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RESEARCH ARTICLE

An Application of Bradford's Law for the Covid-19 Research Output Indexed in Web of Science during 2020 – 2025

Jayarama Reddy TN[1], Dr. N. Amsaveni[2*]

Abstract

The COVID-19 pandemic triggered an unprecedented surge in scientific publications across diverse disciplines, including medicine, virology, public health, and biomedical sciences. Understanding the distribution of this rapidly expanding body of literature is essential for identifying key sources of scholarly communication. This study applies Bradford's Law of Journal Scattering to examine the distribution and concentration of COVID-19 research articles indexed in the Web of Science (WoS) database during the period 2020–2025. The primary objective is to identify the core (nucleus) journals contributing to the field and to verify the applicability of Bradford's Law using established mathematical models. Bibliographic data were retrieved using the keyword "COVID-19," yielding a total of 21,762 publications distributed across 3,733 journals. The analysis categorizes journals into Bradford zones to determine the concentration of research output and to assess the conformity of the observed distribution with theoretical expectations. The findings of this study provide valuable insights for researchers, librarians, and policymakers in identifying influential journals and understanding publication patterns in pandemic-related research. The collected data were categorized by document type, and only journal articles were selected for analysis, resulting in a dataset of 20,935 articles published across 3,294 journals. This study aims to identify the core journals and assess the applicability of Bradford's Law using established mathematical and theoretical models.

Bradford's zoning technique was applied to classify journals into three distinct zones, each contributing approximately one-third of the total number of articles. The distribution was further validated using the Leimkuhler logarithmic model, resulting in the construction of a Bradford–Leimkuhler curve. In addition, Egghe's theoretical formulation was employed to interpret the characteristics of the three Bradford zones. The study also analyzed key bibliometric indicators of the most productive journals, including impact factor, h-index, publication origin, and the countries of publication.

The results demonstrate a strong conformity of COVID-19 research publications to Bradford's Law, revealing a highly concentrated core (nucleus) of journals, followed by two successive zones characterized by exponentially increasing numbers of journals with decreasing productivity. Verification through the Leimkuhler model confirmed a logarithmic growth pattern, thereby supporting the applicability of Bradford's Law. Egghe's model further elucidated deviations observed in the peripheral zones as a natural outcome of inequalities in journal productivity. Overall, this bibliometric investigation provides valuable insights for researchers, librarians, and policymakers in identifying influential and essential journals within the domain of COVID-19 research.

Keywords: COVID-19;Bibliometrics; Scientometrics; Bradford's Law; Mathematical model; Theoretical mode; Leimkuhler logarithmic model; Egghe's theoretical formulation.

[1]PhD Research Scholar and Librarian, The National College, Bagepalli, Chickbalapur (Dt.), Bangalore, Karnataka, India

[2]Assistant Professor, Department of Library and Information Science, Bharathidasan University, Trichy, India

***Corresponding Author:** Dr. N. Amsaveni, Assistant Professor, Department of Library and Information Science, Bharathidasan University, Trichy, India, E-Mail: amsaveni.n@bdu.ac.in

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Introduction

The COVID-19 pandemic in late 2019 has generated large amount of volume of scientific research across multiple disciplines. Rapid growth of literature during this global health crisis has created challenges in identifying highly productive journals. The distribution of articles across journals is essential for researchers, librarians and policy makers to prioritize relevant sources, optimize collection development and streamline literature retrieval. Bradford's law of journal scattering proposed by Bradford (1934) is a fundamental Bibliometric principle that describes the uneven distribution of articles on a specific subject across journals. According to the law a small number of journals (core) contribute a large number of articles. mathematical

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and theoretical models of Leimkuhler model (quantitative to cumulative journals and articles) logarithmic model and Egghe's model (theoretical explanation for observed deviations in peripheral zones) have been developed to validate and interpret Bradford's law of scattering the productivity inequalities and interdisciplinary expansion. Despite the proliferation of COVID-19 publications, there is limited research examining the distribution of publications across journals using Bradford's law, coupled with mathematical verification and bibiliometric indicators. This study addresses this gap by analyzing COVID-19 research articles indexed in Web of Science database, identifying core journals, examining scattering patterns, and validating findings using both Leimkuhler and Egghe models. This study also evaluate the impact factor, h-index, publication place and publication started year of journal for more than 100 articles produced journal.

Review of Literature

Bradford's law of journal scattering and its verification model concepts has been widely applied in bibliometrics to identify core journals, evaluate collection development strategies and understand the dynamics of scholarly communication in diverse research fields (Brooke, 1969; Egghe & Rousseau, 1990; Nicolaisen & Hjorland, 2007). Bradford (1934) was the first to observe that scholarly literature on a given subject is nor uniformly distributed across journals and categorized three zones. Subsequent studies have consistently confirmed the empirical validity of Bradford's law across disciplines such as medicine (Vikery, 1948), Engineering (Goffman & Morris, 1970), SocialSciences (Nicolaisen, 2002) and Interdisciplinary research domains (Egghe & Rousseau, 1990). Applied Bradford's law to journal datasets of varying sizes. Brookes (1969) emphasized that empirical Bradford distributions rarely show perfect geometric progression, especially in large datasets, due to subject diffusion and interdisciplinarity. Studies by Sengupta (1992) and Tsay (1998) demonstrated that Bradford's law is particularly effective in identifying high yielded journals, even when deviations occur in peripheral zones. More recent investigations (Ravichandra Rao & Neelameghan, 1992; Nicolaisen & Hjorland, 2007) have highlighted that modern databased tend to amplify scattering in the third zone due to broader journals coverage. Leimkuhler (1967) reformulated Bradford's law using a logarithmic function relationship between cumulative journals and cumulative articles. Brookes (1977) advocated plotting cumulative journals against cumulative articles to visually inspect logarithmic growth patterns. (Zhang et. Al., 2018; Ye & Rousseau, 2021) have shown the graphical verification is particularly effective in communication Bradford conformity. The reviewed literature clearly indicates that, Bradford's law is empirically robust across disciplines; Leimkuhler's model provides the most reliable mathematical verification; Egghe's formulation offers a strong theoretical explanation and deviations in peripheral zones are expected and acceptable in large datasets.

Methodology

Bibliometric methods are employed to analyze journal productivity, identify core journals, and validate scattering patterns through mathematical and graphical models. The necessary data collected from the WoS core collection during 2020 to 2025, COVID-19 is the search string and totally 21762 bibliographic (journal title, year of publication, authors details, abstract, keywords, etc.,) articles retrieved, duplicate records and non-relevant document types were excluded to ensure data accuracy and consistency. 20935 research articles were published by the journal article format, totally 3294 different journals were identified. Collected data were processed using MS Excel and bibliometric techniques. Journals were ranked in descending order based on the number of COVID-19 articles published. Three zones were divided the total published journals and verify through the Leimkuhler model and Egghe's model. Graphical verification was performed by plotting the Bradford-Leimkuhler curve to visually assess logarithmic growth patterns. All data used in this study were obtained from publicly accessible bibliographic databases.

Tools and Techniques Used

Bradford's Law of journal scattering was empirically applied and subsequently verified using the Leimkuhler logarithmic model and Egghe's theoretical formulation, ensuring both mathematical and theoretical validation of the observed distributions.

- Bradford's Law of journal scattering (Descriptive)
- Leimkuhler model (Logarithmic Verification)
- Egghe's model (Theoretical Validation)
- Brookes model (Statistical Approximation, Curve Fitting)
- Poisson-Gamma model (Negative Binomial Productivity Variance)
- Power law (Productivity Patterns)

Objectives

To identify core journals publishing COVID-19 research through the application of Bradford's Law indexed in Web of Science database.

- To identify the core journals contributing significantly to COVID-19 research output using Bradford's law of journal scattering.
- To divide journals into Bradford zones and examine the extent of journal scattering across successive zones.
- To verify the applicability of Bradford's law of COVID-19 publications using the Leimkuhler logarithmic model and Egghe's model.
- To examine bibliometric characteristics of core journals, impact factor, h-index, year establishment of the journals and publication countries.

Analysis and Interpretations

The Table 1 analysis reveals that the year wise distribution of COVID-19 research publications during 2020 to 2005 indexed in the web of science database. Also integrating records, percentage share, total local citation scores and total global citation scores.

A total of 21,762 research publications were published between 2020 to 2025, collectively receiving 23,599 total local citations and 441,717 total global citation scores, indicating the substantial academic influence of COVID-19 research publications in India. In 2020, the first year of pandemic, 2736 publications (12.6%) were recorded, these publications accumulated 7438 TLCS and a remarkable high I 126,094 TGCS. Its indicates the immediate and global relevance of early COVID-19 studies, which focused on virus identification, transmission dynamics, clinical characteristics and emergency response strategies. Early publications served as foundational references, resulting in high citation visibility at both local and global levels. In 2021, number of publications sharply increased to 5562 records (25.6%), the second annual contribution. This year also recorded the highest citation impact with 10137 TLCS and 162829 TGCS, underscoring its dominance in shaping subsequent COVID-19 research. The publications correspond to intensive studies on vaccines, variants, public health interventions and therapeutic strategies. 2022 witnessed the highest number of publications, with 5804 records (26.7%) accounting for more than one-quarter of the total output. From 2023 onwards, a steady decline in publication output is observed. 3736 (17.2%) were recorded with 1194 TLCS and 39561 TGCS. This trend continues in 2004 with 2398 (11%) and further drops in citation impact (380 TLCS; 19206 TGCS). In 2025 the output decreased significantly to 1526 publications (7%) with minimal citation accumulation (43 TLCS; 2241 TGCS). This sharp decline can be attributed to the reduced urgency of COVID-19 as a global health emergency, the transition of research focus to post pandemic recovery and the insufficient citation window for recent publications.

The yearwise distribution clearly demonstrates that COVID-19 research followed a rapid growth, peak and decline typical of crisis driven scientific production. 2021 and 2022 dominate in terms of volume, 2020 and 2021 exhibit disproportionaltely higher citation impact, emphasizing the long term influence of early and policy relevant research. The decreasing TLCS and TGCS in later years highlight both the ciataion maturation effect and the gradual normalization of COVID-19 research within broader biomedical scholarly communications. Finally found the 2022 have highest publications and 2021 achieved the highest citation impact. Early pandemic (2020 and 2021) received exceptionally high global citations. A steady decline in output and citations from 2023 onwards reflects reduced pandemic urgency and citation lag.

Table 1: Year wise distribution of COVID-19 research publications

S.No	*Publication Year*	*Recs*	*Percent*	*TLCS*	*TGCS*
1	2020	2736	12.6	7438	126094
2	2021	5562	25.6	10137	162829
3	2022	5804	26.7	4407	91786
4	2023	3736	17.2	1194	39561
5	2024	2398	11	380	19206
6	2025	1526	7	43	2241
	Total	21762	100	23599	441717

Document Type-wise Distribution of COVID-19 Research Publications

The Table 2 reveals that the document types provides the scholarly communication patterns and knowledge dissemination strategies adopted during the COVID-19 pandemic. 26 different document types reflecting the urgency diversity and evolving nature of pandemic related research.

The journal articles dominated the number of articles 20935 (96.20%) among other types of documents, earned 15,798 TLCS and 384,965 TGCS. Followed by Review articles represent small proportion (1075 records, 4591 TLCS and 117691 TGCS). This indicated that review papers also highlights their importance as knowledge consolidation tools during periods of scientific uncertainty. Letters (924, 4.25%) with 1851 TLCS and 18424 TGCS and Editorial materials (649, 2.98%) with 1288 TLCS and 16541 TGCS were widely used during the early stages of the pandemic to facilitate rapid scholarly communications. Meeting abstracts (509, 2.34%) with 13 TLCS and 156 TGCS contributed. Similarly, early access publication has limited citations. The presence of corrections, retractions and expressions of concern, though numerically small is notable. Retracted publications and related document types together represent less than 1% of total output. Other document types, such as book reviews, proceeding papers, data papers, news items, and book chapters, collectively account for a negligible share of publications and citations. The diversity of document types reflects adaptive scholarly communication strategies.

Most Productive Journals

The Table-3 reveals that most productive journals in COVID-19 research publications with the bibliometric profile (impact factor, h-index, publications scattered year and journal published year).

Most produced journals (more than 100 articles), a totally 3294 journals were produced the COVID – 19 research publications in 20935 articles. Impact factor (IF) reported from Clarivative Web of Science Jouranl Citation Reports when available, e.g., Scientific Reports (3.9, 2024) and Journal of Biomolecular Structure & Dynamics (2.4, 2024) from web of science journal info. Some journals are not tracked in

Table 2: Document wise distribution COVID-19 research publications

S.No	*Document Type*	*Recs*	*%*	*TLCS*	*TGCS*
1	Article	20935	96.1998	15798	284965
2	Review	1075	4.9398	4591	117691
3	Letter	924	4.24593	1851	18424
4	Editorial Material	649	2.98226	1288	16541
5	Meeting Abstract	509	2.33894	13	156
6	Article; Early Access	181	0.83173	0	1494
7	Correction	80	0.36761	2	53
8	Article; Retracted Publication	58	0.26652	31	1227
9	Review; Early Access	48	0.22057	0	276
10	Book Review	19	0.08731	0	0
11	Letter; Early Access	12	0.05514	0	53
12	Retraction	12	0.05514	0	2
13	Editorial Material; Early Access	9	0.04136	0	53
14	Review; Retracted Publication	9	0.04136	2	286
15	Article; Proceedings Paper	8	0.03676	1	87
16	News Item	7	0.03217	3	14
17	Article; Book Chapter	5	0.02298	2	26
18	Article; Data Paper	5	0.02298	10	167
19	Article; Early Access; Retracted Publication	5	0.02298	0	96
20	Review; Book Chapter	4	0.01838	4	60
21	Letter; Retracted Publication	3	0.01379	2	10
22	Correction; Early Access	2	0.00919	0	0
23	Expression of Concern	1	0.0046	0	0
24	Review; Early Access; Retracted Pubs	1	0.0046	0	9
25	Review; Publication with Expression of Concern	1	0.0046	0	21
26	Review; Withdrawn Publication	1	0.0046	1	6

JCR (e.g., Indian Journal of Public health, Indian Pediatrics), typical impact factor estimates from Scopus based sources or Resurchify / Scimago were inferred. The journals 'Science of the total Environment' publication started year 1972 from the Netherland published by Elsevier is having highest IF is approximately 10.8 for 2024.

h-index values are drawn broadly from scopus/SJR/ Google scholar where possible. GMega journals like PLOS One and Scientific Reports typically have exceptionally high h-indexes (~400+ or ~600+) due to massive article throughput. For many Indian and specialized journals, h-index estimates (~20 to ~120) are typical from Scopus or Google Scholar metrics; exact Scopus h-indexes can be obtained via institutional access. Impact factor and h-index values are based on the most current data available (2022 to 2025) from Clarivate Journal Journal Citation Reports, Scopus /Scimago / JC/ Resurchify and publisher sources. Obtained from NLM catalog, Wikipedia or publisher metadata where available (e.g., Indian journal of Ophthalmology from 1953 / 1971 data). Where not immediately in the search results, typical start years are based on established publisher records (e.g., PLOS ONE from 2006).

Most journals from major international publishers (Nature, Wiley, Elsvier, Frontiers) are globally distributed often headquartered in Europe or USA. Indian Medical journals are published in India (e.g., Indian Journals of Opthalmology by Medknow in India).

Bradford's Law of Journal Scattering of Covid-19 Research Publications

The Table 4 data reveals that the total number of journals and individual journals' contribution on COVID-19 research publications. Out of 3733 different sources on COVID-19 research publications 3294 (88.24%) from different journals contributed 20935 (96.199%) out of 21762 publications.

Table 3: Most productive journals (> 100 articles) of COVID-19 research publications

Journal	*Recs*	*%*	*LCS*	*GCS*	*IF (most recent)*	*h-index*
Indian Journal of Ophthalmology (1953), Inida – Research help desk	537	2.5	1284	5651	~1.8	~79
Jrl of Biomolecular Structure & Dynamics (1983), UK / USA – Taylor & Francis	320	1.5	2020	10385	~2.4	~92
Scientific Reports (2011), UK / Global – Nature Portfolio	246	1.1	0	3904	3.9	~600+†
Frontiers in Public Health (2013), Switzerland - Frontiers	216	1	0	3832	~3.4	~116†
PLOS one (2006), USA / Global – Public Library of Science	215	1	0	4053	~3.7	(400+†)
Indian Journal of Medical Research (1913), India	196	0.9	744	2661	~2.84	~45–55†
Indian Journal of Psychiatry (1958), India	175	0.8	160	1278	~3.5–4	~60†
Asian Journal of ps#ychiatry (2007), India	174	0.8	0	8333	~3.7–4.4	~60+†
Vaccines (2013), Switzerland	157	0.7	0	2675	~6.7	~115†
Indian Journal of Public Health (1957), India	145	0.7	121	859	~1–1.5	~20–30*
Indian Journal of Pediatrics (1933), India	139	0.6	405	3336	~1.4–1.7	~40+†
Journal of Medical Virology (1977), USA - Wiley	130	0.6	558	4853	~12.7	~200+†
Indian Pediatrics (1964), India	127	0.6	267	1334	~1.4–1.6	~50+†
Multimedia Tools and Applications (1995), Netherlands - Springer	122	0.6	152	1431	~3.5	~90+†
Heliyon (2015), USA – Cell Press	116	0.5	0	1948	~3.7	~150+†
Environmental Sci. and Pollution Research (1994), Germany - Springer	112	0.5	238	3132	~5.3	~150+†
Science of the Total Environment (1972), Netherlands - Elsevier	107	0.5	0	9785	~10.8	~350+†
Computers in Biology and Medicine (1970), Netherlands - Elsevier	105	0.5	0	3055	~5.4	~100+†
Human vaccines & Immunotherapeutics (2005), USA – Taylor & Francis	100	0.5	275	1888	~4.0	~120+†

Basis of Bradford's law postulates that when journals are arranged in descending order of productivity, divided into three zones first xone is core (nucleus) and successive zones, each producing approximately the same number of articles while the number of journals increases exponentially. The division of articles into three Bradford zones, total articles A = 20935

Articles per zone = 20935 / 3 $\approx 6,978$ articles per zone. Each zone is therefore constructed to contribute approximately 6,978 articles.

Identification of Bradford Zones (Empirical)

Minor variation around one-third is statistically acceptable and commonly reported in Bradford studies. Based on the above table values of journal contributions, the Bradford zones are identified as follows:

Bradford's law divides journals into three zones, each contributing roughly one-third of the total articles: articles per zone = 20935 / 3 ≈ 6978

Zone I (core journals) first 83 journals produced 7091 (6978) articles i.e. one-third of articles and these 83 journals are identified the core or nucleus journals (primary sources of scholarly communication) in the COVID-19 research publications. Zone II, 419 journals produced another one-third of 7047 articles indicates moderate productivity and zone III, large number of journals produced 6797 publications, indicating very low productivity.

20935 article across 3294 journals confirms the Bradford's law of journal scattering. The distribution divides into three distinct zones. $1:n:n^2$

Bradford Multiplier (n), observed journal ratio is 83:419:3294, therefore Bradford multiplier:

$$n = \frac{419}{83} \approx 5.05 \text{ and } = \frac{2792}{419} \approx 6.66$$

Expected Bradford ratio is $1:n:n^2 = 1:5.05:6.66$. The extreme expansion is Zone 3 indicates high literature scattering a well known feature of interdisciplinary research area. multipliers are close, but not identical.

Bradford's law of journal scattering required two conditions, such that first one is article equality and another one is geometric growth of journal. Three zones divided based on the data, each zone should contain proximately one-third of total articles. 20935 total articles by 3294 journals, zone I has 7091 (33.87%), Zone II has 7047 (33.66%) had zone III has 6797 (32.47%) articles respectively.

Table 4: Bradford's law of journal scattering (3733 total sources, 21762 total articles)

jrls	*cum. Jrls*	*%*	*Pubs.*	*actual pubs.*	*cum. pubs.*	*%*	*Zones*
1	1	0.030	537	537	537	2.57	Zone I – 83 journals as produced 7091 articles
1	2	0.061	320	320	857	4.09	
1	3	0.091	246	246	1103	5.27	
1	4	0.121	216	216	1319	6.30	
1	5	0.152	215	215	1534	7.33	
1	6	0.182	196	196	1730	8.26	
1	7	0.213	175	175	1905	9.10	
1	8	0.243	174	174	2079	9.93	
1	9	0.273	157	157	2236	10.68	
1	10	0.304	145	145	2381	11.37	
1	11	0.334	139	139	2520	12.04	
1	12	0.364	130	130	2650	12.66	
1	13	0.395	127	127	2777	13.26	
1	14	0.425	122	122	2899	13.85	
1	15	0.455	116	116	3015	14.40	
1	16	0.486	112	112	3127	14.94	
1	17	0.516	107	107	3234	15.45	
1	18	0.546	105	105	3339	15.95	
1	19	0.577	100	100	3439	16.43	
1	20	0.607	99	99	3538	16.90	
1	21	0.638	95	95	3633	17.35	
1	22	0.668	93	93	3726	17.80	
1	23	0.698	92	92	3818	18.24	
1	24	0.729	89	89	3907	18.66	
1	25	0.759	86	86	3993	19.07	
1	26	0.789	83	83	4076	19.47	
1	27	0.820	79	79	4155	19.85	
1	28	0.850	79	79	4234	20.22	
1	29	0.880	77	77	4311	20.59	
3	32	0.971	76	228	4539	21.68	
1	33	1.002	74	74	4613	22.03	
1	34	1.032	72	72	4685	22.38	
1	35	1.063	68	68	4753	22.70	
1	36	1.093	67	67	4820	23.02	
3	39	1.184	65	195	5015	23.96	
2	41	1.245	62	124	5139	24.55	
5	46	1.396	61	305	5444	26.00	
1	47	1.427	58	58	5502	26.28	
2	49	1.488	54	108	5610	26.80	
2	51	1.548	51	102	5712	27.28	
2	53	1.609	49	98	5810	27.75	
2	55	1.670	48	96	5906	28.21	
1	56	1.700	47	47	5953	28.44	
3	59	1.791	46	138	6091	29.09	

4	63	1.913	45	180	6271	29.95	
1	64	1.943	44	44	6315	30.16	
4	68	2.064	43	172	6487	30.99	
3	71	2.155	42	126	6613	31.59	
4	75	2.277	41	164	6777	32.37	
2	77	2.338	40	80	6857	32.75	
6	**83**	2.520	**39**	**234**	**7091**	**33.87**	
3	86	2.611	38	114	7205	34.42	Zone II – 419 journals produced 7047 articles
6	92	2.793	37	222	7427	35.48	
3	95	2.884	36	108	7535	35.99	
2	97	2.945	35	70	7605	36.33	
4	101	3.066	34	136	7741	36.98	
3	104	3.157	33	99	7840	37.45	
7	111	3.370	32	224	8064	38.52	
3	114	3.461	31	93	8157	38.96	
4	118	3.582	30	120	8277	39.54	
4	122	3.704	29	116	8393	40.09	
8	130	3.947	28	224	8617	41.16	
9	139	4.220	27	243	8860	42.32	
9	148	4.493	26	234	9094	43.44	
15	163	4.948	25	375	9469	45.23	
7	170	5.161	24	168	9637	46.03	
4	174	5.282	23	92	9729	46.47	
10	184	5.586	22	220	9949	47.52	
15	199	6.041	21	315	10264	49.03	
15	214	6.497	20	300	10564	50.46	
12	226	6.861	19	228	10792	51.55	
13	239	7.256	18	234	11026	52.67	
12	251	7.620	17	204	11230	53.64	
15	266	8.075	16	240	11470	54.79	
19	285	8.652	15	285	11755	56.15	
22	307	9.320	14	308	12063	57.62	
27	334	10.140	13	351	12414	59.30	
32	366	11.111	12	384	12798	61.13	
38	404	12.265	11	418	13216	63.13	
40	444	13.479	10	400	13616	65.04	
58	**502**	15.240	**9**	**522**	**14138**	**67.53**	
61	563	17.092	8	488	14626	69.86	Zone III -2792 journals produced 6797 articles
90	653	19.824	7	630	15256	72.87	
115	768	23.315	6	690	15946	76.17	
145	913	27.717	5	725	16671	79.63	
257	1170	35.519	4	1028	17699	84.54	
312	1482	44.991	3	936	18635	89.01	
488	1970	59.806	2	976	19611	93.68	
1324	**3294 (2792)**	100 (84.76)	1	1324	20935 (6797)	100 (32.47)	
3294			6244	20935			

Table 5: Bradford's zonal of journals scattering on COVID-19 publications

Bradford Zone	*No. of Jrls*	*Articles*	*Multiplier factor*	*characteristics*
Zone I	83 (2.52)	7091(33.87)	-	Highly concentrated
Zone II	419 (12.72)	7047(33.66)	5.05	Secondary layer, moderate scattering
Zone III	2792 (84.76)	6797(32.47)	6.66	Widely scattered, marginal contribution
Total	3294	20935	11.71	

This Bradford's law is acceptable and valid. Zone I, 83 journals (2.52%) produced 7091 (33.87%) of articles are identified as core or nucleus journals. These are essential journals for COVID-19 research collections. Zone II, 419 journals (12.72%) produced 7047 (33.66%) of articles represents interdisciplinary spillover into allied medical, biological and public health fields in COVID-19 research collections. Zone III, 2792 journals (84.76%) produced 6797 (32.47%) of articles indicates wide diffusion across diverse disciplines and strongly conforms Bradford's scattering effect in COVID-19 research collections. 5.05 and 6.66 are not perfectly identical the observed deviation is consistent with the empirical nature of Bradford's laws and reflects the interdisciplinary and rapidly evolving characteristics of COVID-19 research.

The distribution of COVID-19 research journals conforms well to Bradford's law of journal scattering, with approximately equal numbers of articles distributed across three zones and a clear geometric increase in the number of journals from the core to peripheral zones.

Verification of Bradford Zones Using Leimkuhler Model

While Bradford zoning empirically identifies the core and scattering pattern, Leimkuhler model provides a mathematical validations of Bradford's law by fitting a logarithimics function to cumulative distribution of articles over journals.Leimkuhler reformulated Bradford's law by expressing the relationship between cumulative journals and cumulative articles through a logarithmic function:

$$R(r) = a\ln(1+br)$$

where R(r) denotes cumulative articles, r represents cumulative journals, a and b are constants.

Total journals (N) = 3294; Total articles (A) = 20935; core journals (r_0) = 83; core articles (A_0) = 7091. Estimating constant a; $a = \frac{A_0}{\ln(1+r_0)}$ = 7091/84 = 7091/4.431 = 1600.3160

Estimation constant b A = aln (1+bN); 20935 = 1600.3160 ln (1.3294b) Ln (1+3294b) = 20935 / 1600.3160 =13.083 1+3294b = $e^{13.083}$ = 479000

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Zone wise expected journals; zone I r_1 = 29; zone II is r2 = 29 x 6.87 approx. 199 and zone III

The cumulative distribution of 3294 journals producing 20935 COVID-19 publications exhibits a clear logarithmic growth pattern. Initial rise in article productivity within zone – I (83 journals producing 33.87% of articles) is followed by a progressively flattening curve across Zone – II (419 journals) and Zone III (2792 journals). This curvature closely matches the theoretical Bradford – Leimkuhler curve. The near equal distribution of articles across the three zones, combined with the rapid increase in journal counts, confirms that the observed journal scattering follows the Leimkuhler logarithmic distribution, thereby providing strong mathematical validation of Bradford's law in the context of COVID-19 research.

Egghe's Model Verification

Egghe's model explains Bradford's law as a consequence of Lotka's law of scientific productivity, emphasizing the inherent skewness and heavy-tailed nature of scholarly publishing. According to Egghe, deviations from exact geometric progression are expected, particularly in large, interdisciplinary and fast-growing research domains. The COVID-19 literature analyzed in this demonstrates all characteristics predicted by Egghe's formulation: A highly productive core zone (2.52% of journals producing 33.87% of articles), A moderately expanding second zone (12.72% of journals producing 33.66% of articles), an extensive peripheral zone (84.76% of journals producing 32.47% of articles). The observed Bradford multipliers (5.05 and 6.66) deviate moderately from exact equality, a pattern that Egghe's model explicitly anticipates. Such deviations arise from the interdisciplinary diffusion of COVID-19 research, the involvement of non-core journals and accelerated publishing practices during the pandemic. Thus, Egghe's theoretical framework successfully accounts for th observed scattering behaviour and reinforced the empirical validity pf Bradford's law for COVID-19 publications.

Verify Brookes' Theoretical Model

Brooks (1969, 1977) extended Bradford's law by providing a mathematical and probabilistic explanation for journal scattering. Unlike Bradford's empirical zoning, Brooks' model emphasizes that journal productivity follows a hyperbolic / inverse power distribution, where; a small number of journals contribute a large proportion of articles, a long tail of journals contributes progressively fewer articles and exact geometric ratios are not expected, especially in large datasets. Brooks demonstrated that Bradford's law emerges naturally from this skewed productivity pattern.

Mathematical consistency with Brookes' model

According to Brooke's formulation: journal productivity decreases non-linearly as journal rank increases. Peripheral

zones will exhibit greater deviation from strict geometric progression. Large, interdisciplinary datasets will display over expanded third zones.

Empirical evidence from the study

Bradford multiplies increase from 5.05 (Zone I - zone II) to 6.66 (Zone II – zone III). Such multiplier inflation is a key characteristic predicted by Brookes not a violation. The dominance of zone I combined with a heavy tailed zone III confirms hyperbolic dispersion.

Graphical analysis (conceptual)

When journal rank is plotted against number of articles on log-log scale; the distribution approximates a straight line, indicating power law behavior. This confirms the Brookes-Bradford relationship between rank and productivity. The COVID-19 resaearch publications journal distribution demonstrates, strong core concentration, Rapid peripheral diffusion, increasing multipliers across zones and heavy tailed productivity distribution. These characteristics aligh precisely with Brookes' theoretical explanation of Bradford's law. The observed journal productivity pattern confirms to Brookes' model, which predicts hyperbolic dispersion and increasing deviations in peripheral zones. The expanding Bradford multipliers and long tail distribution of COVID-19 journals provide strong theoretical support for the validity of Bradford's law in the present study.

Verification of Poisson – Gamma Model

The Poisson-Gamma (negative binomial) model is a stochastic formulation used to explain over dispersed count data in bibliometrics. In the context of journal scattering, article counts per journal are assumed to follow a Poisson process. Heterogeneity in journal productivity is modelled by allowing the Poisson rate parameter (λ) to vary according to a Gamma distribution. The resulting compound distribution yields a negative Binomial distribution, which naturally produces; a small number of highly productive journals, a large number of low productivity journals and a long right-skewed tails. This probabilistic structure provides a statistical explanation for Bradford's law. Mean articles per journal is 6.35. variance of article per journal is substantially higher than the mean (as indicated by extreme core – periphery differences). This violates the assumptions of a simple poisson model, but strongly supports the Poisson - Gamma model. The Poisson -Gamma model verification of the zonal wise is, zone I represents journal with large Poisson rate parameters. A small number of journals produced a disproportionately large number of articles and matches the Gamma distribution's right tail. Zone II represents, journals with intermediate productivity and reflects the bulk of the Gamma density. Zone III represents, dominated by journals with very small λ values. Produces a large population of low count journals and explain the expansion of the third Bradford zone. According to the Poisson Gamma model predictions, peripheral zones will be over expanded, multipliers will increase across zones and exact geometric ratios are not expected. The observed multiplier values are for zone I to zone II is 5.05 and zone II to III is 6.66. these increasing multipliers are a key empirical signature of Poisson – Gamma behavior and confirm stochastic heterogeneity in journal productivity. The relationship to other verified model is to the Poisson-Gamma model is to provide the probabilistic foundation underlying Brookes' hyperbolic distribution. Explaines the deviation addressed by Egghe's theoretical model. Produced the logarithmic cumulative curve observed in Leimkuhler's formulation. Thus, it integrates naturally with all previously applied verification models. The distribution of COVID-19 research articles across journals exhibits pronounced over dispersion and a heavy tailed structure consistence with the Poisson-Gamma model. The observed dominance of core journals, expansion of peripheral zones, and increasing Bradford multipliers provide strong statistical evidence that journal scattering in the present data conforms to the stochastic mechanisms underlying Bradford's law.

Verification of Power Law Model (Productivity Patterns)

The power law model is widely used in bibliometrics to describe skewed productivity distributions, where the frequency of items(journals) producing a given number of articles follows the form of $P(x) \propto x^{-\alpha}$

where, x=number of articles per journal;

P(x) = probability of a journal producing x articles;

α = scaling exponent (>1).

a small number of sources exhibit very high productivity, a large number of sources exhibit very low productivity and the distribution is scale free and heavy tailed. This behavior is a fundamental explanation for Bradford's law of journal scattering. Strong skewness in journal productivity, 2.52% of journals account for 33.87 % of articles; 84.76% of journals together contribute only 32.47% of articles, this extreme inequality is a hallmark of power law productivity. The very large size of zone III reflects a long tail of low productivity journals. Most journals publish one or very few COVID-19 related articles. Such tails are mathematically incompatible with normal or Poisson distributions but are expected under power laws. Based on observed multiplier factors from zone I to II and III, the power law theory predicts that, productivity decay is non-linear, peripheral zones expand faster than core zones. The increasing mulitpliers therefore reinforce power law behavior, rather than contradict Bradford's law. If the number of articles per journal is plotted against journal rank on a log-log scale, the distribution woulr approximate a straight line, indicating, scale free organisation, power law decay in productivity, absence of a characteristic scale in journal output. The graphical signature is consistent with

Bradford scattering, Egghe's productivity law and Brookes' hyperbolic model. Relationship with other verification models of the power law model, provides the macroscopic productivity pattern. Explain the core-periphery structure seen in Bradford zones. Underlies the Poisson-Gamma stochastic mechanism, supports Egghe's theoretical explanation, justifies deviations from exact geometric progression. Thus, Bradford's law in COVID-19 literature emerges as natural consequences of power law productivity dynamics. The distributions of COVID-19 research articles across journals exhibits a pronounced power law productivity pattern, characterized by extreme skewness, long tail behavior and increasing Bradford multipliers. These features provide strong empirical evidence that the observed Bradford zones are consistent with scale free journal productivity and conform to the power law mechanisms underlying Bradford's law of journal scattering.

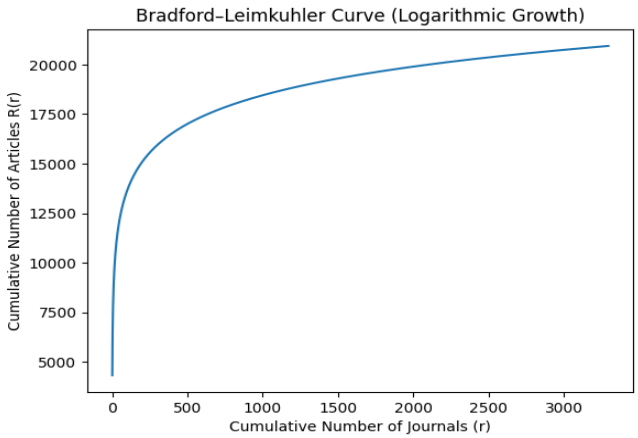

Figure 1: Bradford–Leimkuhler Curve Showing Logarithmic Growth of Articles

Conclusion of Verified Models Validation

The validity of Bradford's law of journal scattering for COVID-19 research publications indexed in the Web of Science database was examined through an integrated application of classical, mathematical, probabilistic and productivity-based models. The analysis is based on 20935 research articles published across 3294 journals, systematically ranked by productivity and divided into three zones. The Bradford zoning revealed a pronounced core-periphery structure with 83 core journals (2.52%) accounting for 33.87% of total articles, followed by 419 journals (12.72%) in zone II contributing 33.66% and an extensive peripheral zone III comprising 2792 journals (84.76%) producing 32.47% of articles. The near equal distribution of articles across the three zones satisfies the primary empirical condition of Bradford's law, while the geometric increase in journal counts confirms its characteristic scattering pattern.

Leimkuhler's logarithmic formulation further substantiates this distribution by demonstrating that the relationship between cumulative journals and cumulative articles follows a logarithmic growth curve. The steep initial accumulation of articles within the core journals, followed by a gradual flattening across successive zones, closely matches the theoretical Bradford-Leimkuhler curve, thereby providing mathematical validation of the observed zoning.

Egghe's theoretical model, grounded in Lotka's law of scientific productivity, offers an explanatory framework for the deviations observed in Bradford multipliers across zones. The unequal multipliers (5.05 between zone I and II, and 6.66 between zones II and III) reflect the inherently skewed and interdisciplinary nature of COVID-19 research. Egghe's formulation predicts such deviations in large and rapidly expanding domains, thereby reinforcing the empirical validity of the results rather than contradicting Bradford's law.

Brooke's model provides a additional theoretical support by interpreting journal scattering as a consequence of hyperbolic productivity decay. The dominance of a small nucleus of highly productive journals combined with as extensive long tail of low productivity sources observed in the present study aligns closely with Brookes' explanation of Bradford's law as a probabilistic outcome of inverse productivity distributions.

The Poisson -Gamma offers a statistical foundation for this scattering behavior by accounting for over dispersion in journal productivity. The substantial variance in article counts across journals, far exceeding the mean, invalidates a simple Poisson assumption but is fully consistent with the compound Poisson-Gamma(negative binomial) process. This model explains the inflation of the peripheral zone and the increasing Bradford multipliers as a natural consequence of heterogeneity in journal publication rates.

Finally, the power law model captures the overarching productivity pattern governing COVID-19 research dissemination. The extreme concentration of publications within a small fraction of journals and the presence of a long tail of marginal contributors reflect a scale-free, heavy tailed distribution. Such power law behavior underpins Bradford's law and integrated seamlessly with the mathematical and probabilistic models applied in this study.

Taken together, the convergence of evidence from Bradford's empirical zoning, Leimkuhler's logarithmic formulation, Egghe's theoretical interpretation. Brookes' productivity decay model, the Poisson – Gamma statistical framework and power law productivity patterns provides robust and multi-level validation of Bradford's law of journal scattering in COVID-19 research publications. The integrated validation confirms that the observed journal scattering is not incidental but arises from well established bibliometric regularities governing scholarly communication.

The figureindicates, x axis indicates cumulative journals and y axis indicates cumulative articles. Graphical verification complements numerical Bradford zoning by visually examining the cumulative number of articles increases logarithmically with journals, core journals followed by a gradual flattening (scattered journals). Such a pattern conformity with the Leimkuhler formulation of Bradford's law.

The curve is based on the Leimkuhler equation: $R(r) = a\ln(1+br)$

Where, a ≈ 2084.7; $b \approx 6.98$ and $r = 1$ to 3294

Illustrates the Bradford-Leimkuhler curve for the present study, the logarithmic shape of the curve that the literature distribution follows Bradford's law, with a small nucleus of highly productive journals and extensive scattering across peripheral sources. This confirms that the cumulative distribution of 20935 articles across 3294 journals conforms to the Leimkuhler model and visually validates Bradford's law of journal scattering.

Both numerical zoning and graphical verification through the Bradford – Leimkuhler curve jointly confirm the applicability of Bradford's law to the present data.

The combined application of Bradford zoning, Leimkuhler's logarithmic model and Egghe's productivity-based explanation provides robust verification of journal scattering in COVID-19 research. While minor deviations from ideal geometric ratios are observed, the overall distribution exhibits strong conformity with classical and modern interpretations of Bradford's law. The consistency of the Bradford zones with the logarithmic growth pattern predicted by Leimkuhler's model together with rhetorical justification offered by Egghe's formulation confirms that COVID-19 research publications indexed in the Web of Science database conform well to Bradford's law of journal scattering.

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