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Lotka's Law and Pattern of Author Productivity in the Area of Physics Research

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ABSTRACT

The paper aims to analyse authorship distribution in physics literature and to examine the validity of Lotka's law of scientific publication productivity. A list of journal articles on various aspects of physics research cited in the doctoral theses of University of Kerala, Thiruvananthapuram, South India was compiled for the study. Using 'straight count' of authorship, a total of 1,665 personal authors were identified and 3,367 authors were identified by using 'complete count'. K-S statistical test and Chi-square test were applied to verify the applicability of Lotka's law in the two approaches. The productivity distribution did not fit either set of data for two different author communities when Lotka's law was applied in its original form. This confirms that law does not applicable to authors of the physics literature.

Keywords: Lotka's law, University of Kerala, scientific productivity, bibliometrics, physics literature

1. INTRODUCTION

Classifying and counting scientists, books, papers and citation, as early statistical bibliographers set out to do, remain a fairly extemporary activity as long as data continued to be examined outside a mathematical framework that would let them disclose meaningful patterns in the documentation process. The turning point occurred between the 1920s and the 1930s, when three basic bibliometric studies were published: Lotka' work on the distribution of scientific papers among authors; Bradford's contribution on the scattering of papers on a given subject in scientific journals; and Zipf's work on the distribution of words in a text[1]. Lotka, Bradford and Zipf used simple mathematical statements and graphical devices to express the empirical relation between sources and the items they produce in three areas: Authors producing papers, journals producing papers on a given subject, and texts producing words with a given frequency.

Three regularities occur in bibliometrics to which have been given the name 'law': Lotka's Law of Scientific Productivity (authors publishing in a certain discipline), Bradford's Law of Scattering (distribution of publications), and Zipf's law of Word Occurrence (ranking of word frequency). Lotka's law dealt with author publishing and the number of papers published. It is regarded as one of the classical laws of bibliometrics[2].

The validity of Lotka's law has been studied by a number of researchers who have applied the model to data sets in many subject areas. Most notable are the contribution of Pao[3] and Nicholls[4], who found that the Lotka model fitted the majority of the data sets studied. Both have substantially confirmed the validity of the law, having tested it, respectively, against 48 and 70 datasets of empirical author productivity distributions. The authors felt necessary to establish a standard testing procedure for meaningful statistical comparison between different tests of Lotka's law by defining the minimal requirements for each step involved in any validation process. They are:

(a) Specification of the model

(b) Data collection

(c) Estimation of the unknown parameters in the model equation, and

(d) Testing conformity of the observed data to the theoretical distribution by means of a goodness-of–fit test.

2. LOTKA'S LAW OF SCIENTIFIC PRODUCTIVITY

Lotka[5], investigated the literature output of a sample of chemists, and found that, "... the number (of authors) making *n* contributions is about $1/n^2$ of those making one; and the proportion of

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all contributors, that make a single contribution, is about 60 %."

$$p(n) = \frac{k}{n^2}$$

where, *p* is the number of authors producing *n* papers, and where *k* is constant characteristic of a particular subject area.

Lotka gave an acceptably modern mathematical description of his regularity that remains today as the (classic) Lotka's law. However, Lotka's article was not cited until 1941 and his distribution was not termed 'Lotka's Law' until 1949, as said by Potter[6].

Bookstein[7] points out that the following theoretical model

$$p(n) = \frac{k}{n^2}$$

x = 1, 2, 3… k>0, α >0

is a generalised version of Lotka's law; k and α are constants. In other words, the number of authors with x papers is proportional to $1/x^a$

Price[8], also interested in scientists' productivity, has defined a law developed from Lotka's stating that 'half of the scientific papers are contributed by the square root of the total number of scientific authors. In other words, the Price's Square Root Law of Scientific Productivity states that, $N^{½}$ sources yield a fraction ½ of the items.

In most of these studies, the number of publications are considered as a measure of scientific productivity. There are four methods of counting of number of publications[9].

(1) Total counting/normal (standard) counting: Each occurrence of an author is recognised and receives equal treatment, regardless of the number of authors associated with a given article. Therefore, an author receives equal credit, whether he or she is the only author of a publication or one of many (each of the *N* authors receives a credit of 1)

(2) Straight counting/ first author counting: Only the first author is counted, based on the assumption that the first author is the primary contributor to a publication. In deriving Inverse Square Law of Scientific Productivity, Lotka adopted this method (only the first of the *N* authors receives a credit 1)

(3) Adjusted counting/Fractional counting: Authors receive fractional credit or publications with multiple authors (each of the *N* author receives a score of $\frac{1}{N}$).

(4) Proportional counting: If an author has a rank *R* in a paper with *N* authors (*R*=1,2,3…*N*), then he/she receives a score of $\frac{2}{N}\left(1-\frac{R}{N+1}\right)$. In case of proportional counting this formula is obtained by dividing the absolute weights N+1-R by the sum of all ranks: 1+2+…+*N*= $\frac{N(N+1)}{2}$

There are two approaches generally used for organising scientific productivity data:

(i) Size-frequency: A standard frequency approach which models frequency of source *f*(*x*) as a function of the number of items *x*. It allows one to use traditional statistical techniques.

(ii) Rank-frequency: An approach which models the number of items *g*(*x*) as a function of the rank of the source *r*. It emphasis on those sources which have the most productive items, than those having small ranks *r* = 1,2,3,4…

3. LITERATURE REVIEW

Lotka's work went unnoticed for many years. In 1978, a bibliography of 437 works on Lotk's Law and related statistical regularities appeared in the first issue of the journal Scientometrics[10]. Ever since, the convergence of productivity patterns with Lotka's formula has been advocated in as diverse areas of LIS, computer science, semiconductor and micro computer research, medicine, biochemistry, entomology, econometrics, patent literature and web hyperlink distribution[11].

The degree of conformity or non-conformity of various empirical distributions of Lotka's distribution has been tested by many authors. The studies on the fitness of Lotka's law began in a systematic manner was with the work of Pao using least square method with 48 sets of authors productivity data. In 1985, Pao[12] presented the application process of Lotka's law and again in 1986 she studies it in other scientific fields. Modifications to Pao's procedure were proposed by Nicholls[13,14].

The other studies include: Lemoline[15] analysed scientific productivity of CSIR, India; Sen, Taib & Hassan[16] in Information science, Gupta[17] in potato research; Gupta & Kumar[18] in theoretical population genetics; Kawamura[19], *et al*. in dental science literature; Gupta[20], *et al*. studied productivity profile of scientists in engineering sciences; LOTKA, a computer program for fitting Lotka's law was presented by Rousseau & Rousseau[21], and Kumar[22] in computer science; Pulgarin & Gil-Leiva[23] in automatic indexing literature. Rai & Kumar[24] examined Lotka's law among authors and within institutions with the help of empirical data.

Sobrino, Caldes & Guerrero[25] studied the application of Lotka's law in the field of Information Science. Petek[26] studied the personal name headings in the Slovenian online catalogue COBIB. Askew[27]

in her doctoral thesis, tested Lotka's law using the methodology outlined by Pao, in the field of LIS. Larsen & Van Ins[28] analysed the relationship between scientific cooperation, counting method and interdisciplinary publishing with the Lotka's law using Mandelbrot's equivalent distribution model

Pavlyukevich, Penyazkov & Fisenko[29] studied Inznerno-Fizicheski Zhurnal author activity. Ahmed & Rahman[30] examined the validity of Lotka's law in the field of nutrition research in Bangladesh. Nerendra Kumar[31] examined the applicability of Lotka's law to research productivity of CSIR, India. Sen[32] discussed the meaning of author productivity and research productivity and demonstrated how simply the values of Lotka's law can be calculated. Sudhier[33] conducted a study on the application of Lotka's law of scientific productivity in the author productivity distribution of Physics literature appended in the IISc doctoral theses.

Lotka's law has been attracted scientometricians time and again. There have been many studies, which have explored the application of Lotka's law to various subject areas. The review revealed that there were not many studies in the area of physics literature. Hence, this paper attempts study the validity of application of Lotka's law in author productivity distribution of Physics literature.

4. OBJECTIVES

This paper has following objectives:

(a) To analyse the author productivity patterns in the field of physics literature

(b) To examine the validity of Lotka's law using total counting and straight counting of authors

(c) To apply Chi-square test and Kolmolgorov- Smirnov (K-S) goodness-of-fit test for the conformity of Lotka's law.

5. METHODOLOGY AND SOURCE DATA

Data source of the study are the journal citations in the doctoral theses of the University of Kerala, India. The total sample consists of 1,665 first authors as straight count method and 3,367 authors in complete count, appended in the 12 doctoral theses in physics, during the five year period.

The University of Kerala, which occupies the position of the mother university in Kerala, has been at the centre of all higher education activities in state since its very inception. Popularly known as 'God's own country', the tiny state is located in the south western part of peninsular India. The University of Travancore which eventually became the University of Kerala was established in 1937. It is being the oldest university in the Kerala pioneered in undertaking science programmes directly affecting the state. At present, the University has 16 faculties and 41 departments of teaching and research. The department of Physics was formally established in 1970 and the research programme has been in operation since the inception of the department.

The purpose of this study to test Lotka's law of scientific productivity using the methodology outlined by Pao[34], in the field of Library and information Science. Lotka's law is tested using Kolmogorov-Smirnov goodness-of-fit tests and Chi-square test.

5.1 Application of Lotka's Law

Lotka was the first to observe and analyse the productivity patterns of authors in a sample data from Chemistry and Physics. He came out with a general formula, known as Lotka's law and it can be written as

$$x^n y = k \quad (1)$$

where, y is the frequency of authors making n contributions each and k is a constant.

The Lotka's inverse square law can mathematically be written as

$$g(x) = \left(\frac{6}{\pi^2}\right)\left(\frac{1}{x^2}\right), \quad x = 1, 2, 3 \ldots. \quad (2)$$

where, $g(x)$ is the proportion of authors making x contributions.

A generalised form of Lotka's law was presented by Bookstein[2] as

$$g(x) = kx^{-n}, \; x = 1,2,3,4\ldots x_{max}, \; k>0 \quad (3)$$

where $g(x)$ represents the fraction of authors publishing x articles; k and n are parameters to be estimated from the data; x_{max} represents the maximum size or value of productivity variable x; and n is usually ≥ 1.

According to Pao, the following procedure should be followed in studying the application of fit of the Lotka's law to a given citation data sample.

(a)Estimation of parameter 'n'

The first step in the application of Lotka's law is to determine the value of n, which is to be determined either by using the Linear Least Square (LLS) regression method or one of it's equivalent form given by the following formula:

$$n = \frac{\left[N\sum(\ln x.\ln g(x) - \sum \ln g(x)\sum \ln x\right]}{\left[N\sum(\ln x)^2 - (\sum \ln x)^2\right]} \quad (4)$$

where N is the number of pairs of data considered x = 1,2,3.... x_{max}

(b) Estimation of parameter 'k'

The value of k, which is the theoretical number of authors with a single article is determined from the following formula:

$$k = \frac{1}{\sum_{x=1}^{p-1} \frac{1}{x^n} + \frac{1}{(n-1)(p^{n-1})} + \frac{1}{2}pn + \frac{n}{24\times(p-1)^{n+1}}} \quad (5)$$

here, p is assumed to be 20 and *n* is the experimentally computed value of the exponent from the observed distribution.

Once the value of *n* and *k* is determined, then using Eqn. 3, determine the number of authors writing 1, 2, 3,...*x* articles

5.2 Goodness-of-Fit Tests

There are several statistics available for goodness-of-fit tests. Among those tests, the Chi-square test and Kolmogrov-Smirnov (K-S) test commonly used as goodness-of-fit tool.

(a) Chi-square Test

If the observations in a sample fall into certain specified categories or classes it may be of interest to know whether the observed frequencies differ significantly from those which could be expected in these categories on the basis of certain hypotheses or theoretical considerations. The χ^2- test is useful in finding out where a theoretical distribution like Lotka's Law or any other, fits the given observations satisfactorily or not.

(b) K-S Test

The test is accomplished by finding the theoretical cumulative frequency distribution which would be expected under the null hypothesis [$F(x)$] and comparing it with the observed cumulative frequency distribution [$S_n(x)$]. The point at which these two distribution, theoretical and observed show the maximum deviation is determined. Let D = Maximum $|F(x)–S_n(x)|$.The value of D is calculated and compared with the critical value. The null hypothesis is rejected if the calculated value of D is greater than critical value; otherwise not.

6. RESULTS AND DISCUSSIONS

6.1 Dataset for the Straight Count Method

(a) Calculation of parameter 'n'

The first step in the application of Lotka's law is to determine the value of *n*, which is to be determined by Linear Least Square (LLS) method by using the mathematical formula (4).

To compute the parameter *n,* Table 1 of *x* and $g(x)$ is used.

By substituting the values in equation (4), the value of n is calculated as

$$n = \frac{\left[N\sum(\ln x.\ln g(x) - \sum \ln g(x)\sum \ln x\right]}{\left[N\sum(\ln x)^2 - (\sum \ln x)^2\right]}$$

$$n = \frac{8\times 34.6353 - 32.2086\times 10.6046}{8\times 17.5205 - (10.6046)^2} = \mathbf{-2.327}$$

(b) Calculation of value 'k'

The value of parameter *n* is calculated as, *n* = -2.3270

Substituting the given value of *n*, the value of *k* is estimated from the Table of exponents given by Rousseau[35] as, *k* = 0.7

$$g(1) = \frac{0.7}{x^{2.33}} = \frac{0.70}{1^{2.33}} = 0.7000 \qquad g(2) = \frac{0.7}{2^{2.33}} = 0.8508$$

$$g(3) = \frac{0.7}{3^{2.33}} = 0.9122 \qquad g(4) = \frac{0.7}{4^{2.33}} = 0.9447$$

$$g(5) = \frac{0.7}{5^{2.33}} = 0.9645 \qquad g(6) = \frac{0.7}{6^{2.33}} = 0.9777$$

$$g(7) = \frac{0.7}{7^{2.33}} = 0.9871 \qquad g(8) = \frac{0.7}{8^{2.33}} = 0.9941$$

(c) Fractional value of the expected number of authors

By replacing the value of *n* and *k* in Lotka's model equation

$g(x) = kx^{-n}$ and the values calculated are shown in the column 6 of Table 2.

(i) Suitability of Lotka's Law using K-S Statistical Test

To test the applicability of Lotka's law, Coile[36] recommends the K-S statistical test.

For applying K-S test, convert the observed and expected number of authors into fractional values, and take the difference between cumulative

Table 1. Calculation of *n*–Straight count method

x	*g*(*x*)	ln *x*	ln *g*(*x*)	ln (*x*) * ln *g*(*x*)	ln *x* * ln *x*
1	1167	0.0000	7.0622	0.0000	0.0000
2	281	0.6931	5.6384	3.9082	0.48 05
3	109	1.0986	4.6913	5.1540	1.2069
4	40	1.3863	3.6889	5.1139	1.9218
5	27	1.6094	3.2958	5.3044	2.5903
6	15	1.7918	2.7081	4.8522	3.2104
7	14	1.9459	2.6391	5.1354	3.7866
8	12	2.0794	2.4849	5.1672	4.3241
Total	**1665**	**10.6046**	**32.2086**	**34.6353**	**17.5205**

fractional values of observed and expected number of authors, as shown in Table 2.

The maximum difference value, D_{max}, representing the maximum deviation is identified as 0.023.

The table value or critical value of *D* in K-S test at 5 % level of significance is 0.565. While comparing the actual value of *D*, 0.023 with critical value 0.565, it is found that the actual value of *D* does not fall within the critical value of *D*. Therefore, Lotka's law does not fit the author productivity distribution of first authors.

K-S statistical test and Chi-square test are applied to verify the applicability of Lotka's law at 5 % level of significance to the author productivity distribution of first authors of physics literature and it is found that the law does not fit the present set of data in the two methods.

6.2 For the Data set of Complete Count

Coile argued that Schorr's[37] data did not fit Lotka's distribution because he counted co authors (whereas, Lotka's counted only the first authors) and then used Chi-square test which is not an appropriate test to verify the applicability of of Lotka's law. Therefore, the data of this compilation is tested by counting all the authors (complete count) and by applying both, the Chi-square and K-S statistical test to verify the applicability of generalised form of Lotka's law.

Table 2. K-S test on observed and expected distribution of authors

x	g(x)	FOF	CFOF	FEF	CFEF	DOECF
1	1167	0.7009	0.7009	0.7000	0.7000	0.0009
2	281	0.1688	0.8697	0.1508	0.8508	0.0189
3	109	0.0655	0.9351	0.0614	0.9122	**0.0229**
4	40	0.0240	0.9592	0.0325	0.9447	0.0145
5	27	0.0162	0.9754	0.0198	0.9645	0.0109
6	15	0.0090	0.9844	0.0132	0.9777	0.0067
7	14	0.0084	0.9928	0.0094	0.9871	0.0057
8	12	0.0072	1.0000	0.0070	0.9941	0.0059

g(*x*) : Number of authors contributing x number of papers
FOF : Fraction of observed frequency of authors
CFOF : Cumulative fraction of observed frequency of authors
FEF : Fraction of expected frequency of authors
CFEF : Cumulative fraction of theoretical frequency of authors
DOECF : Absolute difference of the observed and expected cumulative frequency of authors.

(ii) Applicability of Lotka's Law using Chi-square Test

To check the suitability of Lotka's law in the author productivity of physics literature, the following method using the Chi-square statistical test is employed. The results of the analysis are presented in the Table 3.

To find out the suitability of Lotka's law in the observed author productivity distribution, compare the calculated Chi-square value obtained, 11.19 with the critical value of Chi-square.

The critical value at 0.05 significance level is 0.83. On comparing, the calculated value of chi-square is greater than the critical value. Thus, again the Lotka's law does not fit in the observed given author productivity distribution of the first authors.

(a) Calculation of the Parameter 'n'

The mathematical formula for calculating the parameter n, using least squares method is given in Eqn. (4).

To compute the parameter *n*, of Table 4 is used.

by substituting the values in the Eqn. (4), as explained in the Table 4.

Table 3. Chi-square test of observed and expected first authors

x	f_o	f_e	f_o-f_e	$(f_o-f_e)^2$	Chi
1	1167	1166	1.50	2.25	0.00
2	281	251	29.95	896.76	3.57
3	109	102	6.73	45.30	0.44
4	40	54	-14.08	198.19	3.66
5	27	33	-5.99	35.88	1.09
6	15	22	-7.03	49.41	2.24
7	14	16	-1.66	2.75	0.18
8	12	12	0.35	0.12	0.01
				Chi	**11.19**

f_o – observed number of authors, f_e – estimated number of authors

Table 4. Calculation of n–whole authors

x	*g*(*x*)	ln *x*	ln (*gx*)	ln (*x*) * ln *g*(*x*)	ln *x* * ln *x*
1	2261	0.0	7.7	0.0	0.00
2	609	0.7	6.4	4.4	0.48
3	231	1.1	5.4	6.0	1.21
4	88	1.4	4.5	6.2	1.92
5	56	1.6	4.0	6.5	2.59
6	39	1.8	3.7	6.6	3.21
7	23	1.9	3.1	6.1	3.79
8	9	2.1	2.2	4.6	4.32
9	15	2.2	2.7	6.0	4.83
10	8	2.3	2.1	4.8	5.30
11	8	2.4	2.1	5.0	5.75
12	6	2.5	1.8	4.5	6.17
13	4	2.6	1.4	3.6	6.58
14	10	2.6	2.3	6.1	6.96
Total		**25.2**	**49.4**	**70.2**	**53.12**

$$n = \frac{14 \times 70.2 - 49.4 \times 25.2}{14 \times 53.12 - (25.2)^2} = -2.41$$

(b) Calculation of the Value 'k'

The value of k is determined by taking the corresponding value *n* = -2.41 from the table of exponents given by Rousseau (1993) as the value of k is 0.73.

By replacing the value of n and k in Lotka's equation $g(x) = kx^{-n}$

The fractional value of expected number of authors are calculated, and the values are shown in column 6 of the Table 5.

(i) Application of K-S Statistical Test

For applying the K-S statistical test, results are tabulated in Table 5.

The difference between the cumulative fractional values of the observed and the expected number of authors are shown in column 7 of the Table 5. The maximum deviation is identified as 0.058. The critical value of *D* in K-S test at 5 % level of significance is 0.391. Here, the actual value of D, 0.058 does not fall within the critical value of D, 0.391. Therefore, the test confirming that the distribution of the data using whole author count doesn't fit Lotka's law.

(ii) Using Chi-square Test

To check whether the author productivity distribution follows the Lotka's alw or not, the Chi- square test is applied to the data. The results of the analysis are tabulated in Table 6.

The calculated value of chi-square obtained is 95.10 and the critical value at 5% level of significance is 4.4. On comparing, it is found that the calculated value of Chi-square is greater than the critical value of chi-square. Thus, again it is conclude that the Lotka's law does not fit in the observed given all author productivity distribution.

The statistical tests show that the Lotka's law in its generalised form does not fit the author productivity distribution pattern prepared for the first authors and for the contribution of all authors.

Table 5. K-S test–whole authors

x	*g*(*x*)	FOF	CFOF	FEF	CFEF	DOECF
1	2261	0.672	0.672	0.730	0.730	**0.058**
2	609	0.181	0.852	0.137	0.867	0.015
3	231	0.069	0.921	0.052	0.919	0.002
4	88	0.026	0.947	0.026	0.945	0.002
5	56	0.017	0.964	0.015	0.960	0.004
6	39	0.012	0.975	0.010	0.970	0.006
7	23	0.007	0.982	0.007	0.976	0.006
8	9	0.003	0.985	0.005	0.981	0.004
9	15	0.004	0.989	0.004	0.985	0.005
10	8	0.002	0.992	0.003	0.988	0.004
11	8	0.002	0.994	0.002	0.990	0.004
12	6	0.002	0.996	0.002	0.992	0.004
13	4	0.001	0.997	0.002	0.993	0.004
14	10	0.003	1.000	0.001	0.994	0.006

Table 6. Chi-square test of observed and expected distribution of whole authors

x	f_o	f_e	f_o-f_e	$(f_o-f_e)^2$	*Chi*
1	2261	2458	-196.9	38773.5	15.8
2	609	462	146.8	21541.3	46.6
3	231	174	57.1	3258.3	18.7
4	88	87	1.1	1.2	0.0
5	56	51	5.2	27.5	0.5
6	39	33	6.3	39.6	1.2
7	23	23	0.4	0.2	0.0
8	9	16	-7.3	54.0	3.3
9	15	12	2.7	7.3	0.6
10	8	10	-1.5	2.4	0.3
11	8	8	0.4	0.2	0.0
12	6	6	-0.2	0.0	0.0
13	4	5	-1.1	1.1	0.2
14	10	4	5.8	33.2	7.8
Chi					**95.10**

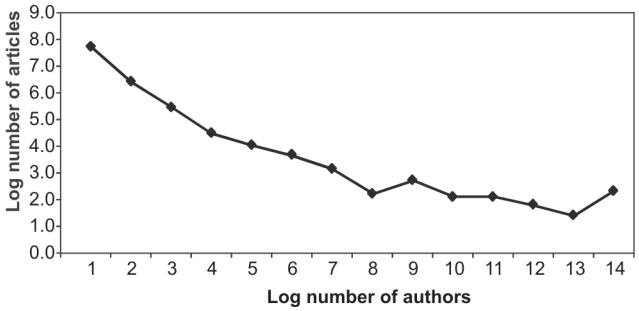

Figure 1. Log-log plot of number of authors and number of articles.

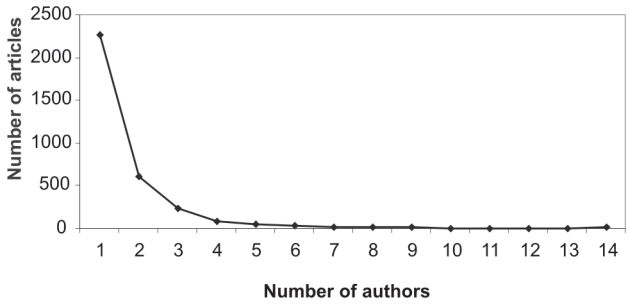

Figure 2. Plot of number of authors and number of publication.

The log-log graph in which the number of authors and their respective number of articles of the given data of physics literature are shown in Fig. 1.

The graphical representation of the author productivity data is shown in Fig. 2. The graph is plotted with number of authors in X-axis and the number of articles in the Y-axis.

7. CONCLUSIONS

Lotka's law of author productivity is regarded as one of the classical laws of bibliometric. The present study showed that Lotka' generalised law is not applicable to physics literature.

K-S test and chi-square test are applied to verify the applicability of Lotka's law of scientific productivity. The statistical tests show that the Lotka's law in its generalised form does not fit the author productivity distribution pattern prepared for the straight count and for the contribution of complete count of the University of Kerala theses citations.

This is a preliminary study on authorship productivity in the field of physics research and this study may trigger more such studies for the purpose of testing Lotka's law in the various branches of physics. Future research could be directed to authorship and productivity studies in physics based on various institutions in the country and contributions from different databases.

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