in the field. further indicate ongoing exploration of both linear and nonlinear optical properties of graphene-based materials.

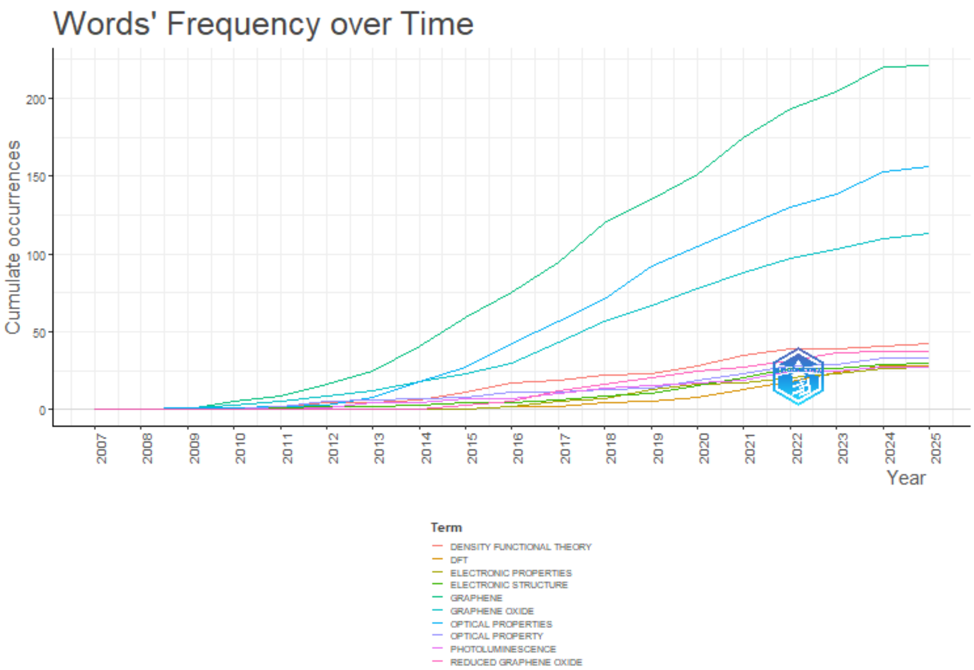

Figure 4(c): Temporal evolution of first ten most used keywords.

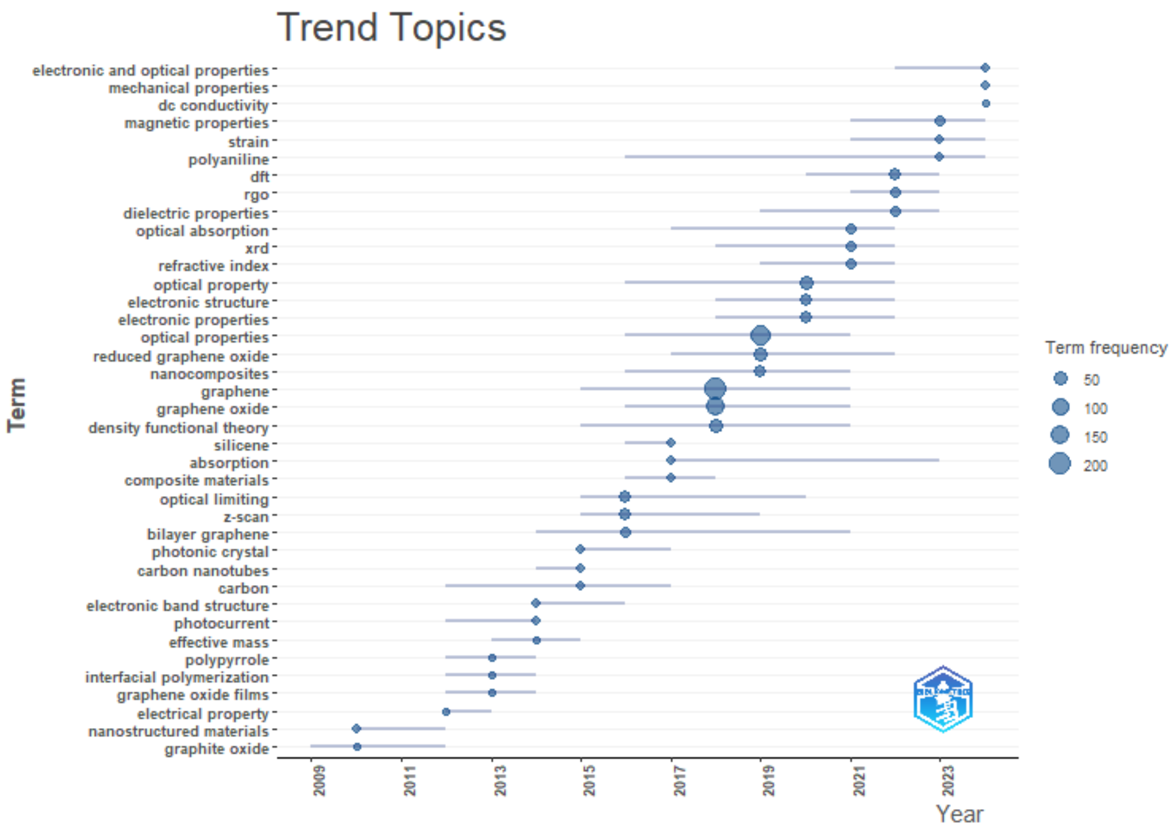

Figure 4(d): Temporal evolution of trend topics on the optical properties of graphene.

3.3 Co-word Analysis:

Figure 5 illustrates the keyword co-occurrence analysis, commonly referred to as co-word analysis, conducted using the Bibliometrix R package. The keyword co-occurrence network organizes frequently associated keywords into distinct thematic clusters related to the research topic. Each cluster represents a specific theme within the broader research domain, highlighting the conceptual structure and interrelationships among research areas.

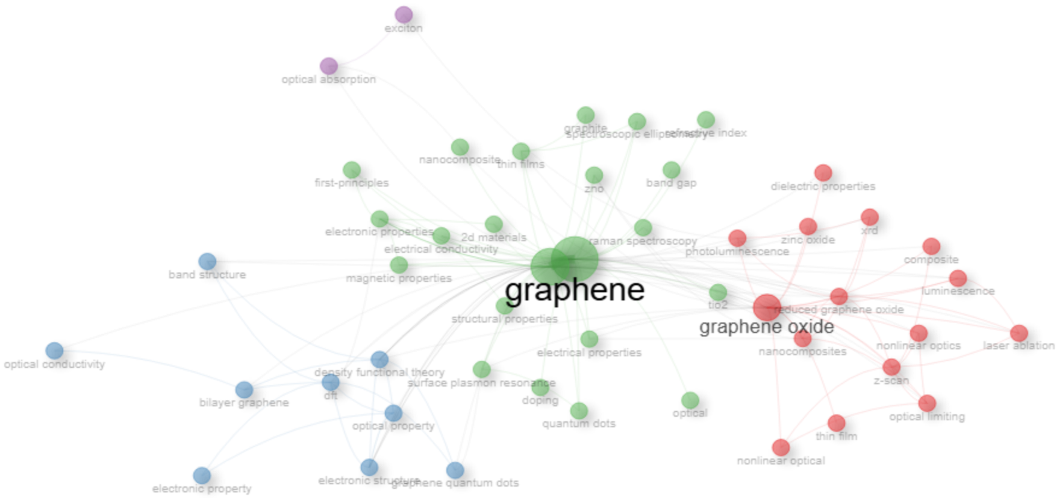

Figure 5: Keyword co-occurrences obtained through bibliometrix R package.
A total of four keyword clusters were obtained through bibliometrix R package. The red cluster primarily focuses on graphene oxide and other two-dimensional materials, emphasizing nonlinear and luminescent optical phenomena. Key research topics include luminescence and photoluminescence, optical limiting, laser ablation, and a range of nonlinear optical effects. This cluster also highlights essential characterization techniques such as X-ray diffraction (XRD) and the Z-scan technique, which are widely employed to characterize 2D matarials. Additionally, themes related to light-matter interaction and sensor applications indicate the relevance of these materials in photonic and optoelectronic device development.

The blue cluster comprises keywords such as graphene quantum dots, two-dimensional materials, band structure, and optical and electrical properties. This cluster strongly reaffirms the extensive use of density functional theory (DFT) as a fundamental computational tool for understanding and predicting the electronic and optoelectronic behaviour of 2D materials. The emphasis here is on correlating band-structure features with optical absorption and charge transport characteristics.

The green cluster represents graphene quantum dots and other 2D materials, focusing on their optical, structural, electrical, and magnetic properties. It highlights key optical parameters such as refractive index and advanced phenomena like surface plasmon resonance, underscoring the importance of plasmonic effects in graphene-based nanostructures. Density functional theory and first-principles calculations form the backbone of this cluster, providing theoretical insight into structure-property relationships. Experimental characterization techniques, including Raman spectroscopy and spectroscopic ellipsometry are prominently featured for probing graphene and its derivatives. Purple cluster is centred on excitons and optical absorption processes in two-dimensional material systems. It is devoted to understanding excitons-bound states of electrons and holes-and their critical role in governing light absorption and optical transitions in low-dimensional materials. This cluster reflects fundamental studies aimed at elucidating excitonic mechanisms that underpin the optoelectronic response of 2D materials.

The statistical parameters of the leading keywords appearing in the keyword co-occurrence map are presented in Table 4. These keywords are arranged hierarchically based on their betweenness centrality(60) values. A higher betweenness centrality indicates the greater importance of a keyword within the network, as it reflects its role in connecting different research themes and facilitating knowledge flow across the network. Other centrality measures viz. closeness and page rank centrality(60) are also given in Table 4 for identified nodes.

Table 4: Centrality details of the first ten keywords

Node	Cluster	Betweenness	Closeness	PageRank
graphene	3	577.0138925	0.01754386	0.171078746
optical properties	3	314.5696107	0.015151515	0.150412369
graphene oxide	1	159.6803678	0.013513514	0.082226501
dft	2	29.23437885	0.011363636	0.026444681
photoluminescence	1	27.95141721	0.010752688	0.016259299
optical property	2	20.55822954	0.010416667	0.027228749
optical absorption	4	17.76557688	0.01	0.009864546
reduced graphene oxide	1	12.65756017	0.011904762	0.029411868
density functional theory	2	9.478087209	0.011494253	0.038611443
optical limiting	1	5.238340192	0.010752688	0.024137335

3.4 Thematic Map Analysis:

The thematic map is divided into four quadrants representing emerging or declining themes, niche themes, basic themes, and motor themes. A total of eight clusters is identified and positioned within the map according to their
centrality and density coordinates, as illustrated in Figure 6. Centrality reflects the importance of a theme within the overall research field, whereas density indicates the internal coherence, strength, and level of development of a theme. Themes with high centrality serve as a foundation for broader research areas, while high density signifies well-connected, mature, and extensively investigated topics. The centrality and density values corresponding to basic, motor and emerging theme clusters are summarized in Table 5.

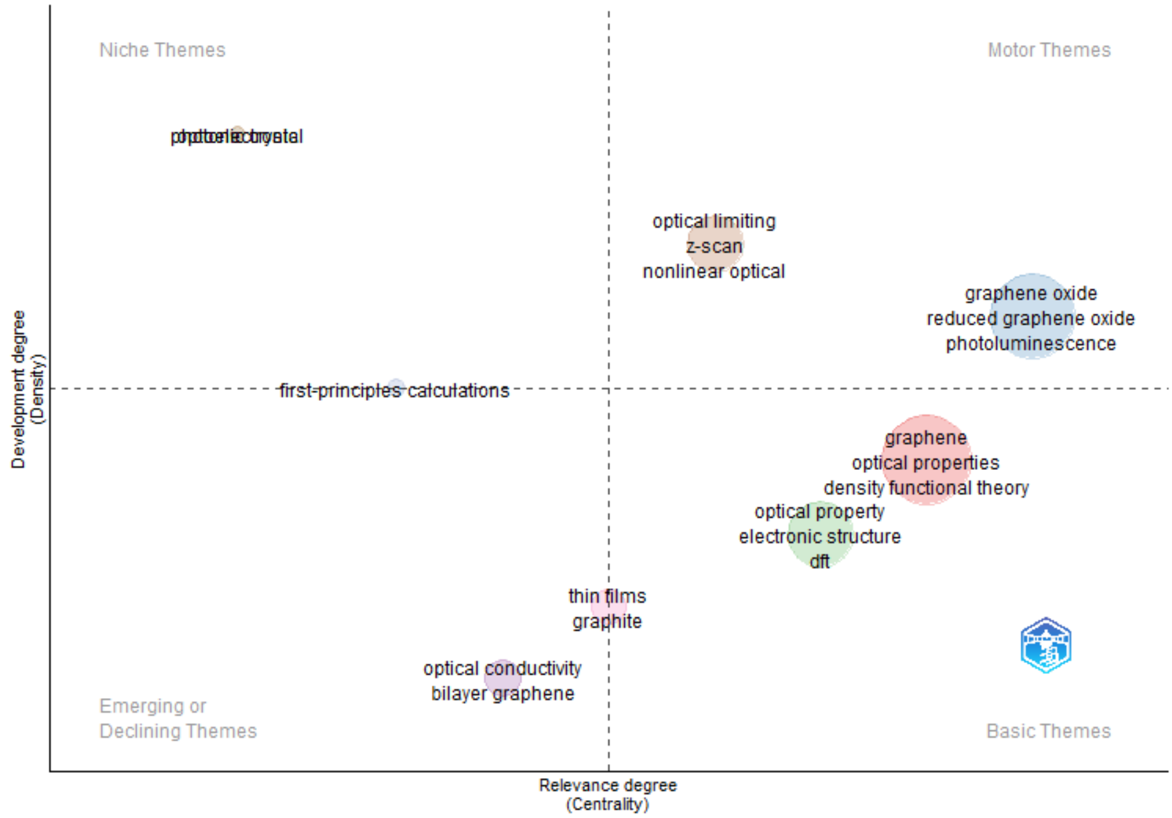

Figure 6: Thematic map on the optical properties of graphene.

The emerging or declining theme quadrant is characterized by low density and low centrality, representing either nascent research directions-such as bilayer graphene optical conductivity-or topics that are gradually losing momentum relative to more active areas, for example, graphene oxide-based photonics. The thematic map has been constructed using author keywords.

Table 5: Centrality and density details of all the clusters

Cluster	Callon Centrality	Rank Centrality	Callon Density	Rank Density	Cluster Frequency
graphene	0.569336162	16.03007018	8	4	654
graphene oxide	0.573935165	16.9714542	9	6	450
optical property	0.256368161	15.90742888	7	3	134
optical conductivity	0.069480519	10.45454545	4	1	21
optical limiting	0.111868786	17.16601879	6	7	73
thin films	0.107103175	11.66666667	5	2	19

The basic theme quadrant, located in the lower-right region of the map, represents the foundational backbone of the research field. This quadrant comprises two clusters led by the keyword's 'graphene' and 'optical property' containing 29 and 10 associated terms, respectively. Cluster details are shown in Table 6. The graphene cluster encompasses keywords related to various forms of two-dimensional materials and their dominant optical properties, including optical absorption, dielectric function, excitonic effects, and electronic and electrical properties. It also highlights theoretical frameworks and computational approaches through keywords such as density functional theory, first-principles calculations, and tight-binding models. In addition, this cluster reflects research on the optoelectronic properties of 2D materials and their associated sensor applications.

The 'optical property' cluster primarily focuses on density-functional-theory and first-principles investigations of the electronic structure, optical behaviour of MoS_2 and related heterostructures. Emphasis is placed on absorption characteristics, doping-induced modulation of properties, and structure-property relationships relevant to optoelectronic applications. The statistical parameters of the "graphene" and "optical property" clusters, organized according to betweenness centrality hierarchy, are presented in Table 6.

The motor theme quadrant is characterized by high density and high centrality, indicating both the maturity and the central importance of these themes within the research field. Keywords in the motor theme clusters form the structural core of the domain; they are well developed, highly interconnected, and strongly relevant to ongoing research. Consequently, the clusters in this quadrant drive investigations into the most active and contemporary research topics. Two clusters are identified in the motor theme quadrant. The centrality details of motor theme cluster are presented in Table 7.

The 'graphene oxide' cluster encompasses core materials and composite systems, including graphene oxide, reduced graphene oxide, ZnO, TiO_2, carbon nanotubes, and various metal-oxide/graphene oxide nanocomposites.

Table 6: Basic Theme Cluster Details				
Graphene Cluster				
Occurrences	**Keywords**	**Betweenness centrality**	**Closeness centrality**	**Page Rank centrality**
220	graphene	6699.52758	0.00215983	0.09146001
156	optical properties	3525.440067	0.00198807	0.06742168
42	density functional theory	1655.017669	0.00175747	0.02000827
27	electronic properties	846.6655062	0.00158479	0.0134972

19	graphene quantum dots	459.1367179	0.00162602	0.00662492
Optical property cluster				
33	optical property	1152.739674	0.00177305	0.015857366
30	electronic structure	319.0222383	0.001605136	0.015135034
28	dft	668.9171521	0.001724138	0.015724477
8	absorption coefficient	256.0982272	0.001848429	0.003946328
7	doping	242.1356311	0.001694915	0.00372401

Table 7: Cluster Details of clusters in Motor Theme Quadrant				
Graphene Oxide				
Occurrences	**Keywords**	**Betweenness centrality**	**Closeness centrality**	**Page Rank centrality**
113	graphene oxide	4791.01791	0.002057613	0.048205328
37	reduced graphene oxide	2002.675974	0.001845018	0.018948591
27	photoluminescence	983.4684661	0.001788909	0.010681741
24	nanocomposites	953.7451971	0.001644737	0.012616671
20	nonlinear optics	560.02153	0.001683502	0.008826101
Optical Limiting Cluster				
24	optical limiting	463.7132481	0.001536098	0.011174439
21	z-scan	522.1629181	0.001533742	0.01324848
7	nonlinear optical	322.1456124	0.001577287	0.00493158
6	nonlinear absorption	3.870219969	0.001222494	0.002794887
5	reverse saturable absorption	39.70464694	0.001302083	0.003301072

This cluster includes keywords associated with a wide range of optical phenomena, spanning both linear and nonlinear optics, such as luminescence and photoluminescence, absorption, transmittance, refractive index and nonlinear optical effects. It also highlights diverse fabrication routes of graphene including hydrothermal synthesis, laser ablation, and thin-film processing as well as key characterization techniques such as Raman spectroscopy, X-ray diffraction (XRD), scanning electron microscopy (SEM), and spectroscopic ellipsometry. Furthermore, the cluster reflects application-driven research on the optical properties of graphene-based materials for optoelectronics, photocatalysis, and supercapacitor applications.

The ‘optical limiting’ cluster represents critical nonlinear optical phenomena, including nonlinear absorption, saturable absorption, reverse saturable absorption, and related nonlinear optical effects. This cluster underscores the use of graphene and related two-dimensional materials in optical limiting applications for laser protection and advanced photonic devices. It also emphasizes the Z-scan technique as a widely adopted and reliable method for characterizing nonlinear optical responses in 2D material systems.

Clusters located in the upper-left quadrant, characterized by low centrality and high density, represent niche themes. The keywords associated with these clusters, such as photochemical and photoelectrochemical processes, correspond to specialized optical phenomena that are internally well developed and mature but remain weakly connected to the broader graphene research landscape.

3.5 Factorial Analysis:

In the factorial map(61)analysis is shown in figure 7. Factorial Axis 1 (horizontal axis) represents a transition from fundamental electronic and structural investigations to application-oriented optical and optoelectronic functionalities. On the negative side of Axis 1, keywords such as electronic structure, electrical property, density functional theory, first-principles calculations, band structure, and bilayer graphene emphasize theoretical modeling and intrinsic material properties are appearing. Progressing toward the positive side of Axis 1, the thematic focus shifts to optical engineering and photonic applications, characterized by terms optical properties, plasmon resonance, photoluminescence, nonlinear optics, laser ablation, optical limiting, and luminescence. Factorial Axis 2 (vertical axis) captures the evolution from basic property characterization to complex structure-property-performance relationships. Lower values along Axis 2 are associated with foundational descriptors such as electrical property and optical property, whereas higher values highlight advanced material architectures and characterization techniques, including nanocomposites, quantum dots, spectroscopy ellipsometry, Raman spectroscopy, refractive index, and electrical conductivity. Together, the two axes reveal a coherent research trajectory that integrates theoretical modeling, spectroscopic validation, and functional optical performance, underscoring the maturation of graphene research from fundamental physics toward technologically relevant optoelectronic applications.

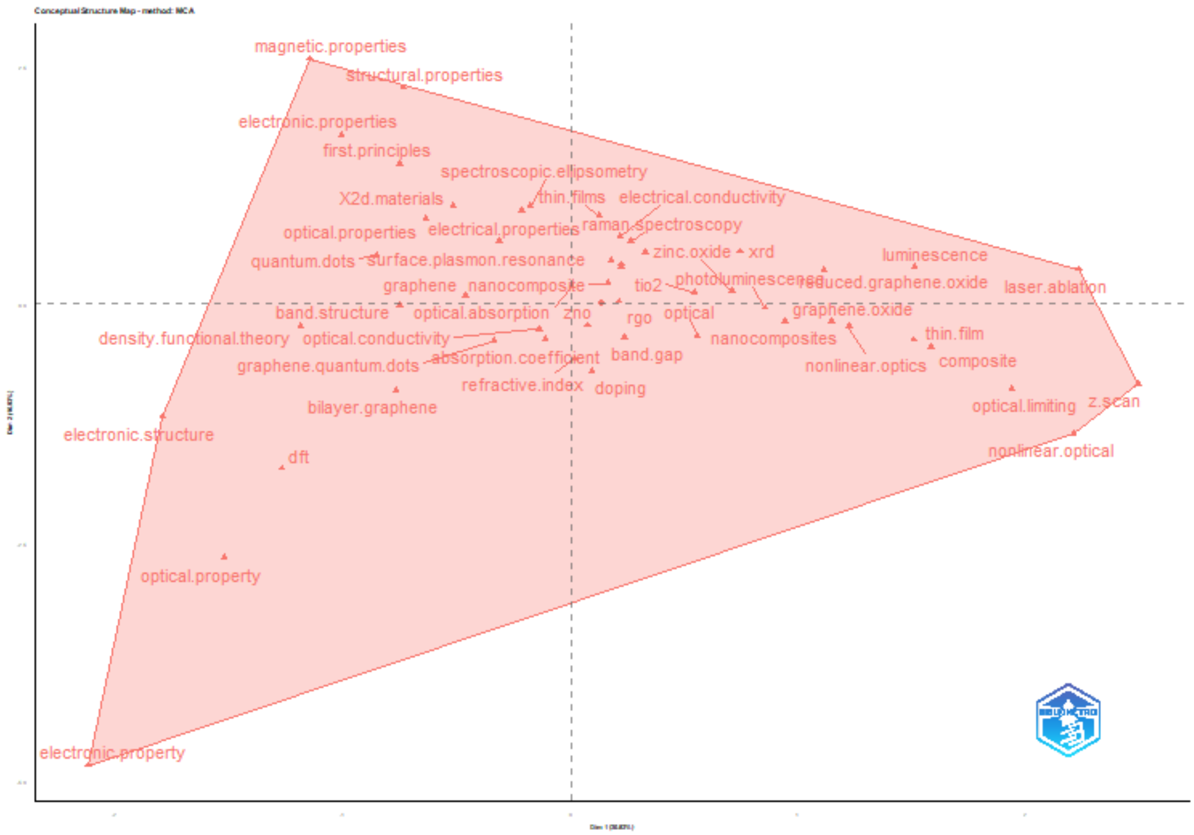

Figure 7: Factorial analysis on optical properties of graphene.

3.6 Mapping of Keyword Clusters to Real-World Applications and Commercial Products:

Graphene and related two-dimensional materials have attracted significant attention for optical and photonic applications due to their broadband optical absorption, tuneable band structure, high carrier mobility, and strong nonlinear optical responses. These properties enable their use in ultrafast photonics, optical limiters, photodetectors, and advanced optoelectronic devices. In particular, graphene-based saturable absorbers are widely employed in mode-locked laser systems developed by BATOP GmbH, while high-precision photonic and optical components are commercially available from Thorlabs. Furthermore, graphene-enabled optical materials contribute to next-generation display and optoelectronic technologies produced by LG Display. illustrating the transition of graphene optical research from fundamental studies to practical industrial applications. This keyword-to-application mapping demonstrates that graphene optics research has progressed beyond fundamental photophysical investigations toward device integration and commercialization. Author keywords from various clusters of Table 2, Table 3 and Table 4 are mapped into the realizable products. Actual products are listed in the column 3 of Table 5.

Table 5: Journey from keywords to applications and Real-World Products				
Keyword Cluster	**Application Domain**	**Real-World Product / Technology**	**Company / Organization**	**Verified Website**
Graphene oxide, reduced graphene oxide, graphene, carbon nanotubes, nanocomposites, thin films	Gas sensing and biosensing	Graphene-based gas sensors and biosensing platforms	Graphenea	https://www.graphenea.com
Graphene, CNT, nanocomposites, conductive composites	Energy storage systems	Graphene-enhanced supercapacitors for electric vehicles and grid storage	Skeleton Technologies	https://www.skeletontech.com
Graphene composites, conductive additives, nanostructures	Battery technology	Graphene-based aluminium-air and lithium-ion battery materials	Log9 Materials	https://log9materials.com
ZnO, TiO_2, graphene composites, heterostructures	Photocatalysis and environmental remediation	Photocatalytic coatings and water purification systems	TOTO Ltd.	https://www.toto.com
MoS_2, graphene heterostructures, bilayer graphene	Photodetectors and optoelectronic devices	High-sensitivity photodetectors and optoelectronic sensors	Hamamatsu Photonics	https://www.hamamatsu.com
Quantum dots, graphene quantum dots	Displays, bioimaging and LEDs	Quantum-dot based QLED displays	Samsung Electronics	https://www.samsung.com
Nonlinear optics, saturable absorption, optical limiting	Ultrafast laser systems	Graphene-based saturable absorbers for	BATOP GmbH	https://www.batop.de

		mode-locked lasers		
Optical absorption, refractive index, dielectric function	Optical materials and photonics	Photonic and optical components for lasers and optical systems	Thorlabs	https://www.thorlabs.com
Optical conductivity, photoluminescence, dielectric properties	Display and photonic technologies	OLED display panels and photonic devices	LG Display	https://www.lgdisplay.com
Bandgap engineering, charge transfer, excitons, electronic structure	Solar energy conversion	Thin-film photovoltaic modules	First Solar	https://www.firstsolar.com
DFT calculations, first-principles calculations, tight-binding model	Computational materials design	Atomistic simulation tools for materials modelling	Synopsys	https://www.synopsys.com
Photonic crystals, optical materials, sensors	Optical communication and photonic devices	Silicon photonic integrated circuits	Intel Corporation	https://www.intel.com
Photocatalysis, nanostructured oxides	Air purification and antimicrobial surfaces	Photocatalytic air purification systems	Panasonic	https://www.panasonic.com

Conclusions:

Keyword co-occurrence analysis reveals that 2D materials spanning from graphene, graphene oxide, to bilayer graphene, MoS_2, quantum dots, heterostructure have been studied through various advanced spectroscopic techniques to exploit their potential in optical and optoelectronic devices for sensing and energy storage.

Temporal evolution of keywords shows a shift from general graphene based 2D material identification, synthesis and characterization to the study of advance materials like bilayer graphene and silicene. These studies comprise of detailed investigations, tuning of the physical properties and computational modelling of these materials for advance optic and optoelectronic technological applications.

Co-word analysis highlights the study of 2D general and advanced materials and their characterization by advanced characterization techniques such as z-scan and ellipsometry. Density functional theory has been used to study the electronic structure and other properties. Practical applications of graphene oxide ZnO composites have been explored in areas such as optoelectronics sensors and light matter interactions.

The basic theme clusters are centred on density-functional-theory-driven studies of various properties of graphene and graphene-derived nanostructures (quantum dots and nanoribbons), MoS_2 and related heterostructures for sensing and optoelectronic applications. The motor theme clusters emphasizes on photoluminescence, nonlinear optical response, dielectric properties, and bandgap modulation, characterization techniques with applications in optoelectronics, photocatalysis, and energy storage.

The conceptual structure, obtained through factorial analysis highlights a dominant theme centred on the optical, electronic, and optoelectronic functionality of graphene-based materials. A strong emphasis is given on structure-property correlations, spectroscopic characterization toward technologically relevant optoelectronic applications.

The integration of three different methods of keyword analysis gives a comprehensive and holistic view of the past studies, present exploration in various directions and the future research fronts, evolving and motor themes on optical properties of graphene. The use of two software enhances the knowledge about the optical properties of graphene by giving some common insights as well as some distinct information.

Information in Table 5 provides a conceptual bridge between fundamental optical physics, bibliometric clusters, and commercial deployment. Keyword in table 5 correspond to distinct optical attributes, not just generic material usage. These attributes directly translate into real-world products, strengthening the technology-readiness and application relevance of graphene optical research.

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