INTERNATIONAL JOURNAL OF ACADEMIC RESEARCH IN BUSINESS & SOCIAL SCIENCES
Vol 15, Issue 2, (2025) E-ISSN: 2222-6990

A Comprehensive Review and Bibliometric Analysis of Fireflies Bioluminescence from 2010 to 2023 Worldwide Trend

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To Link this Article: http://dx.doi.org/10.6007/IJARBSS/v15-i2/24547 DOI:10.6007/IJARBSS/v15-i2/24547

Published Date: 02 February 2025

Abstract
This comprehensive review and bibliometric analysis of fireflies' bioluminescence from 2010 to 2023 worldwide trend provides valuable insights into the evolving trends and maturation of the field. Utilizing data from the Scopus database, the study analyzed 2957 documents using bibliometric techniques such as co-citation analysis, bibliographic coupling, and co-word analysis. The analysis reveals a significant decline in document production, a trend possibly influenced by shifts in research focus, reduced funding, or changes in the scientific landscape. Despite the decline, the average citations per document remain relatively high, indicating ongoing relevance. The study also highlights the global collaboration trends, keyword diversity, and citation impact, offering insights into the evolving dynamics of fireflies' bioluminescence research. The findings underscore the importance of this field in various applications, including biomedical, pharmaceutical, and bioanalytical contexts, as well as its potential in technological advancements like biosensors.
Keywords: Bibliographic Coupling, Bibliometric Analysis, Bioluminescence, Co-Citation Analysis, Fireflies'

Introduction
The study of bioluminescence in fireflies has garnered significant attention in the scientific community, offering a glimpse into the mesmerizing flashing behaviour observed during their mating rituals and communication. The Firefly Algorithm (FA) is a computational optimization technique that was inspired by this natural phenomenon (Yang, 2009; Yang & Zhao, 2020). The algorithm emulates the dynamic patterns of firefly swarming and flashing and guides the optimisation procedure through the utilisation of attraction, random search movement, and light intensity variation. The Firefly algorithm aims to efficiently explore and exploit the search

space in optimisation problems by imitating the bioluminescent communication and swarming behaviour exhibited by fireflies (Yang & Zhao, 2020).

Bibliometrics refers to the application of statistical methods to analyse citation data and perform network analysis on diverse entities such as authors, journals, institutions or affiliations, nations, and keywords. Bibliometrics utilise citation and frequency analysis techniques to identify study clusters, provide insights into current research interests, and reveal trends related to developing subjects in a particular field of study (Moshobane et al., 2022). Bibliometric analysis is a method that can be employed to uncover worldwide scientific outcomes for assessing studies that have been carried out and published involving countries/institutions, journals, co-citations, influential authors, and the most influential keywords, as well as areas of active research and future directions in specific fields (Lan et al., 2024).

Understanding the structure-function relationships of the proteins involved in bioluminescence is crucial for unravelling the mechanisms underlying this fascinating phenomenon. Bibliometric analysis has been widely utilized to reveal historical development, quantify existing trends, and obtain reliable indicators showing the quality of publications (Lam & Habil, 2021). This approach allows researchers to comprehensively capture the subsequent development trends and identify influential articles, main research fields, and new research directions in the study of bioluminescence (Xiong et al., 2021; Li et al., 2022).

In addition, fireflies are widely recognised as luminous organisms, and extensive research has been conducted on the ecological aspects and response mechanisms of bioluminescence (Al-Handawi et al., 2022; Oba & Schultz, 2022). In recent times, luciferase-generated bioluminescence has emerged as an important tool in the investigation of gene regulation and expression (Orlova et al., 2003). The most investigated and important bioluminescence system is firefly luciferase. Numerous biomedical, pharmaceutical, and bioanalytical applications, among others, have been successfully implemented on account of this system's exceptionally desirable characteristics (Vieira et al., 2012). Furthermore, the FA, an optimisation technique, has garnered a lot of interest from researchers in the last few years. Utilising the responses of fireflies to the light emitted by other fireflies, this algorithm falls under the category of swarm intelligence algorithms (Blum & Li, 2008; Fister et al., 2013).

The comprehensive review and bibliometric analysis of fireflies' bioluminescence from 2010 to 2023 provide a valuable resource for researchers and scholars in this field. By synthesizing the global scientific research status, influential articles, and emerging trends, this analysis contributes to advancing our understanding of the molecular mechanisms and functional significance of bioluminescence in fireflies. In this study, we aim to explore the dynamic evolution of the field of firefly bioluminescence research from 2010 to 2023. Our primary research question (RQ) is “How has the field of firefly bioluminescence study evolved from 2010 to 2023, and what are the key trends, advancements, and gaps identified through a comprehensive review and bibliometric analysis of the relevant literature during this period?”

Materials and Methods

Criteria for Choosing Bibliometric Analysis Database

All the data executed in January 2024 on the Scopus academic database (https://www.scopus.com) by extracted publication records spanning 13 years, from 2010 to December 2023. The obtained data from Scopus was next exported to Microsoft® Excel® for Microsoft 365 MSO (Version 2311 Build 16.0.17029.20028) in the format of a.csv file, which was downloaded for analysis. The selection of the Scopus database for bibliometric analysis was based on its comprehensive coverage, structured, and detailed indexing, rendering it a widely favoured option and frequent adoption among bibliographic databases (Fister et al., 2013; Eito-Brun, 2018; Kavle et al., 2022). Scopus is an organized and indexed database for scientific production, providing capabilities for metadata export (Cobo et al., 2011). The selection of Scopus as the database examined in this study was also based on the need for trustworthy data sources in bibliometric analysis. For instance, Scopus, established by Elsevier, is the preeminent and dependable scholarly database, extensively utilized yet requiring a subscription. Conversely, Google Scholar is identified as a costless database that has issues with the quality of its data (Brika et al., 2021).

The selection of the SCOPUS database was additionally justified by its compatibility with R, a widely used programming language for graphical computations, and its ability to incorporate filters and graphs. An open-source R programming software version 4.3.2 was used in this study. The analyses of the compiled bibliography data were utilized by using Bibliometrix version 4.1.4 (Comprehensive Science Mapping Analysis), together with Biblioshiny. Biblioshiny can perform science mapping analysis using the main functions of the bibliometrix package. The employed techniques encompassed co-citation analysis, bibliographic coupling, and co-word analysis (Donthu et al., 2021). In this study, co-citation analysis identifies influential works in a research field by exploring publication relationships. Bibliographic coupling examines connections among citing publications to understand ongoing themes while co-word analysis investigates topic relationships within a field based on publication content (Donthu et al., 2021).

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)

To conduct a thorough exploration of the global trend in the bioluminescence of fireflies from 2010 to 2023, this study adhered to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) criteria. The PRISMA guidelines were followed to ensure a comprehensive and systematic approach to the bibliometric analysis review. The PRISMA guidelines have undergone an update to PRISMA 2020, enhancing both content and structure. These modifications aim to encourage wider adoption of the guideline, resulting in more transparent, comprehensive, and accurate reporting of systematic reviews (Page et al., 2021). The assessment of the quality and reliability of the review was in accordance with established practices, evaluating the relevance and appropriateness of information based on publishing guidelines. The PRISMA framework guided the adoption of key methods for the discovery and acquisition of information in this bibliometric analysis review (see fig. 1):

1. Systematic Search Strategy (Identification)

The words in a co-word analysis in this study derived and extracted from "keywords", "article titles," "abstracts," and "full texts" for the analysis. To prevent potential bias introduced by the database's regular updates, searches were confined to a single day only and a total of

2957 articles were obtained (see Table 1 for the details of the search query string used in this study). The BOOLEAN approach used in this study is (AND) as follows:

- Topic: ("Bioluminescence") AND ("Firefl*") were searched and queried by concerning on all scientific articles written in English.
- Refined by: Document type (Limited to Article).
- Publication duration: 2010-2013 (13 years).

Table 1
The search query string (Generated by authors)

Database search string	Search string strategy Boolean operators	No. of Articles
Scopus	TITLE-ABS-KEY ((("Bioluminescence") AND ("Firefl*"))) AND PUBYEAR > 2010 AND PUBYEAR < 2023 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (EXACTKEYWORD , "Bioluminescence") OR LIMIT-TO (EXACTKEYWORD , "Firefly Algorithms") OR LIMIT-TO (EXACTKEYWORD , "Optimization") OR LIMIT-TO (EXACTKEYWORD , "Firefly Algorithm") OR LIMIT-TO (EXACTKEYWORD , "Firefly Luciferase") OR LIMIT-TO (EXACTKEYWORD , "Metabolism") OR LIMIT-TO (EXACTKEYWORD , "Luminescence") OR LIMIT-TO (EXACTKEYWORD , "Luciferase") OR LIMIT-TO (EXACTKEYWORD , "Luminescent Measurements") OR LIMIT-TO (EXACTKEYWORD , "Luciferases, Firefly") OR LIMIT-TO (EXACTKEYWORD , "Firefly") OR LIMIT-TO (EXACTKEYWORD , "Luciferin") OR LIMIT-TO (EXACTKEYWORD , "Algorithms") OR LIMIT-TO (EXACTKEYWORD , "Luciferases") OR LIMIT-TO (EXACTKEYWORD , "Fireflies") OR LIMIT-TO (EXACTKEYWORD , "Bioluminescence Imaging") OR LIMIT-TO (EXACTKEYWORD , "Protein Expression") OR LIMIT-TO (EXACTKEYWORD , "Algorithm") OR LIMIT-TO (EXACTKEYWORD , "Firefly Algorithm (FA)"))	2957

2. Inclusion and Exclusion Criteria (Screening Process)

The study's data collection spans from 2010 to 2023, driven by the imperative to concentrate on recent and pertinent research within a specific timeframe. This deliberate approach enables the study to capture the latest trends, developments, and insights pertaining to fireflies' bioluminescence, ensuring that the analysis is founded on the most current information available, thus reflecting the contemporary state of the field. A specific limitation was set only to include articles (document type) in the study, emphasizing a focused and rigorous analysis on scholarly publications. By restricting the inclusion to articles, the study aims to maintain a high level of academic relevance, depth, and quality in its comprehensive review and bibliometric analysis of fireflies' bioluminescence from 2010 to 2023. This deliberate choice contributes to a more scholarly and rigorous examination of the topic.

The decision to exclusively include English language articles in this study is likely rooted in practical considerations and resource constraints. This restriction aligns with the authors' proficiency in English, facilitating easier access to and comprehension of articles published in this language. Additionally, the complexity and resource-intensiveness of translating articles from diverse languages prompted the focus on English articles, streamlining the analysis for a more efficient examination of the available literature. Moreover, English's widespread acceptance as the language of science ensures broader accessibility, reaching a more extensive audience. Figure 1 illustrates the PRISMA diagram, and the general methodological workflow employed in this study, providing a visual representation of the systematic review process and the overall research methodology.

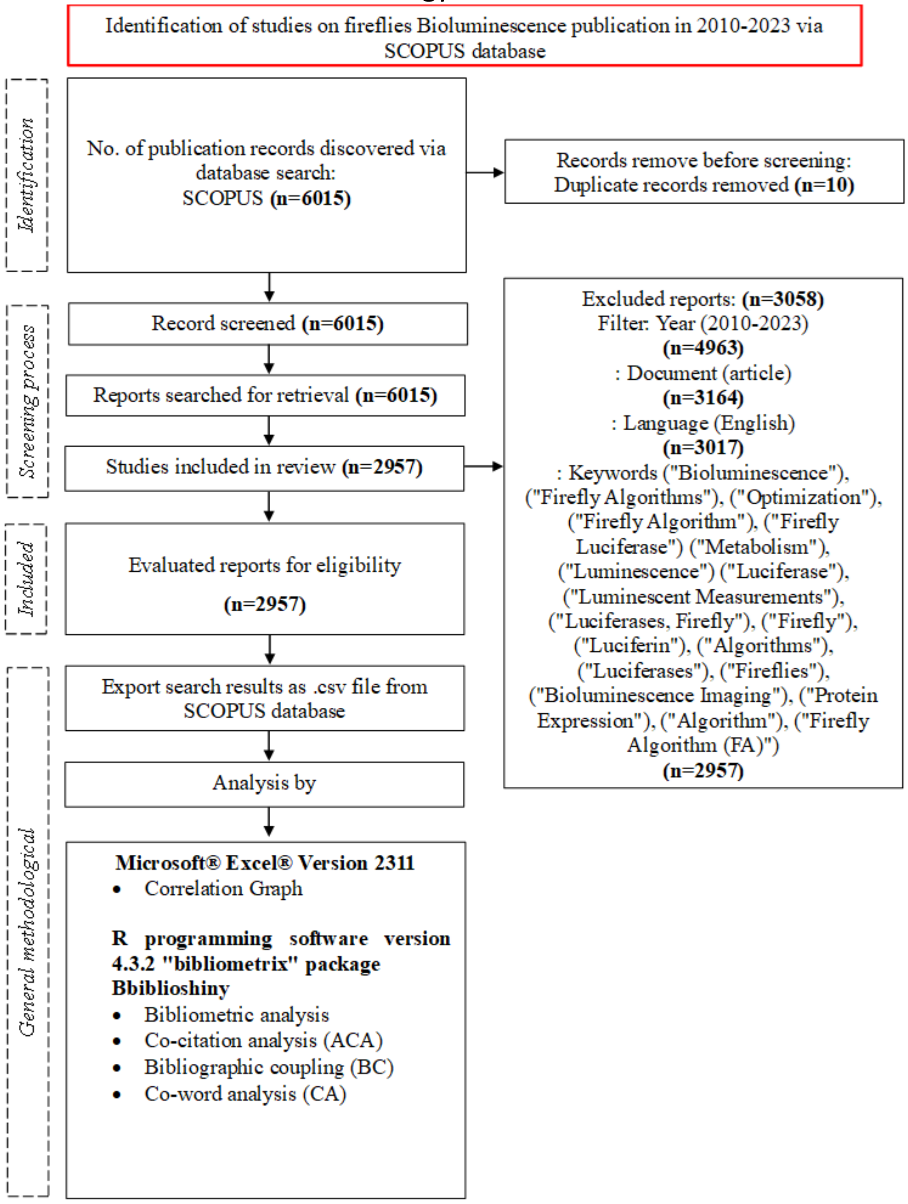

Figure 1. PRISMA diagram and General methodological workflow

Data Analysis

Several data analysis techniques have been employed in this study to unravel the dynamics of fireflies' bioluminescence research from 2010 to 2023. Bibliometric studies incorporate CA to quantitatively evaluate references within scholarly works. This method helps identify influential works, understand research collaboration, track evolving trends, and assess interdisciplinary connections within a specific field. By examining citation patterns, researchers gain insights into the impact and quality of academic publications, enabling a systematic and quantitative evaluation of the scholarly landscape. CA studies emerged with the creation of the Science Citation Index in the 1960s, which examines who researchers cite, the documents they cite, and the journals they cite (Hjørland & Nielsen, 2001; Nicolaisen, 2008; Zhao et al., 2017). While citation analysis is useful for evaluating the impact of publications, it is limited in its ability to reveal networks of connections among scholars (Rao et al., 2013).

BC, on the other hand, delves into connections among citing publications, revealing ongoing themes through shared citations, and offering insights into the intellectual structure and thematic connections within literature. The BC technique, which was initially used to identify research clusters and visualize current advancements in research (Kessler, 1963). While a novel approach for quantifying the connections between various subjects by analyzing the BC strengths was also introduced. It can facilitate the identification of fundamental works in several disciplines and aid in assessing the degree of similarity between different fields. BC quantifies connections by analyzing identical references in two separate articles. When two articles have several identical references, they exhibit a high degree of coupling strength and have a close relationship (Hsiao & Chen, 2019).

CA investigates topic relationships within the field based on publication content, exposing co-occurring terms to unveil thematic emphasis and patterns of association between concepts. CA approach relies on two primary assumptions. Firstly, the author thoughtfully selects keywords that precisely reflect the article's contents. Furthermore, the simultaneous presence of two topics in distinct publications signifies a correlation between them (Feng et al., 2017). The purpose is to highlight the co-word structure of a discipline using network visualization or maps. They also visualized the co-word structure of the auditing discipline, which supplemented the network metrics. The lines in the visualizations represent the incidence of keywords together, while the size of the nodes indicates the importance of the nodes within the network. As the node size increases, its number of connections to neighboring nodes also increases (Uyar et al., 2019).

Result and Discussions

Scientific Production

The bibliometric analysis of fireflies' bioluminescence from 2010 to 2023 encompasses 2957 documents from 1089 sources, primarily journals (Table 2). The negative annual growth rate (-27.19%) indicates a decrease in the production of documents over time. This decline could be influenced by factors such as shifts in research focus, reduced funding, or changes in the scientific landscape. The average age of documents (6.34 years) suggests that a substantial portion of the literature in the field is relatively recent. The declining trend might be a consequence of a reduced influx of new research or a slower pace of publication. While the average citations per document is relatively high (26.46), the declining trend might indicate a decrease in the overall impact or influence of the literature. This could be due to changes in research trends, emerging topics, or shifts in citation practices. The decreasing number of authors (9154) and co-authors per document (4.85) may suggest a contraction in collaborative research efforts or a decline in the number of researchers actively contributing to the field. This could be influenced by factors such as changes in funding, retirement of key researchers, or shifts in academic priorities.

The percentage of international co-authorships (22.96%) indicates a degree of global collaboration. A decline in this percentage may be due to factors like reduced international collaboration, changes in research networks, or geopolitical influences affecting collaborative efforts. The relatively high number of keywords (20911) and references (107235) reflects the complexity and depth of the literature. However, a declining trend might suggest a narrowing focus or reduced diversity in the topics covered. The total number of articles (2957) contributes to the overall understanding of the field's output. The decline could be influenced by changes in research priorities represent a potential influence, as shifting academic interests or the emergence of new scientific fields can redirect resources and efforts. It also may be driven by emerging scientific discoveries or technological advancements that draw attention to other insects.

While resource allocation and funding preferences may shift towards areas perceived as having higher scientific impact or immediate applicability. For instance, Phengodidae, which are also renowned for their bioluminescent capabilities. Consequently, the bioluminescence exhibited by Phengodidae has been thoroughly examined for its potential applications in technology, specifically in the advancement of biosensor development. Biosensors are devices that use biological molecules to detect and measure substances in the environment. Additionally, the unique properties of the bioluminescence in Phengodidae, such as its stability and brightness, make it a promising candidate for use in other biotechnological applications. However, further research is needed to fully explore the potential uses of Phengodidae bioluminescence in technology (Branham, 2005). Other animals that have captured researchers' interest for the study of their bioluminescence include Haemolymph (Vojtek et al., 2014), *Odontosyllis* (Kotlobay et al., 2019), deep-sea anthozoan (Bessho-Uehara et al., 2020), and several others.

Table 2
Bibliometric Overview (2010-2023) (Generated by authors)

Description	Results
Timespan	2010:2023
Sources (Journals, Books, etc)	1089
Documents	2957
Annual Growth Rate %	-27.19
Document Average Age	6.34
Average citations per doc	26.46
References	107235
Keywords Plus (ID)	20911
Author's Keywords (DE)	7424
Authors	9154
Authors of single-authored docs	88
Single-authored docs	100
Co-Authors per Doc	4.85
International co-authorships %	22.96
Article	2957

The annual document production from 2010 to 2023 reveals dynamic trends in research output and citation impact. In 2010, 85 documents represented 2.88% of the total, demonstrating a substantial average of 67.86 citations per document. Subsequent years witnessed changes, with 2019 reaching a peak of 297 documents (10.06%) and a moderate citation impact of 24.24. Interestingly, 2022 experienced a surge in document production, totaling 306 (10.36% of the total), but with a lower average citation impact of 6.94. The final year, 2023, contributed 8.67% of the documents, amounting to 256 publications with a minimal average citation impact of 1.59 (Table 3). The observed variations in both document production and citation impact over the years suggest evolving patterns in research intensity and impact. The decrease in average citation impact in 2022 despite a spike in document production could indicate a shift towards a larger volume of research with lower individual impact. The minimal average citation impact in 2023 further underscores the need for a nuanced understanding of the factors influencing research trends, publication patterns, and their corresponding impacts.

Several factors may lead to a decline in citation impact despite an increase in the number of publications. One possible reason is a shift towards a larger volume of research with lower individual impact, resulting in a decrease in the average citation impact. This means that while the overall number of publications may be increasing, the quality or impact of individual publications may be decreasing, resulting in a lower average citation impact. Additionally, changes in research focus, shifts in citation behavior within specific fields, and alterations in the quality of research outputs can also contribute to a decrease in citation impact (Waltman, 2016). As the volume of publications increases, a decrease in citation impact may signal a dilution of impact. It suggests that as the volume of publications grows, the average citation impact per publication may decrease due to increased competition for attention and citations within the scholarly community. This issue has been studied in the context of various fields and disciplines, and researchers have explored factors contributing to citation dilution, such as changes in publication practices, citation behavior, and the overall growth of scholarly literature (Leydesdorff & Bornmann, 2011; Waltman & van Eck, 2011; Bornmann & Leydesdorff, 2014; Donner, 2018).

The h-index has certain drawbacks as a metric for assessing research impact, one of which being its susceptibility to citation dilution. The authors suggested that alternative indicators, such as percentile-based measures, may be more resilient to this issue (Waltman & van Eck, 2011). In a 2014 study, researchers analyzed different bibliometric variables to evaluate their efficacy in predicting evaluations from peers of research quality (Bornmann & Leydesdorff, 2014). They found that citation-based indicators, such as the h-index, may be susceptible to citation dilution when applied to large datasets. This study in the field of scientometrics aims to examine the correlation between the quantity of publications and the influence of citations (Leydesdorff & Bornmann, 2011). The study found evidence of citation dilution, with a decrease in the average citation impact per publication as the number of publications increases.

Table 3
Annual Document Production and Citation Metrics Over Time (2010-2023) (Generated by authors)

Annual Document Production			Average Citation Per Year		
Year	**Documents**	**Percentage (%)**	**Mean TC per Art**	**Mean TC per Year**	**Citable Years**
2010	85	2.88	67.86	4.52	15
2011	105	3.55	40.16	2.87	14
2012	131	4.43	49.17	3.78	13
2013	174	5.88	45.21	3.77	12
2014	195	6.60	36.71	3.34	11
2015	188	6.37	32.01	3.20	10
2016	219	7.41	31.3	3.48	9
2017	227	7.68	31.81	3.98	8
2018	265	8.98	32.96	4.71	7
2019	297	10.06	24.24	4.04	6
2020	258	8.73	19.88	3.98	5
2021	250	8.47	12.42	3.10	4
2022	306	10.36	6.94	2.31	3
2023	256	8.67	1.59	0.80	2

The data indicates that there is a correlation between "Citable Years" and citation metrics such as "Average Citation Per Year" and "Mean TC per Year". As "Citable Years" decrease, both "Average Citation Per Year" and "Mean TC per Year" tend to decrease as well. For instance, in 2023, where "Citable Years" is the lowest (2), both "Average Citation Per Year" and "Mean TC per Year" are at their minimum values (0.80). Conversely, in 2010, with the highest "Citable Years" (15), "Average Citation Per Year" and "Mean TC per Year" are relatively higher (4.52) (Fig. 2). This correlation suggests that the number of citable years significantly impacts both the average citations per year and the mean total citations per year. A higher number of citable years allows for a more extended period for citations to accumulate, resulting in higher values for both average and total citations. Conversely, a lower number of citable years limits the time available for citations to accumulate, resulting in lower values for both metrics.

There is a consistent bias in the impact of citations that favors papers produced earlier in the year compared to those released later in the year (Donner, 2018). This bias is particularly evident in the citations received within the first three years after publication. Additionally, the bias is more pronounced for author self-citations compared to citations from other authors. Despite this, the study determined that excluding self-citations does not eliminate the bias entirely. The bias in citation impact based on publication month is not solely attributed to self-citations and cannot be fully addressed by excluding them from the analysis. Therefore, researchers should consider the duration over which their work remains citable, as it directly influences the citation metrics. The analysis of citable years provides context to the citation metrics, offering a nuanced understanding of the temporal dynamics of research impact. Fields or topics with longer-lasting relevance and impact may exhibit higher average and total citations over time.

Citation counts and journal impact factors lack validity as direct indicators of the quality of research and fail to encompass each aspect of it. They are frequently regarded as maximizing variables, which may motivate scientists to concentrate on trending subjects rather than making progress in their respective fields. Furthermore, these metrics are susceptible to the impact of irrelevant factors, including the length of the title and the size of the social network. Additionally, the dependability of peer review as an indicator of quality is questioned. Hence, it is advisable to practice caution when employing citation counts and impact factors as indicators of research quality (Dougherty & Horne, 2022).

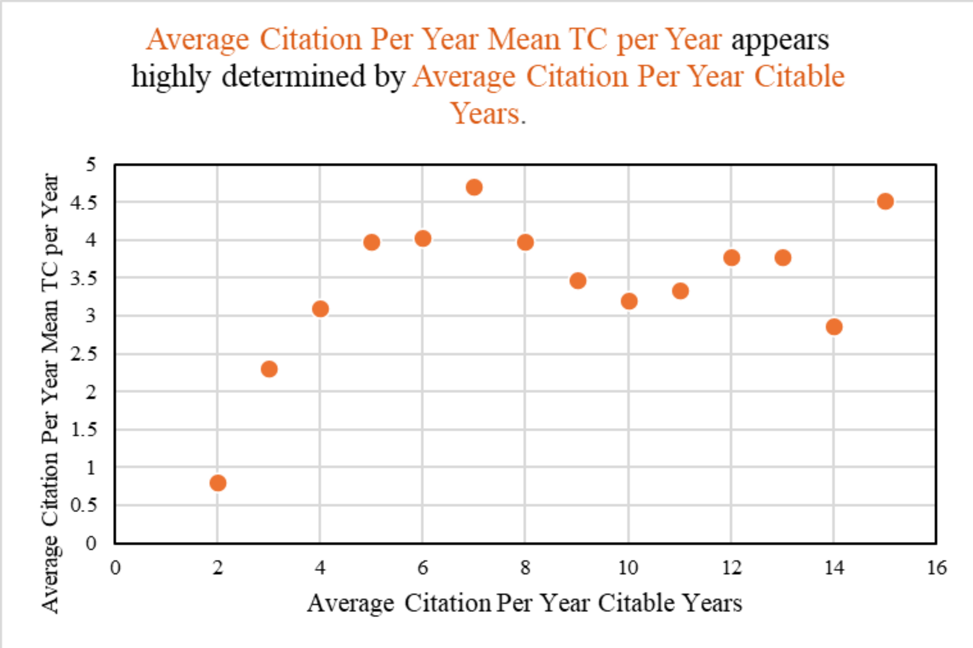

Figure 2. Correlation between Average Citation Per Year, Mean TC per Year, and Citable Years (Generated by authors)

The data indicates a strong correlation between annual document production percentage (%) and the average citation per year (Mean TC per Art). The annual document production percentage represents the proportion of documents produced in a specific year relative to the total, while the average citation per year reflects the average number of times each document is cited annually. Observing the data, there's a general pattern where years with higher document production percentages tend to exhibit higher average citation per year values. For instance, in 2019, which has the highest document production percentage of 10.06%, the average citation per year is 4.04. Similarly, in 2022, with a substantial document production percentage of 10.36%, the average citation per year is 2.31 (Fig. 3).

This correlation suggests that as the volume of research output increases each year, there tends to be a corresponding increase in the average number of citations each document receives annually. This could be indicative of a more active and influential period in the field, where a higher quantity of research is associated with a higher level of impact and recognition by the scholarly community. It's important to note that correlation does not imply causation, and various factors may contribute to this observed relationship, including the overall growth and maturation of the field during certain years. Studies conducted in 2013 have shown that higher publication output can be associated with increased citation rates, potentially indicating a greater influence of the research within the academic community (Ibáñez et al., 2013). Enhanced visibility is a key benefit of a higher publication output, as it elevates the recognition of researchers and their work within the academic community. The increased number of publications contributes to a broader awareness of researchers and their valuable contributions, fostering potential for higher citation rates as fellow scholars engage with and build upon their research.

Moreover, a higher publication output signifies diverse contributions within the field. This diversity in research endeavors explores various aspects of the subject matter, attracting attention from a wider audience. The exploration of different facets of the field enhances impact and may result in increased citation rates as scholars recognize the multifaceted nature of the contributions. Lastly, a higher publication output indicates a state of research momentum within the academic community. This active and vibrant research environment generates interest and engagement among researchers, fostering a dynamic field that progresses over time. The collaborative nature of a thriving research community can lead to increased citations as the momentum propels the collective advancement of knowledge within the field.

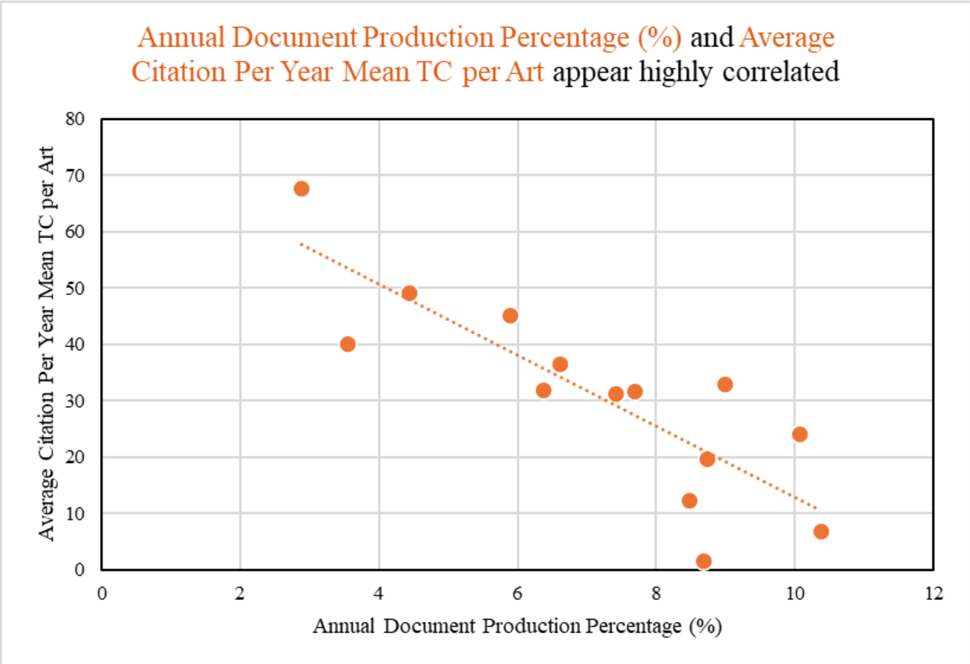

Figure 3. Correlation Between Annual Document Production Percentage (%) and Average Citation Per Year (Mean TC per Art) (Generated by authors)

The data suggests a potential correlation between annual document production and average citation per year, particularly in relation to citable years, which represent the duration during which a document is eligible for citation. This correlation is evident in the observed trends. As annual document production increases, there is a consistent trend of a decrease in both average citation per year and citable years. Notably, years with higher document production, such as 2019 and 2022, exhibit a comparatively lower average citation per year. Conversely, in years with lower document production, like 2013 and 2014, there is a distinct peak in average citation per year. This suggests that during years with fewer documents, each publication tends to receive a higher average number of citations. Possible explanations for this correlation include variations in research focus, quality, and depth of individual documents (Fig. 4).

High document production years may involve a broader range of topics, potentially diluting focus and resulting in a lower average citation per document. In contrast, years with fewer documents might indicate more concentrated or impactful research, leading to a higher average citation per document. It's important to note that correlation does not imply causation, and the intricate relationship between annual document production, average citation per year, and citable years is likely influenced by multiple factors. A comprehensive understanding of this relationship requires a more in-depth analysis, incorporating additional variables and considering the specific context of the field of fireflies' bioluminescence research.

A 2022 study revealed a negative correlation between the number of published works and the average number of citations per article (Madison & Sundell, 2022). The years with higher document production tended to demonstrate a relatively lower average citation per year. While researchers who generate a greater number of publications may be dispersing their efforts across a broader range of topics or producing work of lower quality, potentially leading to fewer citations per publication. Conversely, researchers with fewer publications may concentrate their efforts on a smaller number of high-quality publications, potentially resulting in a higher average citation per publication. It is important to note that this correlation does not necessarily imply a causal relationship, and other contributing factors may be involved.

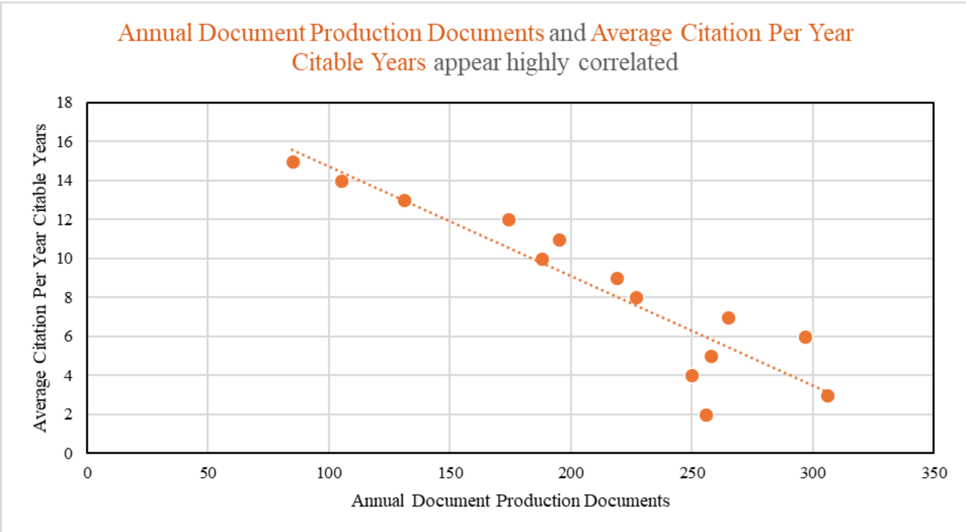

Figure 4. Correlation between Annual Document Production, Average Citation Per Year, and Citable Years in Fireflies' Bioluminescence Research (Generated by authors)

The data provided indicates a clear relationship between "Average Citation Per Year" (Mean TC per Year) and "Mean TC per Art" (Mean Total Citations per Article), suggesting a close interconnection between these two metrics. The positive correlation implies that fluctuations in the average total citations per article influence the average yearly citation rate. Both metrics exhibit a decreasing trend over the years, indicating that, on average, each article receives fewer total citations over its lifetime, and the yearly citation rate diminishes. This correlation could suggest that articles with a higher total citation count tend to maintain a relatively higher yearly citation rate (Mohammed et al., 2021), while those with lower total citations may experience a decline in their yearly citation rate. The interdependence of these metrics underscores the significance of the cumulative impact of individual articles on ongoing yearly citation patterns (Fig. 5). The comprehensive h-index (c-index) is a novel statistic that enhances the discriminatory power of the h-index by considering relative extra citation counts and uncited publications (Mohammed et al., 2021).

The c-index aims to address some of the limitations of the h-index, such as its inability to differentiate between researchers with the same h-index but different citation patterns. The c-index considers the number of extra citations received by a researcher's publications relative to the average number of citations in their field, as well as the number of uncited publications. By doing so, the c-index provides a more comprehensive and nuanced measure of a researcher's impact and productivity (Mohammed et al., 2021). While variations in the mean number of citations per article may have an impact on the average yearly citation rate, page length is an additional factor that can also influence the citation rate. A 1% increase in page length is correlated with a 0.56% increase in the number of citations (Hasan & Breunig, 2021). A recent study highlights that the number of citations has a substantial impact on academics' evaluations of paper quality, hence influencing the way of how papers are referenced (Teplitskiy et al., 2022). Papers with higher citation counts are more likely to be discovered early and read more carefully, potentially leading to more substantive citations. However, the study also reveals that exposing citation counts can decrease the perceived quality of lightly cited papers, particularly for those in the bottom half of citation counts. Additionally, highly cited papers may attract disproportionately rhetorical attention, potentially leading to an increase in rhetorical citations over time.

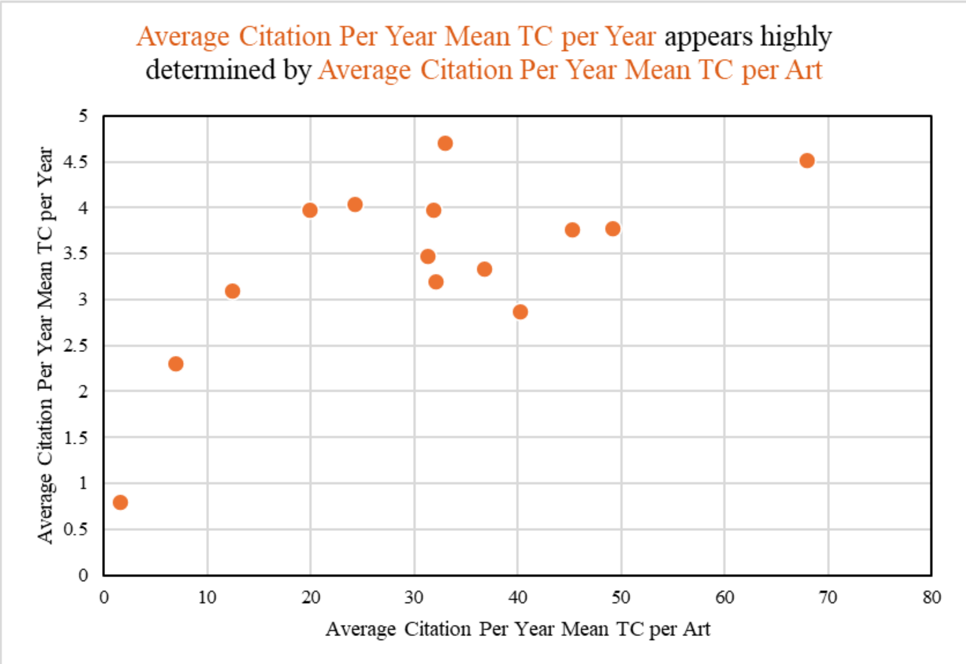

Figure 5. Correlation between Average Citation Per Year and Mean Total Citations per Year in Relation to Mean Total Citations per Article (Generated by authors)

Phases of Evolution in Firefly Bioluminescence Research in 13 Years

The landscape of fireflies' bioluminescence research underwent distinct phases from 2010 to 2023. During the Establishment Phase (2010-2012), the field experienced steady growth, with the number of documents increasing from 85 in 2010 to 131 in 2012. The average annual growth rate during this phase was around 23%, contributing to an overall cumulative percentage growth of approximately 54% from 2010 to 2012. The average citation per year was also noteworthy, with an average of 4.39 citations per document, indicating growing interest and recognition within the research community (Fig. 7).

In the subsequent Expansion Phase (2013-2019), the field demonstrated robust development, marked by a notable increase in document production. The number of documents increased from 174 in 2013 to a peak of 297 in 2019, with an average annual growth rate of approximately 9%. The cumulative percentage growth during this phase was around 71% from 2012 to 2019. The average citation per year remained stable, indicating sustained interest and impact within the field (Fig. 7).

However, in the Maturation Phase (2020-2023), the research landscape experienced a notable shift characterized by a decline in document production. The number of documents decreased from 258 in 2020 to 256 in 2023, with an average annual growth rate reflecting a decline of -11%. The cumulative percentage decrease during this phase was approximately -1% from 2019 to 2023. Correspondingly, the average citation per year also decreased, reaching 2.40 citations per document by 2023. These indicators suggest a maturation and potentially reflective phase within the field, marked by changes in research output and impact (Fig. 6).

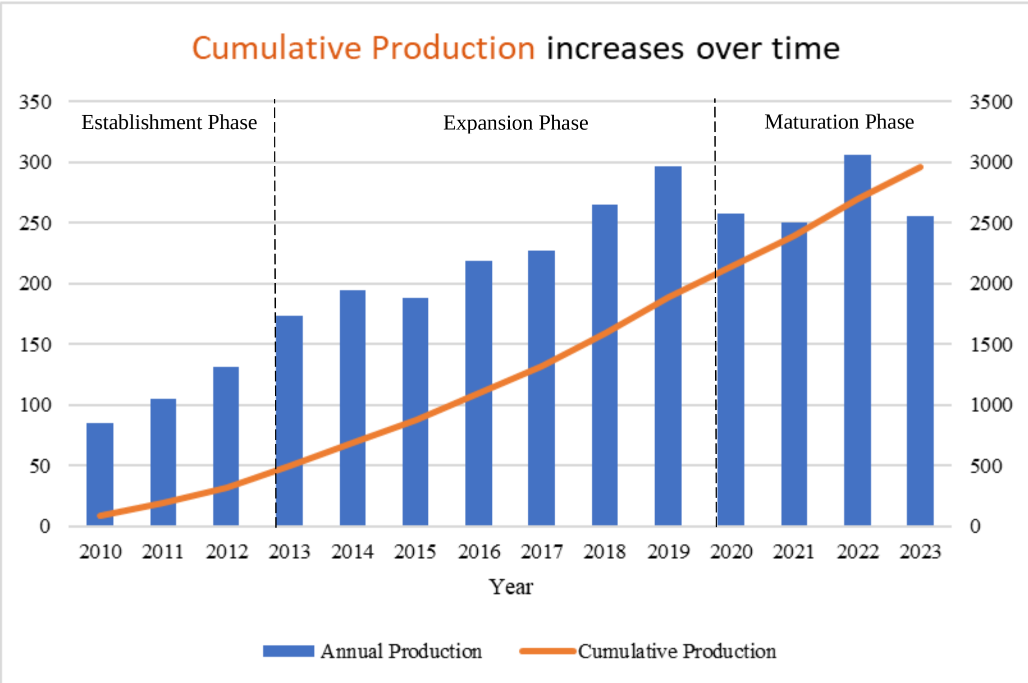

Figure 6. Evolution of Fireflies' Bioluminescence Research (Generated by authors)

Firefly Journal Metrics

The research metric known as the 'g-index' was proposed by Egghe in 2006 with the intention of addressing the limitations of the h-index. It is the greatest number by which the total number of citations for the top 'g' articles equals or exceeds g^2 (Egghe, 2006). By excluding highly cited papers from the 'h-value' and 'Hirsch core', the g-index offers a more accurate assessment of the global citation performance of a collection of articles (Ali, 2021). The 'e-index', which was introduced by Zhang in 2009, aims to rectify the issue where the h-index underestimates the number of citations by prioritizing highly cited papers (Zhang, 2009). It facilitates the assessment of scholars with comparable 'h-index' values but varying total citation counts, and it serves as a supplement to the h-index when evaluating highly cited researchers (Ali, 2021). Nevertheless, the study revealed that the h-index held greater significance in specific academic fields, including medicine and the sciences, in contrast to the humanities, social sciences, economics, and law (Kamrani et al., 2021).

Table 4 provides key bibliometric metrics for journals contributing to the field of fireflies' bioluminescence research. Noteworthy journals include "Plos One" with 64 articles, an h-index of 24, and 2029 total citations since its inception in 2010 indicates that, among its 64 articles, the most-cited 24 have each received at least 24 citations. "IEEE Access," starting in 2018, boasts 60 articles, a h-index of 20, and a high g-index of 32. "Neural Computing and Applications," initiated in 2013 with 42 articles and an h-index of 22, reflects substantial scholarly impact. Journals like "Applied Soft Computing Journal" (starting in 2021) and "Wireless Personal Communications" (since 2014) present newer entrants with promising but relatively lower metrics. "Expert Systems with Applications" stands out with an impressive h-index of 22 and 2571 total citations since 2011. "Energies," starting in 2015, shows promise with 23 articles and a solid h-index of 10. These metrics offer insights into the productivity, impact, and influence of journals in the domain of fireflies' bioluminescence research (Table 4 and Fig. 7). The analysis also suggests that these ten sources play a crucial role in the publication of articles in the specified field, and researchers may prioritize these journals for comprehensive literature reviews or to stay updated on the latest research trends.

Table 4
Journal Metrics in Fireflies' Bioluminescence Research (Generated by authors)

Sources	Articles	h_index	g_index	m_index	TC	NP	PY_start
Plos One	64	24	43	1.6	2029	64	2010
IEEE Access	60	20	32	2.857	1238	60	2018
Neural Computing and Applications	42	22	36	1.833	1318	42	2013
Soft Computing	42	17	29	1.7	891	42	2015
Applied Soft Computing Journal	34	8	13	2	237	13	2021
Wireless Personal Communications	33	12	20	1.091	434	33	2014
Journal Of Intelligent and Fuzzy Systems	29	8	17	0.667	306	29	2013
Scientific Reports	29	13	21	1.083	478	29	2013
Expert Systems with Applications	27	22	27	1.571	2571	27	2011
Energies	23	10	16	1	269	23	2015

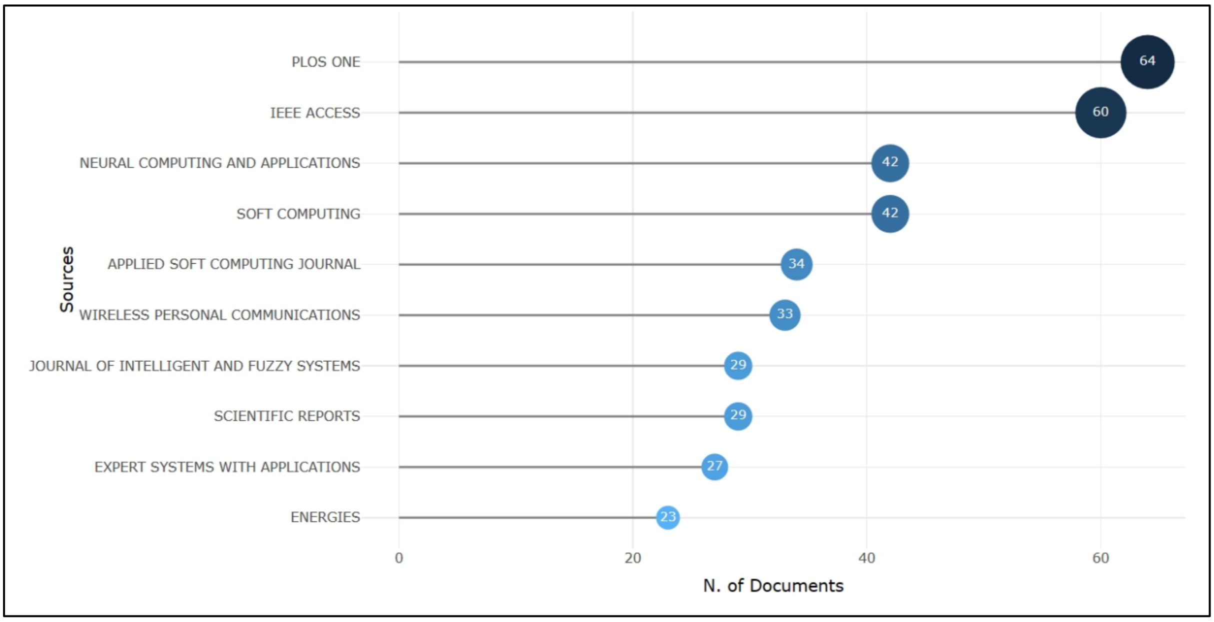

Figure 7. Most Relevant Sources (Generated by authors)

The age of a journal and the discipline or field it covers are significant determinants in bibliometric metrics such as the h-index, g-index, and m-index. When considering multidisciplinary journals such as PLOS ONE and Scientific Reports, which encompass a wide range of subjects, their extensive readership may potentially result in increased citation numbers. Specialized journals, such as Soft Computing and Neural Computing and Applications, may attract more specialized readers, which can influence their metrics due to the relative scale of their respective research communities. Emerging publications such as Applied Soft Computing Journal, which was established in 2021, may initially show lower metrics but hold the capacity to expand gradually as they acquire recognition. Journals that are older, such as Expert Systems with Applications and Journal of Intelligent and Fuzzy Systems, tend to accumulate citations for a longer duration, thereby cultivating a strong standing in their respective disciplines. Journals of diverse fields of study and age, including Applied Soft Computing Journal, Energies, and IEEE Access, present metrics that diverge. Notwithstanding the relatively recent establishment of IEEE Access, its impressive g-index indicates early recognition, whereas Applied Soft Computing Journal demonstrates potential as a newcomer. Expert Systems with Applications is a reputable journal recognized for its significant total citations and high h-index, which contribute to its enduring influence. As for Energies, a journal that was founded in 2008, it demonstrates plausible metrics that may develop further as the publication ages (Table 5).

Table 5
Characteristics of Journals (Publication Year, Industry Experience, and Field of Study) (Generated by authors)

Journal Name	Publication Year	Years in the Industry (as of 2023)	Field of Study
PLOS ONE	2006	17 years	Multidisciplinary
IEEE Access	2013	10 years	Electrical engineering, computer science, and electronics
Neural Computing and Applications	1992	31 years	Neural computing and applications
Soft Computing	1997	26 years	Soft computing
Applied Soft Computing Journal	2001	22 years	Applied soft computing
Wireless Personal Communications	1995	28 years	Wireless communications
Journal Of Intelligent and Fuzzy Systems	1991	32 years	Intelligent systems and fuzzy logic
Scientific Reports	2011	12 years	Multidisciplinary
Expert Systems with Applications	1988	35 years	Expert systems and applications
Energies	2008	15 years	Energy

Corresponding Author's Countries

Table 6 and Fig. 8, highlight that China and India are leading in research output, contributing 598 and 508 articles, respectively. The SCP values signify the number of solo-authored articles, emphasizing individual contributions, while MCP values underscore collaborative efforts involving multiple corresponding authors. The MCP_Ratio serves as a crucial metric, portraying the proportion of collaborative articles in each country's total output, with higher values indicating more frequent collaboration. Examining notable patterns, Malaysia stands out with a notably high MCP_Ratio of 0.509, suggesting a substantial prevalence of collaborative research efforts within the country. Interestingly, the USA, despite having the third-highest research output, exhibits a comparatively lower MCP_Ratio, implying a smaller proportion of collaborative articles relative to its total output. High collaborative ratios may reflect a culture of teamwork and joint research initiatives, while lower ratios may suggest a preference for individual authorship or fewer multi-author collaborations, potentially influencing research culture and dynamics.

Several factors contribute to the high research output in certain countries, such as China: a robust funding mechanism and a well-established research infrastructure. Decades-long acceleration in China's scientific output can be attributed to the country's large investments in R&D. In 2022, China surpassed the United States in the Share score of the Nature Index in the category of natural sciences. This milestone signifies a noteworthy achievement in scientific contributions. Furthermore, in 2022, China surpassed the United States in a key metric, as reported by the National Institute of Science and Technology Policy in Japan: the number of papers whose contributions appeared in the top 1% of most-cited publications. Ahead of the international scientific community, these developments underscore China's expanding influence and leadership. Research papers originating from China frequently show a notable degree of innovation (Woolston, 2023). Papers that include at least one co-author from China are more susceptible to surpassing this limit compared to those that do not. The paper is also of high quality, with an emphasis on novelty (Wagner et al., 2022).

The Open Access (OA) policies and mandates in India, particularly the OA policy implemented by the Council for Scientific and Industrial Research (CSIR) to promote the accessibility of research, have pushed India to the second-highest position in the publication rankings. By publishing in an OA journal or depositing the full-text and metadata in an institutional repository, this policy mandates that all CSIR-funded research papers become OA. Furthermore, it is expected that every CSIR laboratory will create interoperable institutional open access repositories to store research papers, theses, and dissertations. The CSIR-unit for research and development of information products (URDIP) will utilise a central harvester to retrieve these materials. A draft of the new science policy, "Science, Technology, and Innovation Policy 2020," seeks to guarantee extensive accessibility to scholarly knowledge, notwithstanding the absence of a national OA policy in India at present. The "one nation, one subscription" model posits that to establish a nationwide open access policy, the government will engage in negotiations with prominent scientific journal publishers. Under the terms of this proposal, all published material in India will be accessible to all for a single, centrally agreed-upon payment; a single payment mechanism is recommended for reputable APC-based journals. Moreover, fraudulent publishers shall be ineligible for participation in the scheme (Nazim et al., 2023).

The United States is ranked among the top three countries in terms of publishing, primarily due to multiple factors such as a substantial number of science and engineering PhD graduates, a significant quantity of federal research funding, and an intense focus on research support. Moreover, the United States has a long history of allocating resources towards scientific research and development, resulting in the establishment of a solid foundation for scientific advancement and innovation (Hather et al., 2010). The industry of publishing in Malaysia is influenced by initiatives from the government, market demand, and demographic trends. The Malaysian government actively advocates for the promotion of reading and publishing, with the objective of digitizing publications and multiplying the yearly count of new titles. Given the presence of a youthful demographic, there exists a need for literature specifically tailored to children and adolescents. The age composition of the population has a significant impact on the market demand, especially for self-help publications. Furthermore, as digital publishing continues to develop, prominent publishers are acknowledging its significance and initiating the conversion of books into e-book forms. The National Library serves as a prominent purchaser of e-books for its lending library (Lingard, 2016).

Table 6
Geographical Distribution of Corresponding Authors (Generated by authors)

Country	Articles	SCP	MCP	Freq	MCP_Ratio
China	598	480	118	0.202	0.197
India	508	456	52	0.172	0.102
Usa	336	252	84	0.114	0.25
Iran	181	145	36	0.061	0.199
Japan	131	118	13	0.044	0.099
Korea	62	51	11	0.021	0.177

Malaysia	57	28	29	0.019	0.509
Brazil	56	46	10	0.019	0.179
United Kingdom	55	30	25	0.019	0.455
France	40	23	17	0.014	0.425
Australia	34	13	21	0.011	0.618
Turkey	32	30	2	0.011	0.063
Egypt	27	16	11	0.009	0.407
Germany	26	13	13	0.009	0.5
Algeria	24	17	7	0.008	0.292
Portugal	24	20	4	0.008	0.167
Saudi Arabia	22	11	11	0.007	0.5
Netherlands	20	9	11	0.007	0.55
Belgium	19	12	7	0.006	0.368

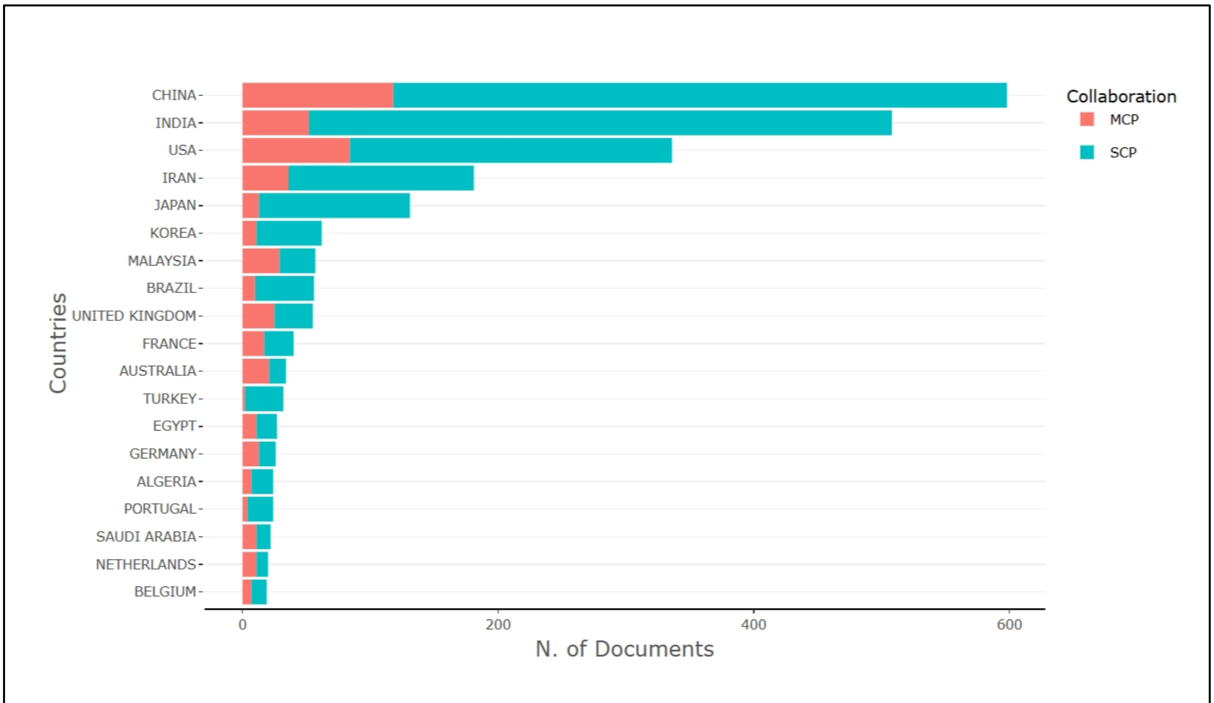

Figure 8. Geographical Distribution of Corresponding Authors (Generated by authors)

Countries' Scientific Production

Table 7 provides a comprehensive overview of global scientific production by country, highlighting the research contributions of various nations. China leads the list with 3457 scientific productions, showcasing its substantial and influential role in shaping global research trends. The United States follows closely with 2735 scientific outputs, maintaining its position as a key player in the international research landscape. India secures the third position with 1649 scientific productions, reflecting its increasing emphasis on research and development and growing impact on the global scientific community. Other notable contributions come from Japan, Iran, South Korea, the United Kingdom, France, Brazil, and Germany, each with varying frequencies of scientific productions.

In recent years, China has become a prominent producer of scientific research, surpassing western OECD countries. The analysis confirms have been done in 2022 shows that China's remarkable progress in the global scientific competition may be attributed primarily to its consistent and massive spending in scientific research, surpassing that of traditional scientific countries. Hence, it is proposed that governmental allocation of funds towards research and higher education serves as the primary means to foster, maintain, and preserve successful scientific output. While United States has also historically occupied an important position in global scientific productivity, providing significant contributions to research output across a wide range of disciplines. Nevertheless, there is a significant trend showing a decrease in the country's worldwide publication percentage in all fields between 1998 and 2018 (Courtioux et al., 2022). The notable decline in scientific production should be considered, particularly in relation to a country's economic level. It is important to recognize that high-income nations like the United States have a substantial impact on global science and engineering articles (Elango et al., 2021).

India's global publication share, and rank underwent a notable increase, with its global rank increasing from 13th in 1998 to 5th in 2018. This indicates a major growth in scientific productivity. Furthermore, India consistently achieved an annual growth rate of 10% in its publishing production from 1998 to 2018, demonstrating an encouraging and stable trend in scientific productivity. Furthermore, India has attained the highest number of citations per paper (CPP) in the subject field of chemical engineering, showcasing the excellence and influence of its publications in this specific discipline. Nevertheless, India had the poorest CPP in the field of veterinary sciences, suggesting disparities in the caliber of published research in various academic areas. Still, India's scientific productivity has shown consistent increase and progress over the years (Elango & Oh, 2022).

Table 7
Global Scientific Production by Country (Generated by authors)

Region	Frequency
China	3457
Usa	2735
India	1649
Japan	923
Iran	641
South Korea	476
Uk	373
France	289
Brazil	274
Germany	254

Conclusion
The bibliometric analysis of fireflies' bioluminescence research from 2010 to 2023 provides several important insights. There has been a notable decline in the production of documents, which may be attributed to changing research priorities, reduced funding, or shifts in the scientific landscape. Despite this, the field continues to exhibit a relatively high average of citations per document, reflecting the ongoing impact and relevance of the research. The analysis indicates a contraction in collaborative research efforts and a decline in the number of researchers actively contributing to the field. This trend might be influenced by changes in funding, the retirement of key researchers, or shifts in academic priorities. The study also

underscores the adaptability and application of the firefly algorithm in various fields, beyond natural bioluminescence. Overall, this review provides a valuable resource for understanding the evolution of firefly bioluminescence research, highlighting both the advancements made and the challenges faced in the field.

This research significantly advances both theoretical knowledge and practical applications in the field of firefly bioluminescence. It theoretically enhances the knowledge base through providing a comprehensive bibliometric analysis that delineates dominant trends, significant research clusters, and developing gaps in the investigation of fireflies' bioluminescence. The study highlights the interdisciplinary character of bioluminescence research by tracking the evolution of the field, integrating ecological, biochemical, and computational sciences. Contextually, the findings are relevant for improving conservation initiatives, directing sustainable practices, and informing technological advancements. The understanding of firefly bioluminescence, for example, has ramifications for the development of biosensor technologies and bioanalytical applications, which are essential for environmental and medical monitoring.

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