Mapping the Research Landscape of Electronic Properties of Graphene: A Citation Network Analysis

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Abstract: *Graphene has obtained an adorable response from researchers and scientists owing to its meticulous structure and astonishing properties. The rapid evolution of research on the electronic properties of graphene has generated a vast and complex body of literature, necessitating systematic quantitative mapping to understand its intellectual structure and developmental trajectory. In this study, a comprehensive citation analysis of global research on the electronic properties of graphene has been performed. Bibliographic records were retrieved from the Web of Science (WoS) Core Collection covering the period from January 2004 to March 2025. Two specialized bibliometric software tools were employed to construct citation networks, visualize relational structures, and evaluate influential publications, authors, and countries. Sankey plot was generated to visualize the relationships among key authors, cited references, and keywords, thereby providing an initial structural overview of the dataset. Direct citation analysis is employed to trace the chronological knowledge flow and identify seminal contributions shaping the field. Network centrality indicators and clustering metrics are applied to identify influential authors, countries, and core publications. Various bibliometric indicators like number of documents, total linking strength, number of citations and normalized citations have been used in the analysis, as they reflect different aspects of contribution. Normalised citations have been evaluated from the Vosviewer map file by writing a Python script. Bibliographic coupling is used to detect contemporary research clusters and emerging thematic frontiers, while co-citation analysis reveals the foundational intellectual base and conceptual interconnections within the domain. By integrating three complementary citation methods, this study provides a structured overview of the knowledge architecture governing research on the electronic properties of graphene. The findings serve as a reference framework for researchers seeking to understand both the maturity and emerging opportunities within this rapidly advancing field.*

Keywords: Direct citation analysis, bibliographic coupling, co-citation analysis, normalized citations, VOS-viewer, Bibliometric R package

I. INTRODUCTION

The isolation of graphene in 2004 marked a transformative moment in condensed matter physics and materials science [1]. Graphene is a single layer of sp²-bonded carbon atoms arranged in a two-dimensional honeycomb lattice and exhibits an unusual electronic band structure. It exhibits linear energy dispersion near the Dirac points, where charge carriers behave as massless Dirac fermions [2]. These unique properties give rise to ultrahigh carrier mobility, ambipolar electric field effect, ballistic transport over submicron distances and unconventional quantum Hall behaviour observable even at room temperature [1–3].

Graphene's electronic properties are intrinsically governed by its atomic structure. The delocalized π-electron network formed by sp² hybridization enables rapid charge transport and high conductivity. The absence of an intrinsic bandgap results in semi metallic behaviour, which provides advantages in transparent conductive electrodes and high-frequency

electronics [4]. External perturbations such as strain, electric fields, chemical functionalization, and substrate interactions can modulate its band structure, enabling tuneable transport properties [5]. Thus, graphene serves not only as a material of technological interest but also as a fundamental platform for exploring two-dimensional electron systems.

The extraordinary electronic characteristics of graphene have translated into several real-world and near-commercial applications. High carrier mobility and saturation velocity have enabled graphene field-effect transistors (GFETs) for high-frequency and radio-frequency electronics [4]. The robustness of the quantum Hall effect in graphene has established new resistance standards in precision metrology [3]. Its high electrical conductivity combined with optical transparency has facilitated its integration into flexible and transparent electrodes for displays and photovoltaic systems. Moreover, the extreme surface sensitivity of graphene to charge transfer processes has led to highly responsive chemical and biosensors capable of detecting single-molecule adsorption events [6]. These technologically driven advancements have significantly accelerated global research activity in graphene electronics, expanding the literature from fundamental band-structure investigations to device-level engineering and system integration.

The rapid and sustained growth of research on graphene's electronic properties has resulted in an extensive and highly interconnected body of scientific literature. Understanding the structural organization, thematic evolution, and relational dynamics of this expanding knowledge base requires systematic quantitative assessment. This can be achieved by bibliometrics [7,8]. Bibliometrics, through the implementation of statistical analysis extracts the root information from the relevant data and analyses the literature quantitatively [9]. It establishes the connection among the metadata through various bibliometric indicators and provides deep insight into the present understanding and the future growth of the topic. Bibliometrics allows to explore the metadata and identify and thematic clusters [10] within using citation analyses. In recent years, visual analytics tools such as Sankey plots [11] have emerged as valuable instruments in bibliometric investigations for illustrating proportional flows and structural relationships within large datasets. Sankey diagrams provide an intuitive representation of directional linkages among authors, publication sources, cited references and keywords within the research domain, offering a macro-level overview of knowledge diffusion patterns. By mapping how research contributions connect across entities and time periods, Sankey visualizations facilitate preliminary structural interpretation before deeper relational network analysis is undertaken. Their integration strengthens bibliometric investigations by contextualizing citation relationships within broader scholarly flows.

To rigorously examine the intellectual evolution of graphene electronics research, citation analysis serves as a core methodological framework within bibliometrics. Bibliometrics applies quantitative techniques to analyse scholarly communication, research performance, and knowledge structures [12]. Citation-based approaches are particularly powerful for identifying influential publications, reconstructing knowledge trajectories, and uncovering the intellectual foundations of a scientific field. Direct citation analysis traces explicit citation links between documents, enabling reconstruction of chronological knowledge flows and identification of seminal contributions [13]. Bibliographic coupling connects documents that share common references, thereby revealing contemporary research clusters and thematic proximity [14]. Co-citation analysis examines how frequently two documents are cited together, uncovering the intellectual base and conceptual structure underlying a research domain [15]. Present study integrates Sankey-based visualization with direct citation analysis, bibliographic coupling, and co-citation analysis to systematically investigate the intellectual architecture of research on the electronic properties of graphene.

Rationale of the study:

- To establish a structural overview of the research landscape on graphene's electronic properties using Sankey plots to visualize relationships among authors, cited references and keywords.
- To reconstruct the chronological evolution of knowledge through direct citation analysis, identifying seminal publications and major developmental milestones.
- To detect contemporary research clusters and thematic proximity using bibliographic coupling, thereby revealing active research fronts within the field.
- To uncover the intellectual foundation of the domain through co-citation analysis, identifying core theoretical works and conceptual interconnections.

II. METHODOLOGY

The data for the study has been taken from the Web of Science core collection from January 2004 to March 2025 on the electronic properties of graphene, resulting 1812 documents. A comprehensive citation analysis has been performed using the bibliometrix R package [16] and VOSviewer software [17]. The data for the analysis was extracted using Boolean operators and the following search query in the title field of publications.

(Graphene OR Graphene oxide OR Graphite) AND (Electronic Properties)

A total of 6106 authors has contributed to the research with 75 single author documents. In the metadata total 42 review articles were found on the electronic properties of graphene in the selected time span.

III. RESULTS AND DISCUSSION

In bibliometric analysis there is no single metric which can comprehensively evaluate the scientific performance of a researcher, journal, source or country. So various bibliometric indicators are used to capture different dimensions of an academic output. When research outputs involve many co-authors, normalized or fractionalized [18,19] bibliometric parameters can precisely assess the contribution of individual author or country. Different bibliometric indicators measure fundamentally different aspects of performance Moed [20]. Full-count indicators primarily reflect the participation and fractionalized indicators suggests actual contribution to a research field. In this study fractionalized [18,19] counting methods have been used to obtain a fair comparisons of research performance across authors, documents, journals, and countries.

Several bibliometric indicators like number of documents, citations, total linking strength (TLS), and normalised citations (NCs) have been used in the analysis. The TLS values give the strength of connections between bibliometric entities, such as authors, institutions or countries within network generated through VOSviewer. NCs values were extracted directly from the corresponding VOSviewer map files using a Python-based data extraction script. Together, these indicators provide a multidimensional assessment of both research productivity and intellectual influence in the literature on the electronic properties of graphene.

The three field Sanky plots [11] of electronic properties of graphene can be generated by choosing any three bibliometric analysis entities. Boxes in the figure 1 represents the strength of the cited references(CR), authors(AU) and keywords(DE). Connection among the three is shown by various lines. Density of lines represent a strong connection among them. Figure 1 represents the connection between authors, citing the references and various keywords. The document by K.S. Novoselov (2004) in Science journal has been represented by the biggest rectangle. It is shown on the left side of the Sanky plot and has been cited maximum number of times by various authors. M. F. Lin has contributed maximum number of documents to the electronic properties of graphene and graphene is the most commonly used keyword among the authors.
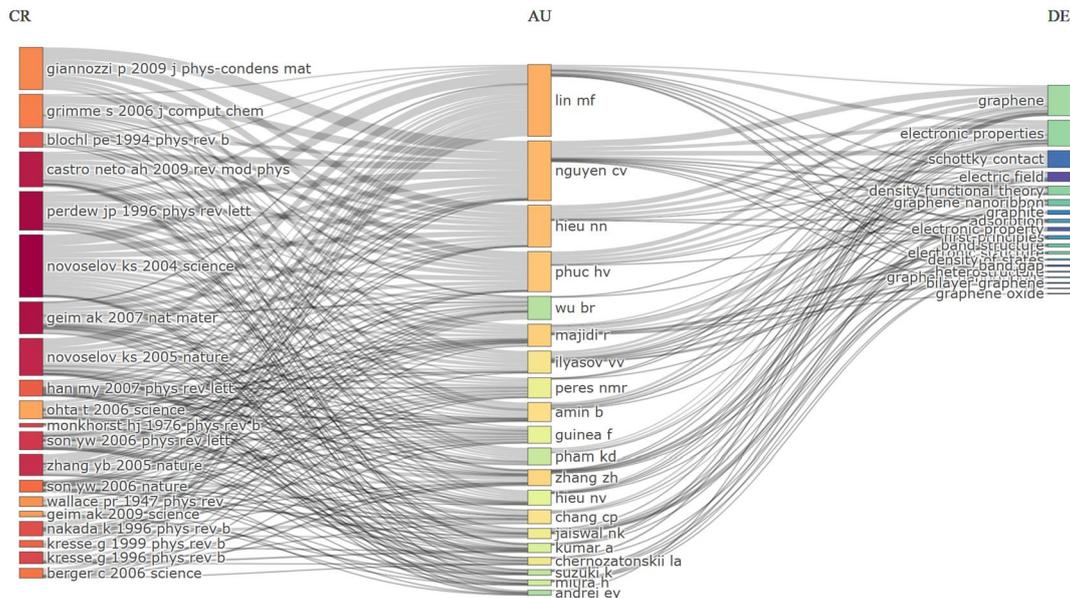
Figure 1: Sanky plot showing the connection among cired references, authors and keywords.

3.1 Citation Analysis

Citations connect a cited and citing document. Direct citation analysis is utilized to get the dynamics of the research field by obtaining information about the renowned authors, documents, journals and countries of the concerned research topic. The connection between the documents can be studied by bibliographic coupling and co-citation analysis. Both the techniques are based on citations but differ in their directionality. Co-citation analysis is a forward-looking approach whereas bibliographic coupling is retrospective in nature. For the three variants of the citation analysis visualization maps have been generated with NCs as weight.

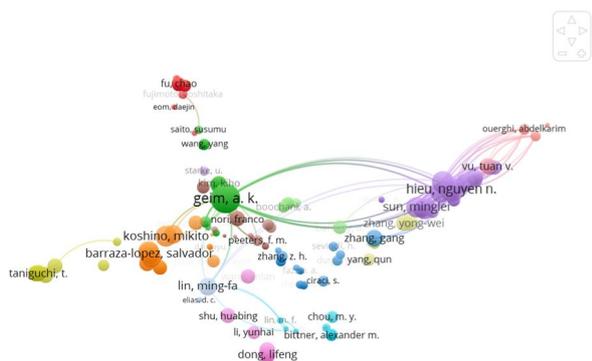| Table 1: Citation Analysis of Authors							
Author (Document)		**Author (Citation)**		**Author (NCs)**		**Author (TLS)**	
Lin, Ming- Fa	23	Peres N.M.R.	21903	Geim, A. K.	55.4508	Higu, Nguyen N.	452
Nguyen Choung V.	21	Geim A.K.	21879	Novoselov, K. S.	55.4508	Nguyen Choung V.	444
Higu, Nguyen N.	20	Novoselov K. S.	21879	Peres, N. M. R.	48.1423	Peres N.M.R.	304
Lin M.F.	16	Guinea F.	21731	Guinea, F.	46.8968	Guinea F.	301
Phuc, Huynh V.	11	Castro Neto A. H.	21483	Castro Neto, A. H.	43.5104	Phuc, Huynh V.	289

3.1.1 Citation-author:

A total of 6106 authors has contributed to the electronic properties of graphene. Citation analysis of the authors is presented in Table 1 based on four bibliometric parameters viz. documents, citations, NCs and TLS. The visualization map of author's citations has been generated by Vosviewer and presented in figure 2(a). It reveals that Lin M. F. has published a maximum of 23 documents followed by Nguyen Choung V. and Higu, Nguyen N. on the electronic properties of graphene. Peres N.M.R. has obtained maximum citations in the present metadata. Maximum normalized citations are obtained by Geim A. K., whereas the TLS is maximum for Higu, Nguyen N. figure 2(a) can be mapped with the NCs
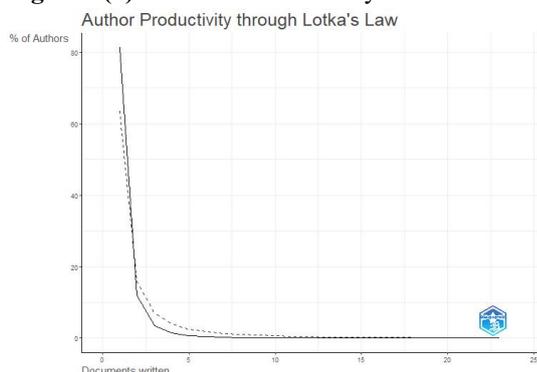
column of Table 1. Most relevant authors obtained through bibliometrix R package are shown in figure 2(b) and can be matched with the first column of Table 1.
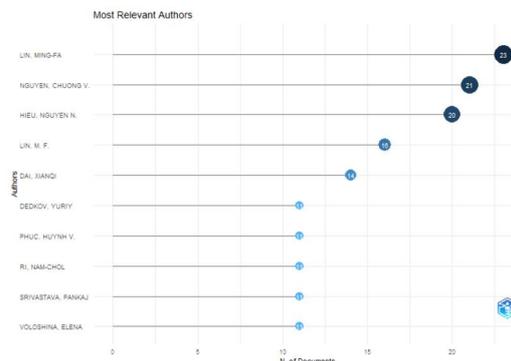
The publication frequency of authors can be studied by Lotka's law [21]. The initial segment of the curve corresponds to occasional contributors and the latter segment identifies the core group of highly productive authors. Dotted line in the figure represents the theoretical distribution. The law suggests that out of 6106 authors; 4964 authors have published only one document. A total of 91 single author documents is present in the present metadata. The results obtained through this law on the present dataset is illustrated in figure 2(c). Authors publication statistics has been shown in figure 2(d), where the red line represents the active time span of the authors. Lin M. F. has the maximum research carrier followed by Mazidi R and Chernozatonskii L. A. Nguyen Nugun C. V., Higu N. N. and Phuc H. V. have published 10 documents in the year 2018.
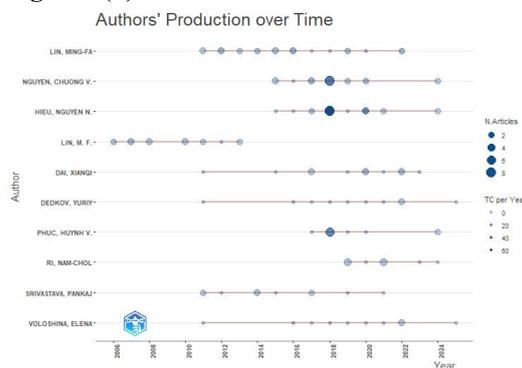

Figure 2(a): Author citation analysis

Figure 2(b): Most relevant authors.

Figure 2(c): Authors productivity by Lotka's law

Figure 2(d): Authors publications and citations as a function of publication year.

3.1.2 Citation-document:

A total of 1882 documents were found on the electronic properties of graphene in the present metadata. Documents citations on three bibliometric parameters viz. citation, NC and TLS have been presented in Table 2(a). Castro Neto is at the top in terms of the above-mentioned parameters. Visualization map based on NC as weight, obtained through Vosviewer is presented in figure 3(a). Documents in the third column of Table 2(a) are listed based on NCs and can be mapped with figure 3(a). Most globally cited authors as obtained through bibliometrix R package are shown in figure 3(b) and can matched with column 2 of Table 2(a). Detailed document statistics with Doi and TNC, TNC per year is given in Table 2(b). Document by Castro Neto received maximum citations as well as maximum NCs, revealing its central importance among the published documents on the electronic properties of graphene.

3.1.3 Citation Source:

A total of 412 journals has contributed to the electronic properties of graphene. Journal citation report based on the selected bibliometric parameters is given in Table 3. Physical Review B has published maximum number of documents on the electronic properties of graphene and has obtained maximum citations, NC and TLS. Visualization map of citation analysis of source has been shown in figure 4(a) and can be mapped with Table 3. Evaluative parameter 'H-index' estimates the impact of a journal. h-index [22] of first few journals as obtained by bibliometrix are shown in figure 4(b). The h-index of Physical Review B is found to be 42 and is maximum among all the journals. Journal of Physical Chemistry C, Physical Chemistry Chemical Physics and Carbon has h-indices of 28, 26 and 23 respectively. Relevant sources are categorized in terms of the documents they publish. Most relevant sources as obtained through bibliometrix are shown in figure 4(c) and can be mapped with the first column of Table 3. According to Bradford's law [23] journals specially contributing to the subject lie in the first zone of figure 4(d), known as the core zone. The core contains 13 journals with Physical Review as the leading journal followed by Physical Chemistry Chemical Physics and Journal of Chemistry C.

Table 2(a): Citation Analysis of Documents						
Document	**Document**	**Citations**	**Document**	**NCs**	**Document**	**TLS**
The electronic properties of graphene	Castro Nato (2009)	20986	Castro Neto (2009)	38.0181	Castro Nato(2009)	48
Wrinkled, rippled and crumpled graphene: an overview of formation mechanism, electronic properties, and applications	Gomez Navarro (2007)	2098	Deng (2016)	25.4334	Rozhkov(2011)	8
The electronic properties of bilayer graphene	Avouris (2010)	1257	Mccann (2013)	22.4717	Mccann(2013)	8
Electronic and optical properties of strained graphene and other strained 2d materials: a review	Ritter (2009)	1168	Naumis (2017)	15.7042	Rozhkov(2016)	8
Electronic properties of phosphorene/graphene and phosphorene/hexagonal boron nitride heterostructures	Mccann(2013)	880	Cai (2015)	15.5376	Pahm (2018)	7

Table 2(b): Detailed Statistics of first ten documents				
Document	**DOI**	**Citations**	**TC per year**	**NTC**
Castro Neto A.H., 2009, Rev. Mod. Phys.	10.1103/RevModPhys.81.109	20986	1234.470588	38.01811594
Gómez-Navarro C., 2007, Nano Lett.	10.1021/nl072090c	2098	110.4210526	8.861118012
Luo Z.Q., 2011, J Mater. Chem.	10.1039/c1jm10845j	861	57.4	10.75737744
Deng S.K., 2016, Mater. Today	10.1016/j.mattod.2015.10.002	822	82.2	25.43342633
Goerbig M. O., 2011, Rev. Mod. Phys.	10.1103/RevModPhys.83.1193	721	48.06666667	9.008210376
Usachov D., 2011, Nano Lett.	10.1021/nl2031037	676	45.06666667	8.445978106
Ding Y., 2011, Physica B	10.1016/j.physb.2011.03.044	647	43.13333333	8.083650643

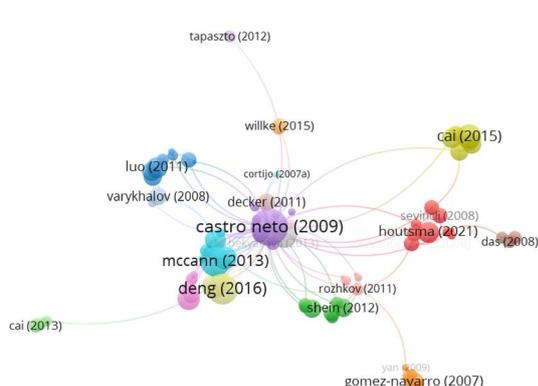|				
Varykhalov A., 2008, Phys. Rev. Lett.	10.1103/PhysRevLett.101.157601	610	33.88888889	7.729452055
Choi S. M., 2010, Phys. Rev. B	10.1103/PhysRevB.81.081407	572	35.75	6.187621919
Martins T. B., 2007, Phys. Rev. Lett.	10.1103/PhysRevLett.98.196803	561	29.52631579	2.369440994

Figure 3(a): Visualization map of citation -document.
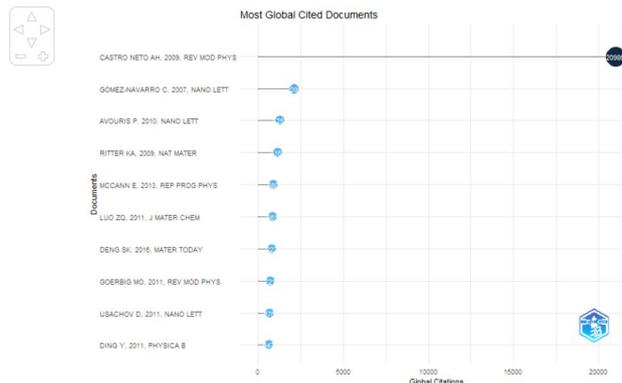
Figure 3(b): Statistics of most globally cited documents.

Table 3: Citation-Source							
Source (Document)		**Source (Citation)**		**Source (NC)**		**Source (TLS)**	
Phy. Rev. B	107	Rev. Mod. Phys.	21707	Physical review B	127.8513	Phy. Rev. B	402
Physical Chem. Chem Phys.	66	Phy. Rev. B	7041	Journal ofPhysical Chemistry C	90.8365	J. Mod. Phys.	379
J. Phy. Chem C	64	Nano Letters	6183	applied surface science	90.3282	Physical Chem. Chem. Phy.	245
Physica E-Low Dim Systm.	59	Phy. Rev. Lett.	3064	Physical Chemistry Chemical Physics	82.8747	J. Phy. Chem C	196
Carbon	48	J. Phy. Chem C	2700	nano letters	77.8467	Carbon	171
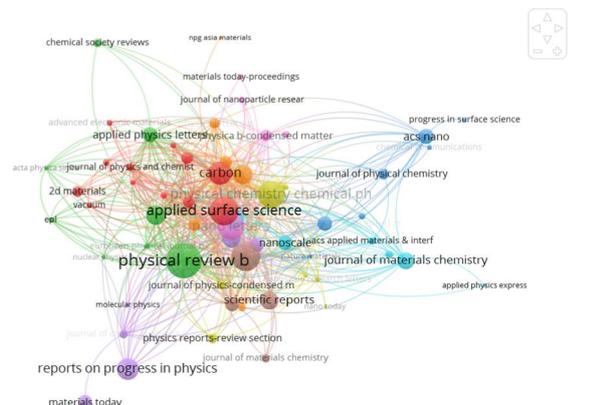
Figure 4(a): Visualization map of source's citation analysis.
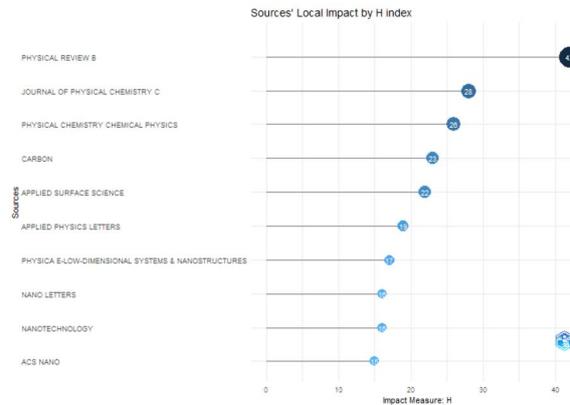
Figure 4(b): H-index of the most cited journals in an hierarchical order.

Figure 4(c): Sources in hierarchical order as a function of number of documents.

Figure 4(d): Core journals publishing research on the electronic properties of graphene.

3.1.4 Citation Country:

Total of 85 countries are involved in the research on the electronic properties of graphene. Citation-country analysis obtained through Vos-Viewer has been presented in Table 4(a). PRC has published maximum n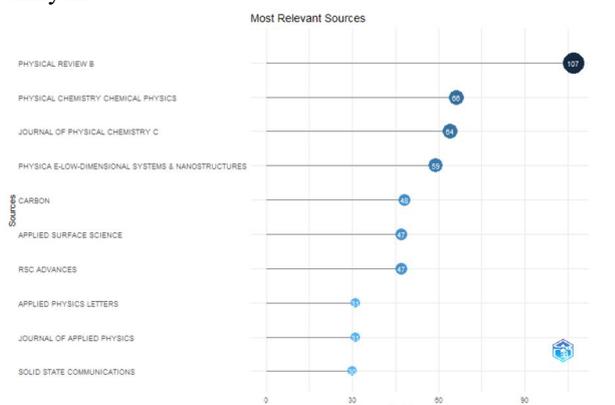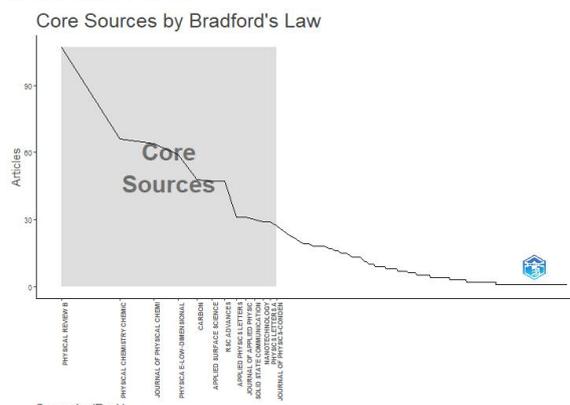umber of documents, obtained maximum NC and had maximum TLS. Visualization map of countries citation analysis has been shown in figure 5(a) with NC as weight. PRC has maximum NC followed by USA, Germany, England and India. The variation of authors' country as a function of number of documents has been presented in figure 5(b) with the demarcation of number of single country publication (SCP) and multiple country publications (MCP). China has published maximum number of papers authored by a single author followed by India and Iran. Maximum collaborative work also has been done by China by contributing maximum MCP followed by USA and Vietnam. The statistics of percentage of publications has been given in Table 4(b). A total of 32% of total number of articles is published by China. The Worldwide collaboration map of countries is presented in figure 5(c). Various parts of the world are shown with different intensities of colour. Darkest colour is attributed to countries contributing the maximum to the electronic properties of graphene according to the published papers.

Table 4(a): Citation-Country

Country (Document)		Country (Citation)		Country (NC)		Country (TLS)	
PRC	554	USA	35602	PRC	560.3885	PRC	2159
USA	236	England	24964	USA	361.6228	USA	1883
India	153	Spain	23331	Germany	158.4394	England	1046
Iran	125	Portugal	22129	England	137.9027	Spain	950
Germany	104	PRC	14007	India	113.7265	Portugal	781

Table 4(b): Publication Statistics of Countries

Country	Article %	Country	SCP	Country	MCP
China	32.1192053	China	491	China	91
USA	7.61589404	India	117	USA	48
India	7.505518764	Iran	100	Vietnam	29
Iran	6.291390728	USA	90	Germany	24
Russia	3.918322296	Russia	51	Russia	20
Germany	3.25607064	Japan	46	France	20
Japan	3.200883002	Germany	35	India	19
Brazil	2.924944812	Brazil	35	Brazil	18
Vietnam	2.70419426	Korea	29	UK	18
Korea	2.538631347	Turkey	21	Korea	17
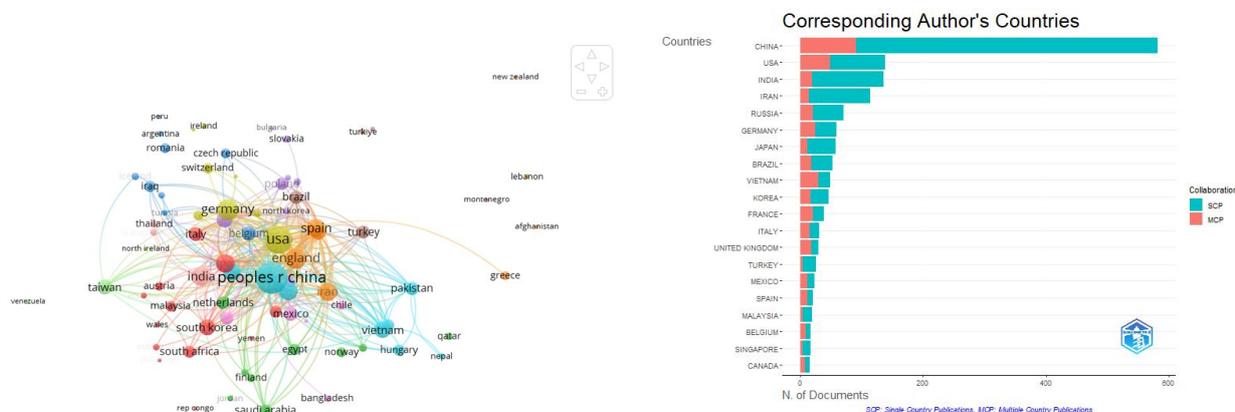
Figure 5(a): Visualization map of country's citation analysis.

Figure 5(b): Single and multiple author publications produced by various countries.

DOI: 10.48175/IJARSCT-31487

Country Scientific Production
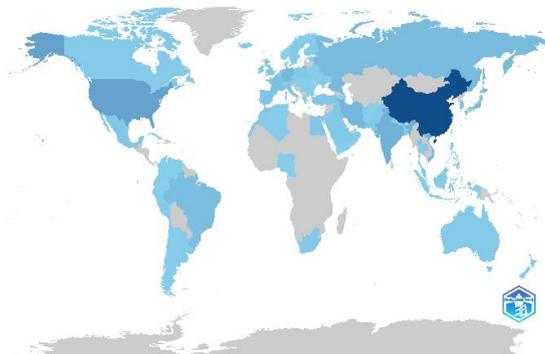
Figure 5(c): Contribution of various countries word wide on the electronic properties of graphene.

Bibliographic coupling:

If two papers (paper X and paper Y) share one or more common references, then X and Y are called bibliographically coupled. The strength of the connection increases if the source documents have a greater number of common references. Bibliographic coupling is a static, time independent retrospective approach for measuring the similarity among the published documents. It clusters the same theme papers based on the citing research paper. It can initiate a connection among the recently published papers and is ideal technique to portray hot research topics.

Table 5(a): Bibliographic Coupling of authors		
Author	**TLS**	**Visualization Map**
Hieu Nguyen N.	1051.64	
Nguyen Chuong V.	1012.07	
Barraza-Lopez Salvador	834.42	
Naumis Gerardo G.	818.25	
Lin Ming F.	738.60	**Figure 6(a):** Visualization map of bibliographically coupled authors.
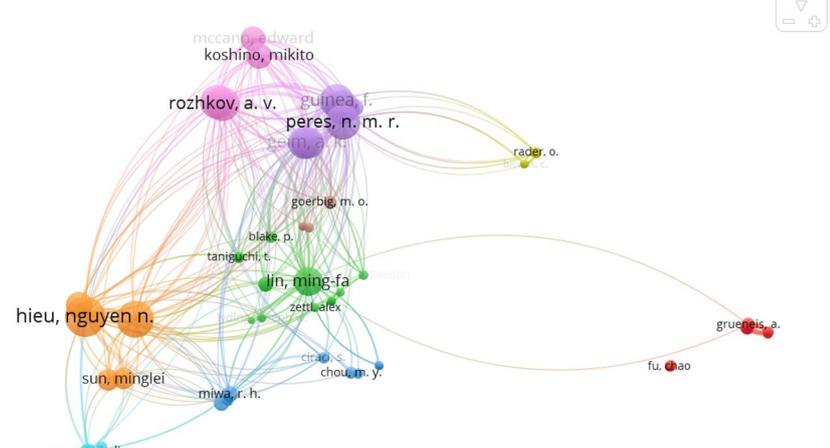
Table 5(b): Bibliographic Coupling of Documents

Document	TLS	Visualization Map
Castro Nato(2009)	268.00	
Mccann (2013)	225.00	
Rozhkov(2016)	205.00	
Andrei(2012)	159.00	
Naumis(2017)	136.00	
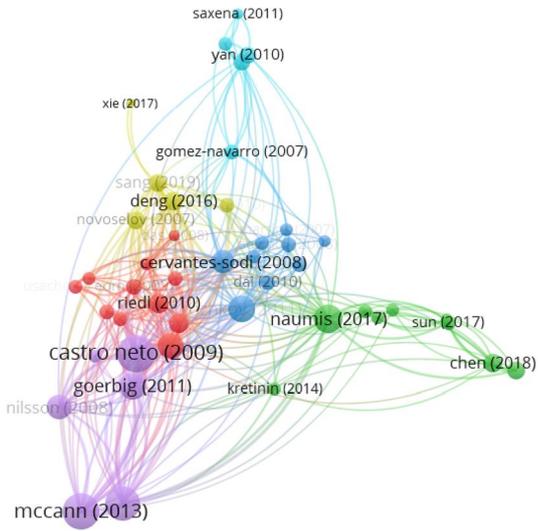
Figure 6(b): Visualization map of bibliographically coupled documents.

First few bibliographically coupled authors in hierarchical order are given in Table 5(a). Hieu Nguyen N. is the most bibliographically coupled author with the other authors followed by Nguyen Chuong V. and Barraza-Lopez Salvador in the present meta data Visualization map of bibliographically coupled authors in figure 6(a) can be mapped with the TLS column of Table 5(a). The documents in Physical Rev. B have the highest bibliographic coupling with the documents in the other journals. Duy Tan Univ. is the most bibliographically coupled institute. Documents authored by PRC are the most bibliographically coupled in comparison to other countries. The documents authored by Castro Neto have the highest bibliographic coupling with other authors present in the meta data. The first few bibliographically coupled documents, sources, and countries listed in Table 5(b), 5(c) and 5(d) and figures 6(b), 6(c) and 6(d) represent the corresponding visualization maps respectively.

Table 5(c): Bibliographic Coupling-Source

Source	TLS	
Physical Rev. B	3052.32	
Phy. Chem. Chem. Phys.	2432.25	
J. Chem. C	2052.97	
RCS Adv.	1695.62	
Physica e Low Dimentional Syst.	1650.16	
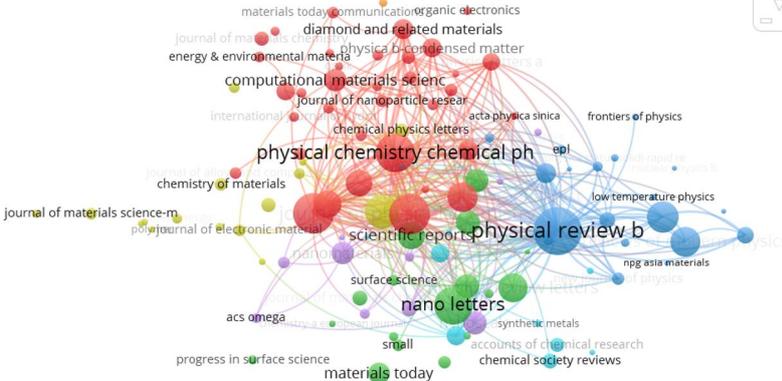
Figure 6(c): Visualization map of bibliographically coupled sources.

Table 5(d): Bibliographic Coupling-Country		
Country	**TLS**	**Map**
PRC	13899.15	
USA	12127.00	
India	4527.05	
Germany	4348.62	
Japan	3524.59	

Figure 6(d): Visualization map of bibliographically coupled countries.
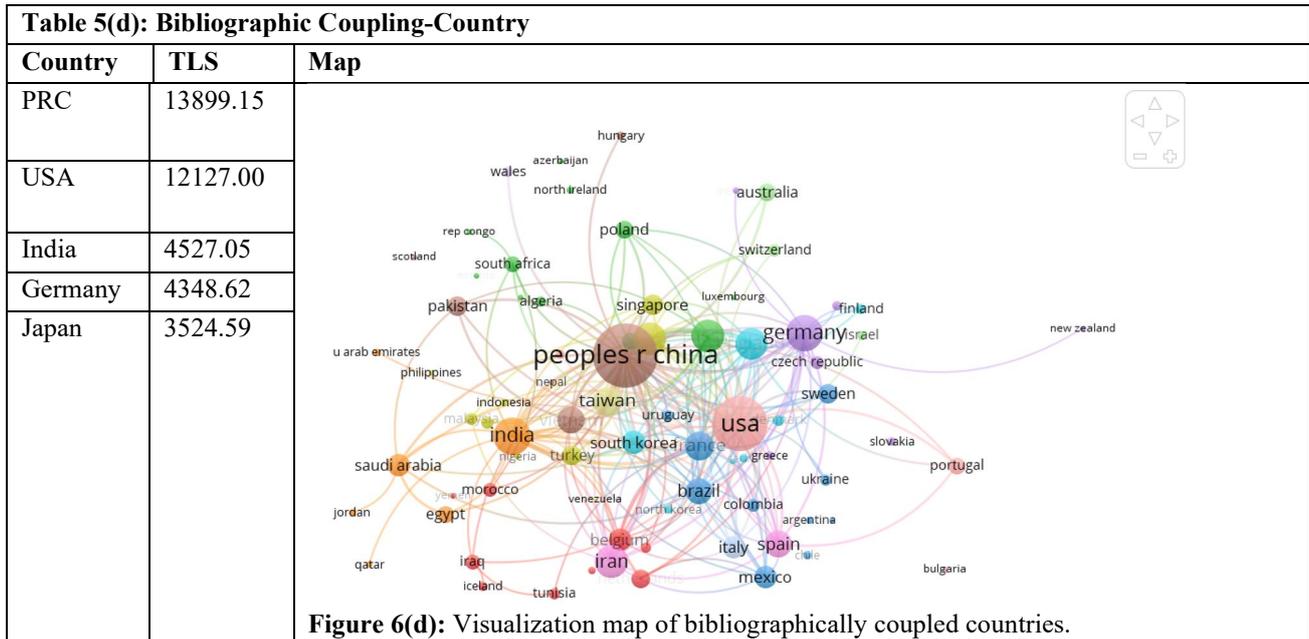
Co-citation analysis:

Co-citation analysis, introduced by Henery Small [15,24], is the most commonly used citation technique. Co-cited publications are the two papers (say paper X and paper Y) which are cited together by a several (papers A, B and C) publications. Then paper X and Y are called co-cited by the citing papers A, B and C. The strength of the connection increases with the increased number of co-cited references. Co-cited references form a cluster and in general they have a common theme. Co-citation analysis can be performed for cited references, authors and journals through Vosviewer. Publications from the co-cited clus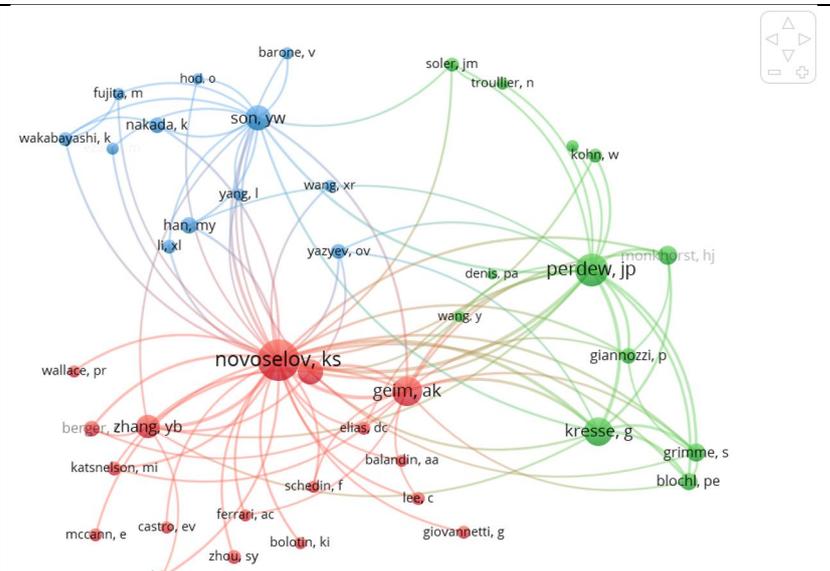ters can be analysed to get the core content. Co-citation analysis is dynamic in nature, specifies how a research field changes overtime and provides intellectual trend of research. The number of citing authors may change overtime due to the dynamics of the topic and evolution of the subject over time. As co-citation analysis considers the number of times two or more documents are cited together by a later paper, it reveals the recurrently cited papers forming the knowledge structure.

A total of 6106 authors has contributed to the research on the electronic properties of graphene. To narrow down the search, authors with 120 or more citations were selected, which resulted in 42 authors. These authors were distributed among three clusters with 17, 11 and 10 items respectively. Results of co-citation-author analysis have been presented in Table 6(a). Novoselov K. S. has been found the most co-cited author followed by Perdew J.P. and Geim A. K. in terms of TLS. A visualization map of co-cited authors has been presented in figure 7(a). Co-citation-author map consists of three clusters. The meta data contains a total of 37685 cited references. A filter of 80 citations per article reduces it to 42 cited references for co-citation analysis. Most co-cited reference if from Novoselov K. S. with 732 citations and TLS od 721. The data in hierarchical order is given in Table 7(b).

Three clusters have been obtained for the co-citated references and are shown in figure 7(b) with different colours. First cluster (red), second cluster (green) and the third cluster (blue) contains 21, 12 and 9 items respectively. Each cluster represents circles of different sizes. Each circle depicts the name of first author followed by year of publication and the journal name. The size of the circle and thickness of line represents the maximum TLS and the strength of co-citations link. All the three clusters have in-cluster as well as intra-cluster collaborations.

Table 6(a): Co-citation-cited Author		
Author	**TLS**	**Visualization Map**
Novoselov KS	1266.13	
Perdew JP	826.04	
Geim AK	665.49	
Kresse G	610.65	
Castro Nato AH	481.02	
		Figure 7(a): Visualization map of co-cited author's analysis.

Total of 3731 journals were found in the metadata for the co-citation- source analysis. Total 52 Journals were selected for the analysis with a capping of at least 200 citations per journal. Co-citation-source analysis has been presented in Table 7(c). Phys. Rev. B has the maximum TLS followed by Out of Phys. Rev. Lett. And nano letters. With 12794, 6808, 3771 citations respectively. Co-citation-source map contains three clusters with 52 items as shown in figure 7(c). First cluster (red) second (green) and third cluster contains 32, 12 and 7 items respectively.

Table 6(b): Co-citation-cited reference		
Cited References	**TLS**	**Visualization Map**
Novoselov KS, 2004, Science, v206, p666	721.00	
Predew JP, 1997, Phys. Rev. Lett. V78,p1396	639.00	
Geim AK, 2007, Nat Mater.v6, p183	450.00	
Castro Nato AH, 2009, Rev. Mod. Phys. V81, p109	445.00	
Novoselov KS, 2005, Nature v438, p197	381.00	
		Figure 7(b): Visualization map of co-cited reference analysis.
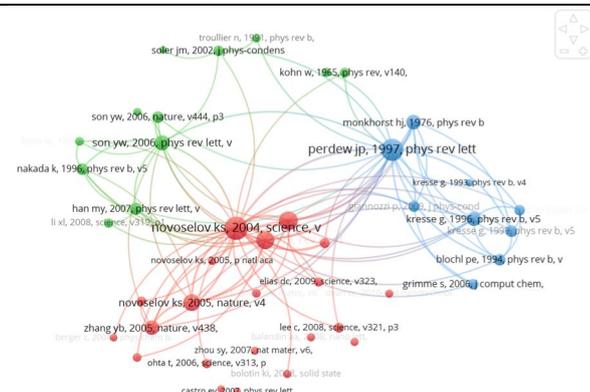
Table 6(c): Co-citation-cited Source		
Source	**TLS**	**Visualization Map**
Phys. Rev. B	9458.27	
Phys. Rev. Lett.	5838.75	
Nano Lett.	3476.24	
Science	2775.54	
Appl. Phys. Lett.	2436.08	
		Figure 7(c): Visualization map of co-cited source analysis.

Conclusions:

The integrated citation, bibliographic coupling, co-citation, and Sankey analyses reveal a highly centralized and structurally consolidated knowledge architecture in graphene electronic properties research. The seminal 2004 Science publication by K. S. Novoselov forms the dominant intellectual anchor, emerging as the most co-cited author and reference and attracting the strongest citation flows in the Sankey visualization. Lin M. F. appears as the most prolific contributor, while Geim A. K. demonstrates the highest normalized citation impact, highlighting the multidimensional distribution of productivity and influence. Castro Neto ranks highest in document-level citation indicators and also represents the most bibliographically coupled publication (2009), underscoring sustained foundational relevance across research fronts. At the journal level, Physical Review B dominates in publication output, normalized citations, h-index, bibliographic coupling, and co-citation strength, establishing it as the principal intellectual hub of the field. Country-level analysis identifies the People's Republic of China as the leading contributor in output and single-author publications, as well as the most bibliographically coupled nation, reflecting strong productivity and thematic cohesion. Collectively, these findings demonstrate that graphene electronics research remains anchored to seminal discoveries while being characterized by concentrated author contributions, cohesive national research activity, and a tightly interconnected citation network.

REFERENCES

[1] K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, and A. A. Firsov, Electric Field Effect in Atomically Thin Carbon Films, Science **306**, 666 (2004).

[2] A. H. Castro Neto, F. Guinea, N. M. R. Peres, K. S. Novoselov, and A. K. Geim, The electronic properties of graphene, Rev. Mod. Phys. **81**, 109 (2009).

[3] K. S. Novoselov, Z. Jiang, Y. Zhang, S. V. Morozov, H. L. Stormer, U. Zeitler, J. C. Maan, G. S. Boebinger, P. Kim, and A. K. Geim, Room-Temperature Quantum Hall Effect in Graphene, Science **315**, 1379 (2007).

[4] F. Schwierz, Graphene transistors, Nature Nanotech **5**, 487 (2010).

[5] V. M. Pereira and A. H. Castro Neto, Strain Engineering of Graphene's Electronic Structure, Phys. Rev. Lett. **103**, 046801 (2009).

[6] F. Schedin, A. K. Geim, S. V. Morozov, E. W. Hill, P. Blake, M. I. Katsnelson, and K. S. Novoselov, Detection of individual gas molecules adsorbed on graphene, Nature Mater **6**, 652 (2007).

[7] Pritchard, A., Statistical Bibliography or Bibliometrics., Journal of Documentation **25**, 348 (1969).

[8] N. Donthu, S. Kumar, D. Mukherjee, N. Pandey, and W. M. Lim, How to conduct a bibliometric analysis: An overview and guidelines, Journal of Business Research **133**, 285 (2021).

[9] De Bellis N., *Bibliometrics and Citation Analysis: From the Science Citation Index to Cybermetrics* (Scarecrow Press, Lanham, MD, 2009).

[10] R. Vogel and W. H. Güttel, The Dynamic Capability View in Strategic Management: A Bibliometric Review, Int J Management Reviews **15**, 426 (2013).

[11] S.-W. Lim, W. Chou, and L. Chen, SankeyNetwork: A clear and concise visualization tool for bibliometric data, MethodsX **14**, 103379 (2025).

[12] Peng Hui Lv • Gui-Fang Wang • Yong Wan • Jia Liu • Qing Liu • Fei-cheng Ma, Bibliometric trend analysis on global graphene research, Scientometrics **88**, 399 (2011).

[13] E. Garfield, Citation Indexes for Science: A New Dimension in Documentation through Association of Ideas, Science **122**, 108 (1955).

[14] M. M. Kessler, Bibliographic coupling between scientific papers, Amer. Doc. **14**, 10 (1963).

[15] H. Small, Co-citation in the scientific literature: A new measure of the relationship between two documents, J. Am. Soc. Inf. Sci. **24**, 265 (1973).

[16] M. Aria and C. Cuccurullo, bibliometrix : An R-tool for comprehensive science mapping analysis, Journal of Informetrics **11**, 959 (2017).

[17] N. J. Van Eck and L. Waltman, Software survey: VOSviewer, a computer program for bibliometric mapping, Scientometrics **84**, 523 (2010).

[18] Aksnes, D.W., Schneider, J.W., & Gunnarsson, M., Ranking national research systems by citation indicators. A comparative analysis using whole and fractionalised counting methods, Journal of Informetrics **6**, 36 (2012).

[19] Schneider, J., An Outline of the Bibliometric Indicator Used for Performance-Based Funding of Research Institutions in Norway, Eur. Polit. Sci. **8**, 364 (2009).

[20] HF Moed, *CITATION ANALYSIS IN RESEARCH EVALUATION*, in *New Developments in the Use of Citation Analysis in Research Evaluation* (Springer, 2005).

[21] Alfred J. Lotka, The frequency distribution of scientific productivity, JOURNAL A OF THE WASHINGTON ACADEMY OF SCIENCES **16**, 317 (1926).

[22] J. E. Hirsch, An index to quantify an individual's scientific research output, PNAS **102**, 16569 (2005).

[23] Drott M. C., Bradford's Law: Theory Empiricism and gap between, Library Trends **30**, 41 (1981).

[24] Henry Small, Co-Citation in the Scientific Literature: A New Measure of the Relationship Between Two Documents, Journal of the American Society for Information Science **24**, 265 (1973).