Electronic Properties of Graphene: Translation from Academia to Industry Through Keyword Analysis

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***Abstract*—** Graphene has been an iconic material to researchers and scientists in the 21st century due to its unique structure and versatile application potential in various electronic devices leading to a plethora of research papers. This huge volume can be categorized by bibliometrics, a quantitative statistical method. In this work, keyword analysis has been undertaken to identify the intellectual structure and knowledge flow of the electronic properties of graphene. The data for the analysis has been obtained by Web of Science from the year 2004 to 2025. Author keywords have been analysed by three complementary analysis methods viz. cluster analysis, thematic map and factorial analysis. Vos-viewer software and the bibliometrix R package ere used for the analysis. The top relevant keywords have been identified based on their co-occurrences in the documents. The trending topics in this field throughout the years were identified. Keywords obtained through thematic clustering have been analysed and their importance was ranked in terms of different statistical variants of centrality. Factorial analysis has also been carried out, and the structure of the research in the field has been found. Extracted keywords from the analyses have been used to map application potential of graphene in various real-life products, underscoring the translation of graphene research from academia to industry.

Keywords: Graphene, Keyword Co-occurrence Analysis, Co-Word Analysis, Bibliometrics, Thematic clusters, Factorial Analysis.

I. INTRODUCTION

Since its experimental isolation in 2004, graphene has attracted extraordinary scientific and technological interest, resulting in a rapidly expanding and highly interdisciplinary body of literature. Graphene consists of a single atomic layer of sp^2-bonded carbon atoms arranged in a two-dimensional honeycomb lattice, making it the archetypical two-dimensional material. Each carbon atom forms three strong in-plane σ bonds with nearest neighbours at a distance of approximately 1.42 Å, while the remaining p-z orbital contributes to delocalized π and π* bands that dominate graphene's low-energy electronic structure [1].

The unique band structure of graphene is characterized by a zero-band gap, where the valence and conduction bands touch at discrete points known as Dirac points located at the corners of the Brillouin zone. Near these points, the energy-momentum relationship becomes linear, and charge carriers behave as massless Dirac fermions rather than conventional Schrödinger electrons [1]. As a result, graphene exhibits exceptionally high carrier mobility, ballistic transport over submicron distances, and unconventional quantum phenomena. One of the most striking manifestations of this physics is the anomalous integer quantum Hall effect, observable even at room temperature due to reduced backscattering and high mobility [2].

These electronic properties have positioned graphene as a cornerstone material for next-generation electronic and optoelectronic technologies. Applications such as high-frequency radio-frequency (RF) transistors, transparent conductive electrodes, and ultrafast photonic devices rely directly on graphene's high carrier mobility, tuneable conductivity, and broadband optical response [3,4]. In particular, graphene field-effect transistors have demonstrated operation frequencies exceeding hundreds of gigahertz, highlighting the strong link between fundamental electronic transport and device-level performance.

Because of this tight coupling between electronic properties and applications, research on graphene electronics spans condensed-matter physics, materials science, electrical engineering, and applied device physics. Several authoritative narrative reviews have comprehensively addressed graphene's electronic transport mechanisms, including scattering, quantum Hall physics, and many-body effects [5,6].

However, while these reviews provide deep physical insight, they do not quantitatively examine how research themes, collaborations, and application-oriented trends have evolved across the rapidly growing literature. Bibliometric analyses have emerged as powerful tools for mapping the intellectual structure and evolution of large research fields. Existing bibliometric studies for graphene have predominantly examined overall publication growth, citation patterns, and country- or institution-level productivity [7,8]. Other studies have focused on application-oriented research domains, particularly graphene-based materials for energy storage [9], composites [10] and sensing technologies [11]. However, despite the central importance of electronic properties to graphene's scientific and technological relevance, a dedicated bibliometric analysis that systematically maps the evolution, thematic structure, and key research fronts of graphene's electronic properties in recent years remains lacking.

Accordingly, this study aims to fill this gap by providing a comprehensive bibliometric analysis of research on the electronic properties of graphene. By quantitatively examining publication trends, keyword evolution, and thematic structures, this work seeks to clarify how fundamental electronic concepts have driven application-oriented research and shaped the development of graphene-based electronic technologies.

Keywords extracted from various analyses have been mapped into applications associated with the electronic properties of graphene and further corelated with the realizable market ready products.

II. BIBLIOMETRIC FRAMEWORK AND OBJECTIVES

Bibliometric analysis is a quantitative methodology that evaluates scientific literature through statistical analysis of publication metadata such as authorship, citations, and keywords [12]. By establishing relationships among publications, bibliometrics enables the identification of influential works, emerging research themes, and the structural evolution of scientific fields [13].

Keyword-based analyses play a central role in bibliometric studies because keywords encapsulate the conceptual content of research articles. Author keywords reflect the authors' intended thematic emphasis, whereas Keywords Plus-automatically generated from cited references-provide complementary contextual information [14]. Co-occurrence analysis of keywords, traditionally referred to as co-word analysis, examines how frequently specific terms appear together and is particularly effective for identifying research fronts and thematic linkages [15].

Several analytical techniques can be employed within keyword co-occurrence analysis, including clustering, social network analysis, and factorial analysis [16] . Among these, exploratory factorial analysis (EFA) is useful for reducing complex, high-dimensional datasets into a smaller number of latent factors that represent underlying research themes [17]. When combined with temporal analysis, these methods enable the exploration of thematic evolution and shifts in research emphasis over time.

In the present study, bibliometric mapping and visualization are performed using VOSviewer, which is widely applied for constructing and visualizing bibliometric networks [18] and the Bibliometrix R package, which provides a comprehensive framework for science mapping and performance analysis [19]. The combined use of these tools allows for robust cross-validation of results and richer interpretation than reliance on a single method.

Objectives of the Study

The specific objectives of this study are to:

i. analyse the temporal growth of publications and citation impact related to the electronic properties of graphene.
ii. identify major research themes through co-occurrences of keywords.
iii. examine the temporal evolution of key terms.
iv. identify core research themes through author co-word analysis.
v. identify the structure of research on the electronic properties of graphene by quadrant analysis of thematic map.
vi. Explore latent thematic structures and their evolution using factorial analysis and thematic mapping.

Data Source

The data for the analysis has been taken from the Web of Science Core Collection from 1st January 2004 to 24th March 2025 for electronic properties of graphene which fetches 1812 documents. Keyword analyses have been performed on the data to fulfil the listed objectives by integrating the results of bibliometric R package and VOS-viewer software. The data for the analysis was extracted from the WOS database employing the following query in the title of the publications.
Title: (Graphene OR Graphene oxide OR Graphite) AND (Electronic Properties)

III. RESULTS AND DISCUSSION

The year-wise publication pattern on the electronic properties of graphene has been shown in fig. 1. Some prominent peaks are appearing in specific years. A maximum of 144 documents were published in the year 2020. In 2015 and 2017 the number of documents published were 134 and 139 respectively.

One can see a downtrend from 2020 onwards which can be due to either the WOS database not having more recent papers or because of a shift in focus away from the electronic properties of graphene.

The year-wise average citations that a document obtained has been shown in fig. 2. We can see two distinct peaks in 2007 and 2009 of 236 and 552 citations per document indicating a higher quotient for collaboration in the early research and a growing interest in graphene's electronic properties. It also corresponds well with the increasing slope seen in fig. 1 around the same years. Since 2015 however we can see a consistent slight decline in average citations.

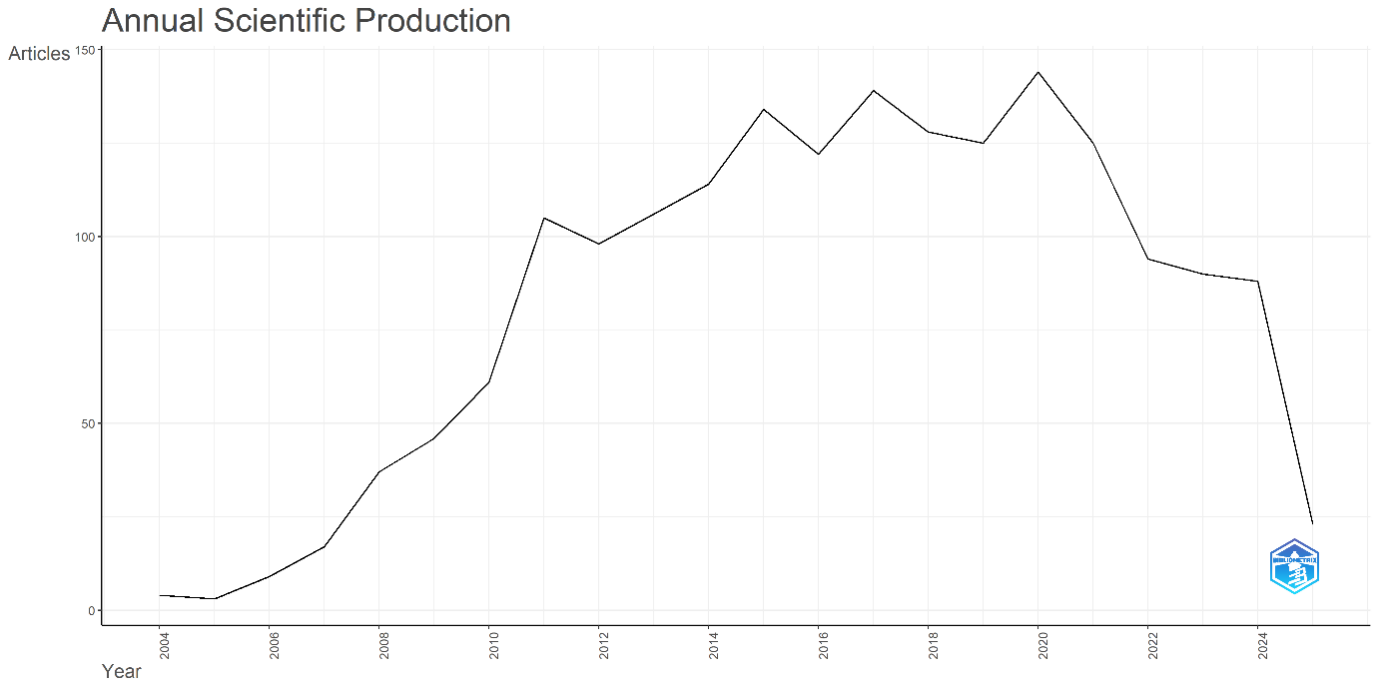

Figure 1: Number of articles as a function of publication year.

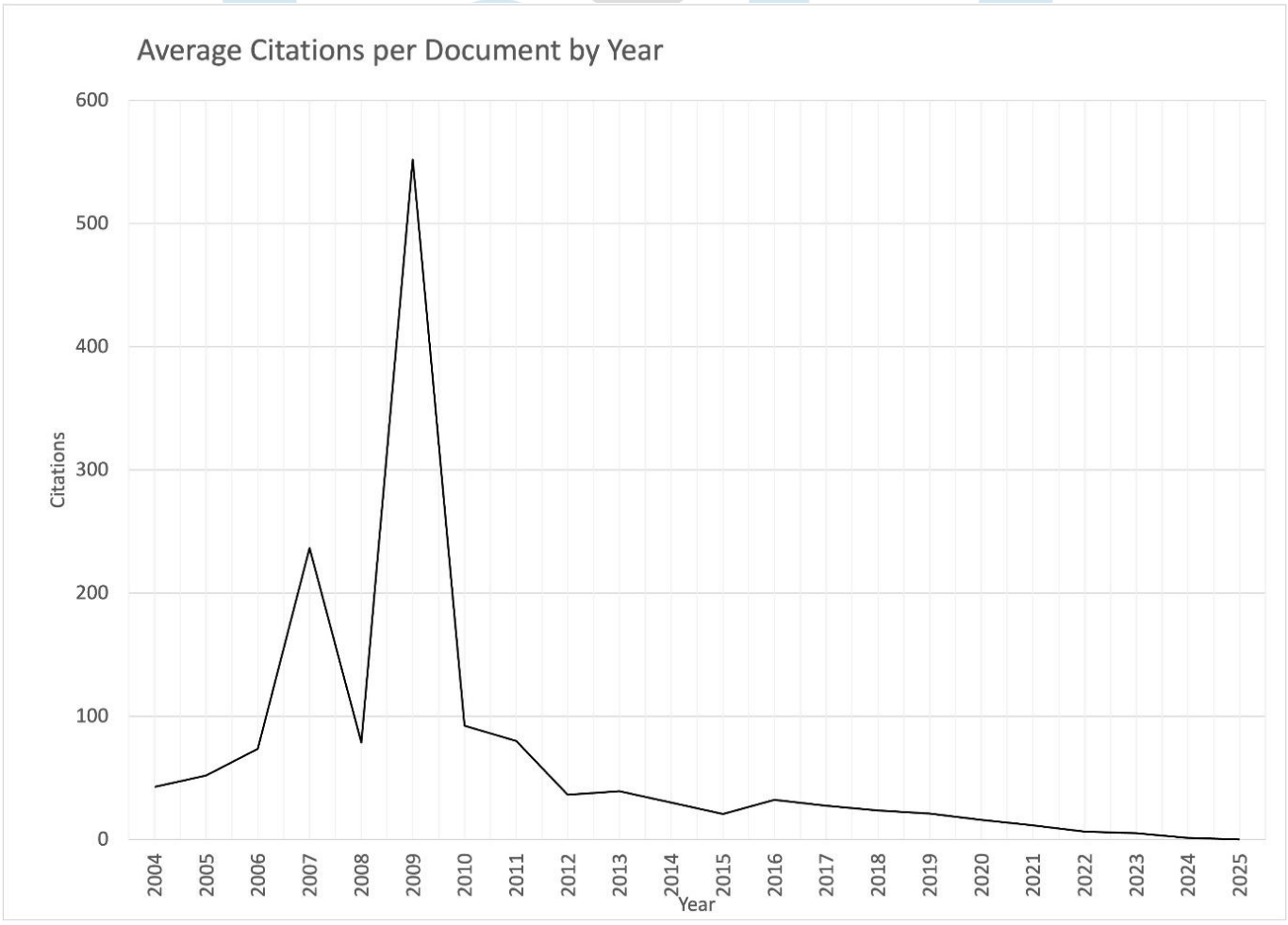

Figure 2: Average citations for a document per year.

Keywords Co-occurrence Analysis

The basic assumption in bibliometrics [20] is that each research field can be characterized by a list of the important keywords. Each publication in the field can in turn be characterized by a sub-list of these keywords. Such sub-lists are like fingerprints of these published articles. Börner et al. [20] suggest that these "fingerprints"' can be used as a similarity measure. "The more keywords two documents have in common, the more similar the two publications are and more likely they come from the same research area".

In the data considered a total of 2282 keywords have been identified. To see strongly connected keywords the minimum co-occurrences of keywords have been selected as 5 in Vosviewer. This resulted in a total of 137 keywords, distributed among 10 clusters for the analysis. Fractional counting has been selected with occurrences of keywords as weight. The visualization map has been shown in fig. 3(a). keywords with highest co-occurrences are represented by the biggest circle. The thickness of the lines represents the strength of connection among the keywords. keywords grouped into same cluster are more likely to reflect identical theme. If each cluster has different keywords, it implies that research field has varied interests. No line connection in a co-occurrence map among keywords indicates marginal relevance.

Most common author keywords present in the first (red) cluster are graphene, graphite and intercalation with 356, 163 and 152 co-occurrences respectively. Cluster number, color and other details in the hierarchy of co-occurrences are given in Table 1. The keywords in the first cluster can be categorized in three groups viz. materials, methods and mechanism, physical properties of and phenomenon associated with 2D materials. Keywords of the Second cluster(green) focus on graphene edge structure, defects, functionalization, electric, magnetic and optical properties, transport phenomenon, theoretical modelling and device-oriented applications. The third cluster (blue) represents the theoretical and first-principles study of 2D materials and their hetero-structure. The fourth cluster (yellow) represents the theoretical modeling of the structure of 2D materials and their properties. Fifth (purple) cluster talks about the density functional theory and is application to zigzag graphene nano ribbons to obtain various electronic properties. Sixth (cyan) cluster contains words like armchair graphene, quantum dots and various properties of graphene and related 2D materials. Seventh (orange) cluster talks about the ab initio calculations related to 2D materials. Cluster eight (brown) mentions the heterostructures, mos_2, and transmission co-efficient, vacancy defects, work function etc. Nineth (pink) cluster contains keywords related to electronic structure of graphene. Tenth (pale pink) cluster has keywords adsorption, defect, interface, semiconductor and vacancy.

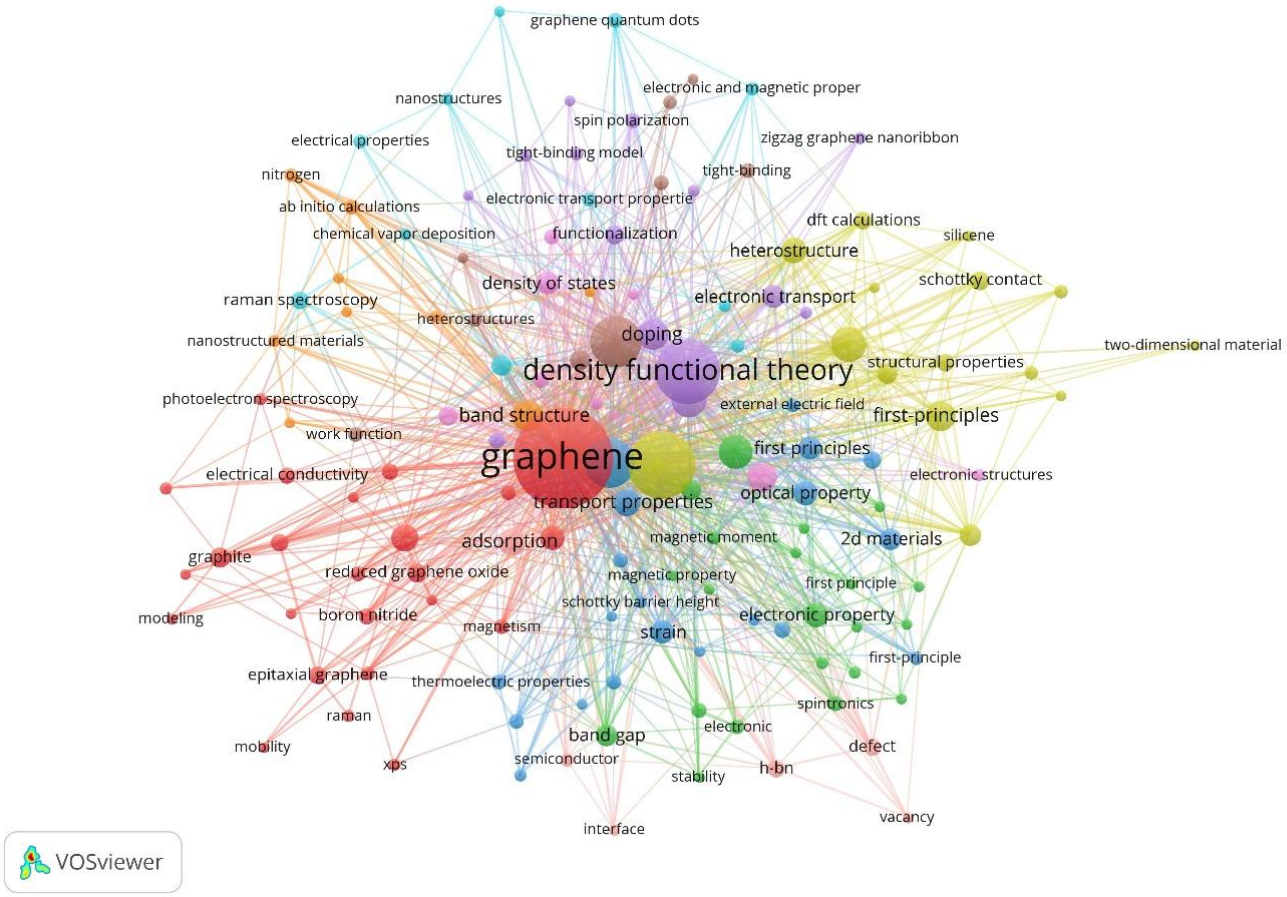

Figure 3(a): Visualization map of author keywords representing 10 clusters.

Table 1: Cluster details in the hierarchical order of links

Cluster No. (Colour)	**Highest frequency keyword of the cluster**	**Link**	**TLS**	**Occurrences**	**Keywords present in the cluster**
1 (Red)	Graphene	117	606	356	24: Graphene oxide, graphite, bilayer graphene, quantum dots, band gap epitaxial graphene, quantum Hall effect, Raman, photo electron spectroscopy, mobility, magnetism, conductivity, intercalation, local density of states, electrical,

					conductivity, boron nitride, mobility, modelling, point defects etc.
4(yellow)	Electronic properties	86	328	163	15: Dft calculations, electronic properties, electric field, first principles calculations, heterojunction, heterostructures, structural properties, 2D materials etc.
5(Purple)	Density functional theory	80	268	152	14: Density functional theory, doping, edge effect, electronic transport, energy band gap, nanoribbons, zigzag graphene nanoribbons, spin polarization, transport properties etc.
8(Brown)	dft	65	173	93	9: Dft, heterostructures, mos2, nanoribbons, transmission co-efficient, vacancy defects, work function, tight binding etc.
2(Green)	Nano-ribbon	37	68	43	21: Armchair graphene, band gap, carrier mobility, density functional theory, electron transport, electronic property, energy gap, fluorination, gas sensor, magnetic moment, magnetic property, optical absorption, spintronics, stone-Wales defect, transport
3(blue)	transport properties	27	62	28	20: 2D materials, band alignment, bilayer graphene, charge transfer, density functional theory, doped graphene, electronic structure, external electronic field, first principle, mechanical properties, optical property, thermoelectric properties, van der Waals hetero-structure, magnetic field etc.
10(Pale pink)	Adsorption	24	53	28	6: Adsorption, defect, interface, semiconductor, vacancy etc.
9(Pink)	First principle calculations	25	46	31	8: Density of states, electronic band structure, electronic structure, first principle calculations, n-doped graphene, thermal conductivity, twin graphene etc.
6 (Cyan)	defects	26	40	15	11: Armchair graphene, chemical vapor deposition, defects, electrical properties, electronic and magnetic properties, electronic and optical properties, electronic transport properties, graphene quantum dots, nano-structures, Raman spectroscopy etc.
7(Orange)	Nitrogen	11	24	7	9: ab initio calculations, band structure, carbon, fermi level, hexagonal boron nitride, magnetic moments, nano structured materials, nickel, nitrogen etc.

Most relevant Keywords

Keyword analysis uses author keywords whereas most relevant keywords are selected from Keyword Plus. Most relevant words obtained through bibliometrix are carbon, graphite, films, gas and total energy calculations with 150, 144, 123, 114 and 110 occurrences are shown in fig. 3(b).

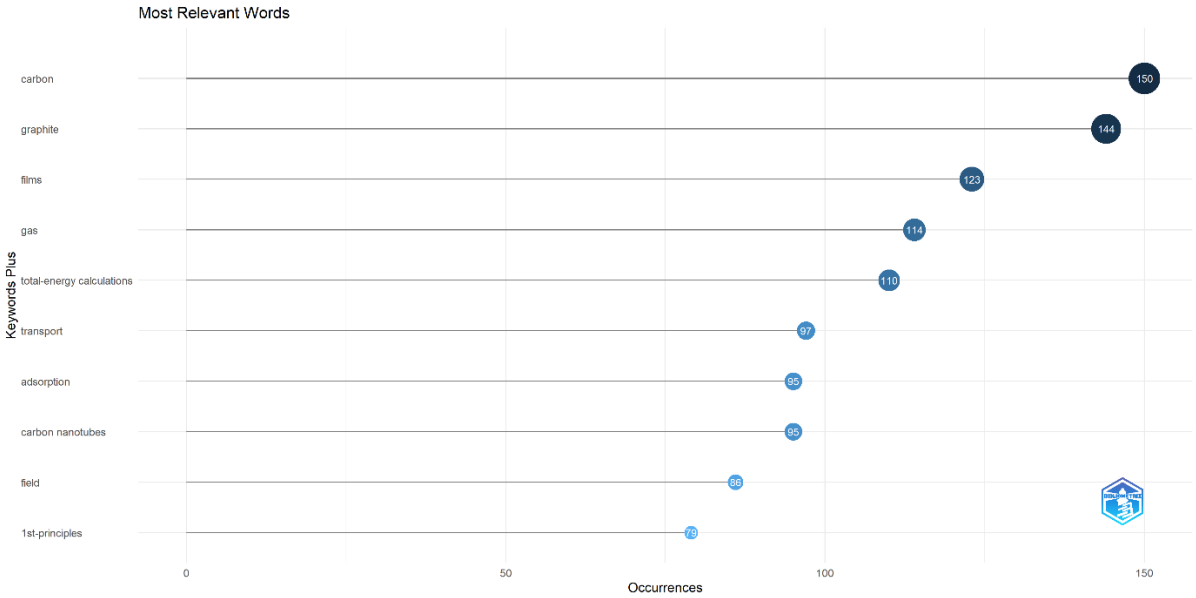

Figure 3(b): Occurrences of most relevant words on the electronic properties of graphene.

Rest of the keywords have less than 100 co-occurrences Most relevant keywords have been shown if fig. 3(c). 'Carbon' has a maximum word frequency making 5% of the total word frequency of the keywords used. Keywords graphite, films and gas make 5%, 4% and 4% share respectively in the total word frequency. First ten high frequency words used in the papers on electronic properties of graphene are shown in fig. 3(d). There is a slow exponential increase in all the cumulative occurrences of keywords over the years. From the year 2007 till the middle of the year 2022 graphite was the most used keyword. Carbon has taken lead from the year 2022 onwards being the backbone of all graphenic materials. Keywords with low co-occurrences were first principle, CNT, adsorption, field and total energy calculations.

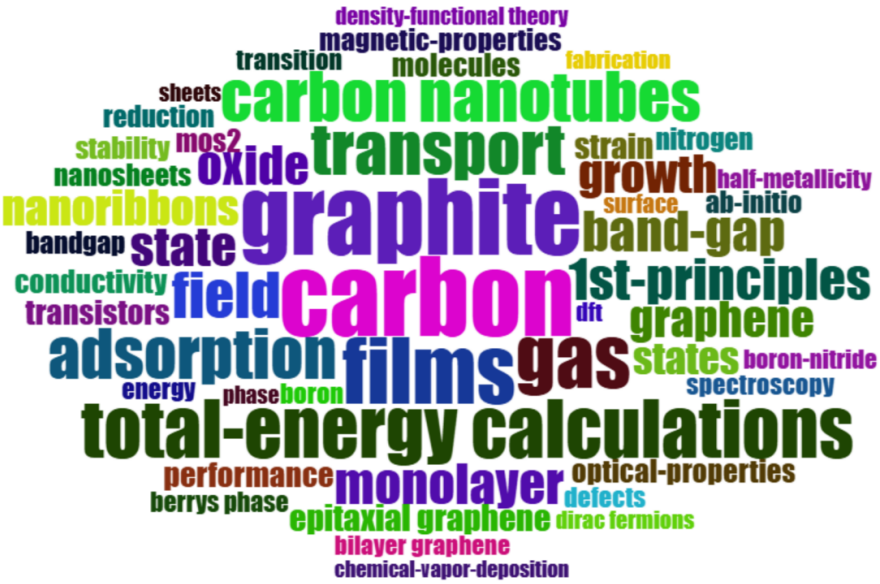

Figure 3(c): Most relevant word used in the literature on the electronic properties of graphene.

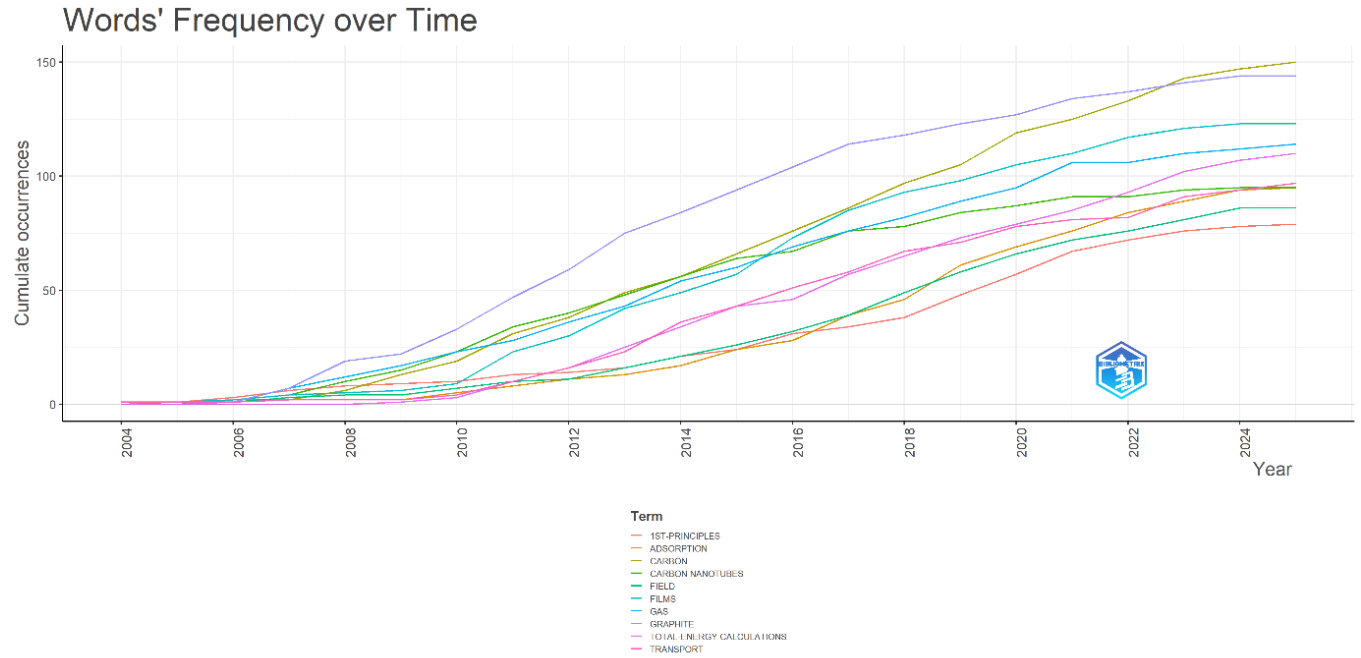

Figure 3(d): Year-wise variation of words' frequency.

Year wise topic trend on the electronic properties of graphene has been shown in fig. 3(e). Graphite and carbon nano tubes were the most trending words in the year 2013. In 2016 the research interest shifted to carbon, films and transport properties. In 2019 the most trending topics were first principles calculations, monolayer and adsorption. Conductivity and stability were the most popular words in 2020. Electrical conductivity, catalysts, design and generation are the trending words in the year 2023-2024. Keyword spectroscopy has the longest time span from the year 2011 till 2020. Atomic structure and carbon have been among the popular keywords for about nine years. Some other keywords like conductivity and mobility have also been used for a longer time.

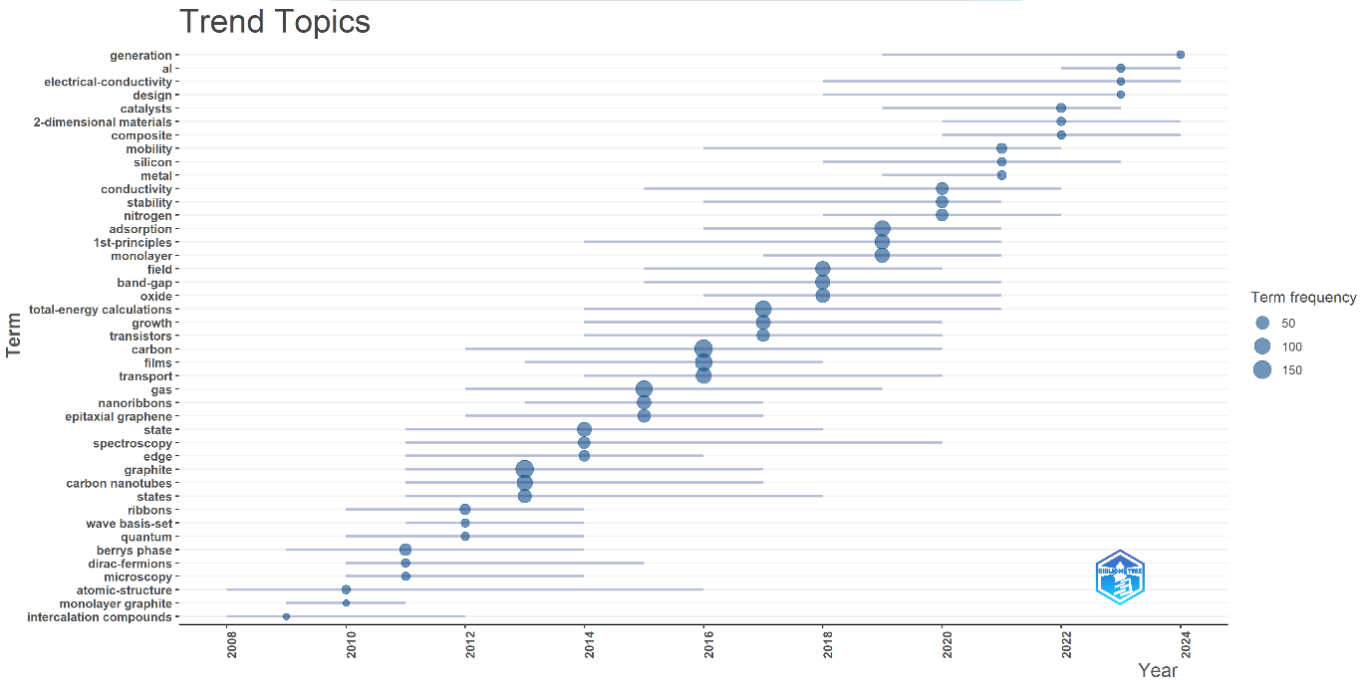

Figure3(e): Temporal evolution of trend topics.

Co-word Analysis

Author keywords have been selected for the co-word analysis. When two keywords appear in the same document, they have a connection between them and the strength of connection among the documents is attributed to the common keywords they share. If the frequency of the co-occurrences of a keyword pair is more, the strength of connection is high.

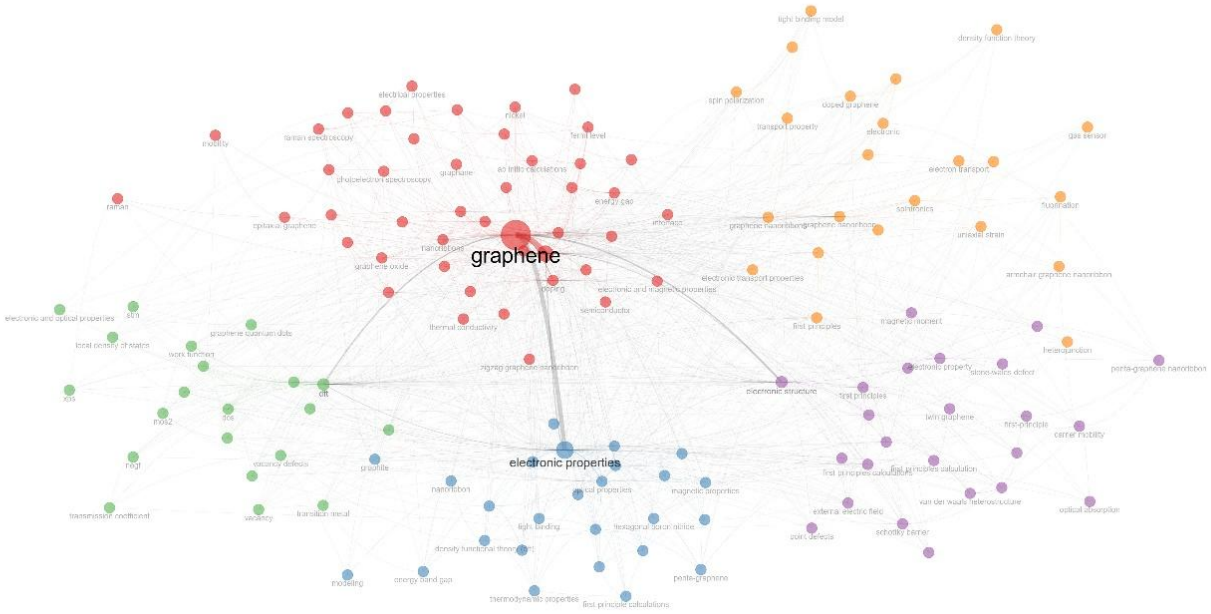

Figure 4: Co-word network obtained through author keywords.

Co-word analysis visualizes the intellectual structure of the topic, which in turn maps into the conceptual space of the research area. Intellectual structure of the topic is dependent on keywords used. The conceptual structure [21] is likely to the change with time as many new and exploratory words may be included in the topic due to technical advancements. Many researchers have used co-word analysis to explore the conceptual network in various subjects [22–26].The co-word analysis through bibliometrix, on the metadata of electronic properties of graphene identifies 6 clusters out of 139 keywords as shown in fig. 4. The clusters are designated as graphene, electronic properties, dft, electronic structure, graphene nano-ribbons having 39, 21, 20, 30, 18 and 11 keywords respectively. 'Graphene' is the biggest cluster and the backbone of all 2D materials and is the most valuable keyword in the metadata. It is represented by the biggest circle in the keyword graph. Density of lines through the graphene node explains its connection with the other nodes within the cluster as well as outside the cluster. Other nodes of the 'graphene' cluster are density functional theory, band structure, doping, defects and band gap etc. This cluster points out towards various transport properties of graphene and related 2d structures with emphasis on band structure engineering, defects and doping effects, hetero structure formation and first principle modelling for nanoelectronics and spintronics.

'Electronic properties' cluster contain keywords based on different properties of graphene like, electronic, electrical, optical, mechanical, magnetic, thermoelectric and structural properties of graphene, Optical properties, magnetic properties, transport and thermodynamic properties. It focuses on Density functional theory and first principles calculations on different forms of graphene such as graphene nanoribbons, silicene, phosphorene and bilayer graphene ribbons and study the strain, electric field and Schottky-contacts on various properties of graphene.

'Dft' cluster contains keywords belonging to various forms of graphene like bilyer-graphene, graphene quantum dots, n-doped graphene, heterostructures and their study using dft and Non-equilibrium Green's function (NEGF) calculations for electronic devices.

The second biggest cluster, 'electronic structure', contains keywords like electron transport, carrier mobility, band alignment and charge transfer. These keywords are closely related to the electronic structure of graphene. The same cluster also has various variants of graphene as armchair graphene nanoribbons, twin graphene and penta-graphene ribbons and theoretical methods like density functional theory and first principle calculations. 'Electronic structure' cluster focuses calculations using first principle on various properties of graphene nanoribbons and other 2D structure with an emphasis on band gap engineering and devise applications. 'Graphene nanoribbons' cluster points toward the transport and spintronics based studies of graphene nanoribbons. 'Graphene oxide' clusters concentrate on the theoretical and experimental investigations of graphene and other 2D structures.

Betweenness centrality [13] is a measure of the importance of a node based on how often the node lies on the shortest path between the other nodes in the network. A node with highest betweenness centrality acts as a link, commands the flow of information and influence between different parts of the network. The details of different nodes and centrality are shown in Table 1 in a hierarchical order of betweenness centrality. Graphene node is represented by the highest betweenness centrality of 4526.157143. The betweenness centrality of electronic properties, dft, electronic structure, graphene nano-ribbons and graphene oxide nodes are 1249.329054, 566.0995921, 329.0029514, 95.90413018 and 77.63355079 respectively in the hierarchical order.

Table 2: Centrality details of various nodes

Node	Cluster number	Betweenness centrality	Closeness centrality	PageRank centrality
graphene	1	4526.157143	0.00636943	0.12286572
electronic properties	2	1249.329054	0.00534759	0.06448799
density functional theory	1	987.8366339	0.00518135	0.05429053
dft	3	566.0995921	0.0047619	0.03563183
electronic structure	4	329.0029514	0.00456621	0.03473548
band structure	1	147.5109136	0.00429185	0.01780775
graphene nanoribbons	5	95.90413018	0.00414938	0.0150305
transport properties	2	84.04355966	0.00401606	0.01260241
graphene nanoribbon	4	82.76350378	0.00420168	0.01481699
graphene oxide	6	77.63355079	0.00393701	0.00793801

Thematic Map

The network of keywords can be represented by the strategic diagram known as thematic maps [27]. Various research themes related to the electronic properties of graphene can be obtained through this map. Thematic map represents the variation of density as a function of centrality having four quadrants as shown in fig. 5. Density corresponds to the development of theme and centrality measures the importance of the theme. Three clusters viz. carbon, total energy calculations and adsorption, having certain keywords are presented in the map. In the map a cluster is located according to its density and centrality co-ordinates. Size of the cluster is related to the co-occurrences of the keywords present in the cluster.

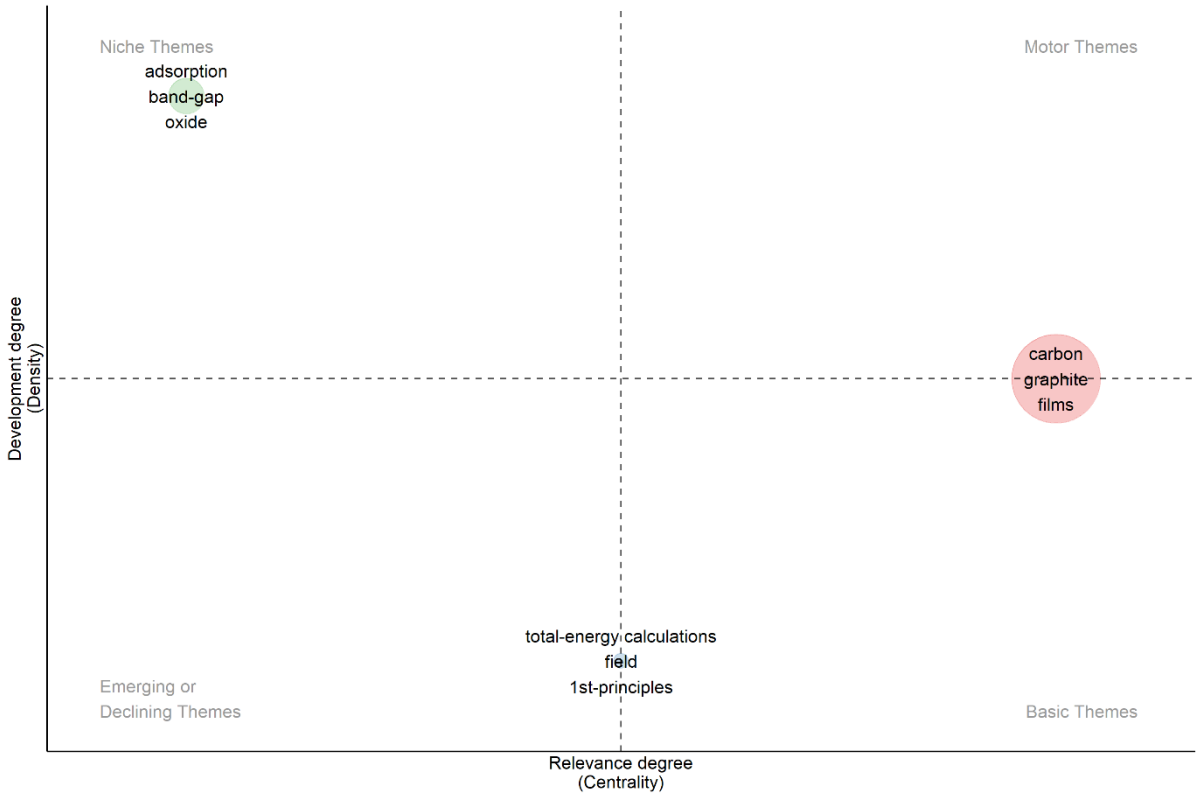

Figure 5: Thematic map of electronic properties of graphene.

The centrality and density details of the clusters are shown in Table 2. Carbon is the biggest cluster having 75 keywords followed by ‘adsorption’ and ‘total energy calculations’ having 62 and 39 keywords respectively. Callon centrality [28] measures the strength and connection of one research theme with the other themes in the network. Callon density talks about the internal development of the theme. In the present metadata ‘carbon’ cluster and ‘adsorption’ cluster have highest Callon centrality and Callon density respectively. Detailed statistics of first few members of the clusters have been shown in Table 3.

Table 3: Centrality and density details of the thematic map clusters

Cluster identity	Callon Centrality	Callon Density	Rank Centrality	Rank Density	Cluster Frequency
Carbon	1.99087499	9.32030632	3	2	2373
Total-energy calculations	1.67808969	8.46225233	2	1	1147
Adsorption	1.44740433	10.3544973	1	3	1403

The keywords in the 'carbon' cluster have four sub-themes viz. graphene and its 2D variants, phenomenon associated with 2D materials, characterization techniques and applications in electronic devices. The cluster 'Total energy calculations' involves properties, calculations, devices, interfaces and phenomenon related to graphene. The third cluster 'adsorption' contains properties, processes, mechanisms, calculations and applications of graphene and its 2D variants.

Table 4: Keyword occurrences and centrality details of the thematic map clusters

Cluster_ Label	Cluster Number	Words	Occurrences	Betweenness centrality	Closeness centrality	PageRank centrality
carbon	1	carbon	150	349.7294	0.002207506	0.019257697
carbon	1	graphite	144	407.239249	0.002277904	0.022785552
carbon	1	films	123	463.277759	0.002293578	0.020283707
carbon	1	gas	114	537.259252	0.002320186	0.016222402
carbon	1	transport	97	312.055346	0.002227171	0.014448733
total-energy calculations	2	total-energy calculations	110	410.5897863	0.002277904	0.016806598
total-energy calculations	2	field	86	446.393038	0.002298851	0.013262653
total-energy calculations	2	1st-principles	79	468.2450083	0.002336449	0.012575753
total-energy calculations	2	monolayer	77	489.1067576	0.002336449	0.012478297
total-energy calculations	2	graphene	69	411.0086219	0.002293578	0.010011438
adsorption	3	adsorption	95	616.133997	0.002358491	0.015842126
adsorption	3	band-gap	77	537.10825	0.002331002	0.012358575
adsorption	3	oxide	74	242.2292821	0.002232143	0.011369416
adsorption	3	performance	47	376.6029379	0.002283105	0.008237058
adsorption	3	conductivity	44	210.9311388	0.002232143	0.005853945

Factorial Analysis

Factorial analysis (Busrul Iman, Imam Yuadi et. al.) has been carried out to study the conceptual structure of research on the electronic properties of graphene. The conceptual structure map is shown in Fig. 6. The map has a triangle-like structure, indicating that the research in this field is distributed among a few relatively distinct thematic directions.

Three keywords, namely berry phase, nitrogen, and MoS_2, are located at the extreme corners of the triangular structure and are far from each other as well as from the central region. This suggests that these topics are less closely related to the main body of research and represent more specialized or niche areas, such as quantum transport effects, chemical doping and functionalization, and graphene-based heterostructures with transition metal dichalcogenides.

The central region of the map contains closely placed keywords such as band gap, defects, density functional theory, stability, and electronic properties. The clustering of these terms indicates that they form the core research theme of the field. These keywords are mainly associated with theoretical and computational studies aimed at understanding and tuning the electronic structure of graphene through defects, doping, and band gap engineering using first-principles calculations.

Keywords appearing in the upper right region of the map, such as CVD, sheets, fabrication, and conductivity, are related to the synthesis of graphene and the evaluation of its electrical performance. Their close grouping points towards studies focusing on fabrication techniques and experimentally measured electronic properties, which are important for device-oriented applications.

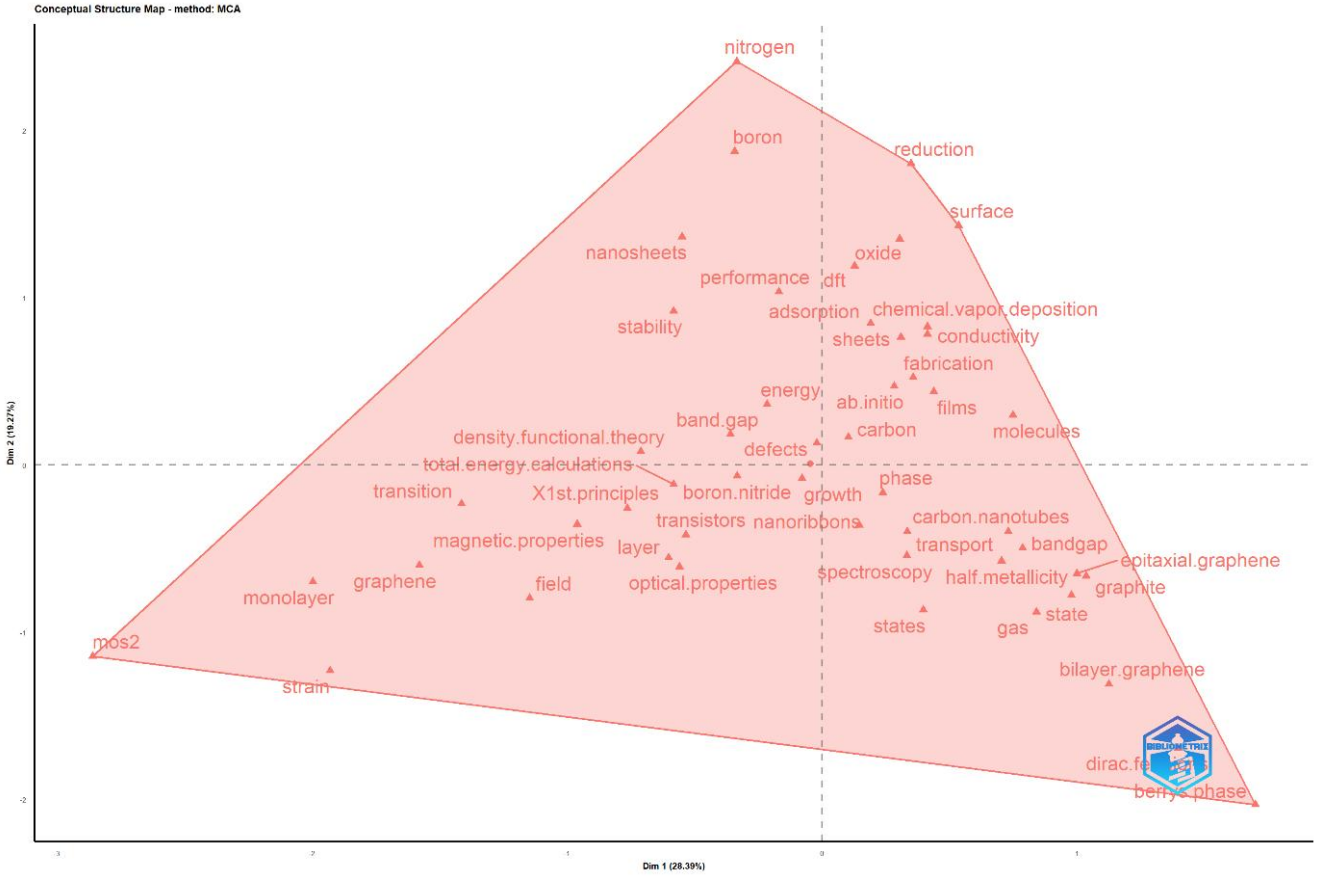

Figure 6: Factorial analysis of conceptual clusters on the electronic properties of graphene.

The lower right region of the map consists of keywords like graphite, nanoribbons, carbon nanotubes, bilayer graphene, and transport properties. These terms are associated with different structural forms of graphene and related carbon-based materials, with emphasis on charge transport, dimensional effects, and band gap variation.

Keywords related to magnetic and optical properties, along with theoretical terms such as ab initio and band structure, are mainly located on the left side of the map. This region represents studies dealing with advanced electronic phenomena and property modulation in graphene and related two-dimensional materials.

Overall, the factorial analysis shows that the research on electronic properties of graphene is conceptually organized into fundamental electronic structure studies, computational and materials engineering approaches, and fabrication- and application-oriented investigations. The spatial separation of keywords reflects conceptual differences among these themes rather than any strict temporal evolution.

IV. MAPPING OF KEYWORD CLUSTERS TO REAL-WORLD APPLICATIONS AND COMMERCIAL PRODUCTS

To extend the scientometric findings toward translational relevance, the dominant keyword clusters were further examined in the context of real-life graphene-enabled products as shown in Table 5.

Table 5: Mapped applications and products based on the electronic properties of graphene.

Keywords in Cluster	Implied / Direct Applications	Graphene-Based Products
Graphene oxide, graphite, bilayer graphene, quantum dots, quantum Hall effect, mobility, conductivity, boron nitride, etc.	High-speed transistors, quantum resistance standards, transparent conductive films	Various graphene transparent conductive films / touchscreens. NanoXplore (GrapheneBlack® powder for conductive composites) https://liveindustryinsights.com/2025/09/top-10-companies-in-the-2d-carbon-material-graphene-industry-2025-market-leaders-powering-next-gen-technologies/ https://www.granophene.com/conductivein
DFT, heterojunction, heterostructures, 2D materials	Tuneable nanoelectronics, heterojunction devices	Levidian Nanosystems https://www.levidian.com
DFT, nanoribbons, spin polarization	Spintronic devices, nanoribbon electronics	(research/prototype stage)

DFT, MoS_2, vacancy defects, work function	2D heterostructure electronics, batteries, sensors, supercapacitors	https://www.skeletontech.com CAP-XX https://www.cap-xx.com https://log9materials.com
Armchair graphene, gas sensor, spintronics	Gas and spintronic sensors	Paragraf Hall-Effect Sensors (magnetic sensors) - Paragraf (UK) https://www.nanalyze.com/2020/12/10-startups-commercializing-graphene-products/
Band alignment, charge transfer, thermoelectric properties	Thermoelectric, charge transport devices	(research/prototype stage)
Adsorption, defects, vacancy	Chemical & gas sensors	Haydale functionalized graphene inks for sensors - conductive/piezoresistive graphene inks. https://haydale.com/graphene-inks/ https://nanotechenergy.com/graphene-products/conductive-inks/
Density of states, band structure, thermal conductivity	High-frequency electronics, thermal management, conductive inks	Graphene for EMI shielding and conductive applications - Nanotech Energy conductive inks https://www.granophene.com/conductiveink
Defects, CVD, graphene quantum dots	Defect-engineered electronics, quantum dot devices	Graphene quantum dots for biosensors, LEDs, photodetectors (various research applications) Versarien https://www.versarien.com
Nitrogen doping, Fermi level, hexagonal boron nitride	Doped graphene electronics, catalytic applications	**2D heterostructure materials, MoS_2 and other TMDs** used in sensor devices.Graphene square https://www.graphene-square.com

V. CONCLUSIONS

In this work, a bibliometric analysis of research on the electronic properties of graphene has been carried out using data retrieved from the Web of Science database for the period 2004 to 2025. Keyword co-occurrence analysis, thematic mapping, centrality measures, and factorial analysis were performed using VOSviewer and the Bibliometrix R package to examine the intellectual structure and thematic organization of the field.

The results show that graphene, electronic properties, and density functional theory are the most important and highly connected keywords, indicating their central role in the literature. Co-word and centrality analyses highlight the dominance of first-principles calculations, band structure studies, defects, doping, and transport properties in understanding and tuning the electronic behaviour of graphene and related two-dimensional materials. Temporal keyword analysis suggests that early research was mainly focused on graphite and carbon-based systems, while more recent studies show increased attention towards conductivity, stability, fabrication techniques, and device-related performance.

The thematic map identifies carbon, total energy calculations, and adsorption as the major research themes, reflecting the close link between fundamental electronic structure calculations and application-oriented studies. Factorial analysis further reveals that research topics are distributed into distinct but related conceptual groups, including fundamental electronic structure and quantum phenomena, computational modelling, and fabrication and application focused topics.

Overall, the present bibliometric study provides a quantitative overview of the development and current structure of research on the electronic properties of graphene. The findings may be useful for understanding the main research directions, identifying well-developed and emerging themes, and offering a general reference for researchers working in this area.

Table 7 depicts the relevance and importance of the electronic properties of graphene, affirms the translation of graphene research to innovative, useful and tailored products.

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