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New Insight Into The Research Of Deep Learning Applications In Finance: A Scientometric Approach

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Abstract—
This study analyzed the research environment for the applications of deep learning in finance (DLAF) based on published papers indexed in the Scopus database from 2007 to 2021. As a result, the publication trends of the published documents were analyzed to identify the most prolific writers, institutions, nations, and funding organizations on the subject. Subsequently, bibliometric analysis (BA) was utilized to examine and delineate co-authorship networks, keyword occurrences, and citations. A systematic literature review was conducted to analyze the scientific and technological advancements in the subject. The findings indicated that the quantity of published documents on DLAF study escalated significantly from 5 to 398 between 2007 and 2021, representing an extraordinary increase of around 7,900% in this field. The elevated production is somewhat attributed to the research endeavors of the foremost research-active academic entities, specifically Chihfong Tsai (National Central University, Taiwan) and Stanford University (United States). The National Natural Science Foundation of China (NSFC) is the most prolific funder in the United States and has the highest volume of published documents. Business study indicated elevated collaboration rates, published documents, and citations among the stakeholders. Keyword occurrence analysis indicated that DLAF research is a highly interdisciplinary field with several focal points and themes, encompassing systems, algorithms, methodologies, as well as security and crime prevention in finance through deep learning applications. According to citation analysis, the most distinguished and prestigious source titles on DLAF are IEEE Access, Expert Systems with Applications, and ACM International Conference Proceedings Series (ACM-ICPS). The comprehensive literature review identified several domains and applications of DLAF research, notably in predictive analytics, credit assessment and management, supply chain, carbon trading, neural networks, and artificial intelligence, among others. DLAF research activities and their influence on the broader global community are anticipated to escalate in the forthcoming years.

Keywords— Deep Learning; Applications; Bibliometric Analysis; Systematic Literature Review, Artificial Intelligence

I. INTRODUCTION

The historical origins of deep learning (DL) date back to the early 1950s and 1960s when researchers sought to reproduce human learning using computer programs [1]. DL is reported to have evolved from the twin fields of conventional statistics and artificial intelligence (AI) to create effective data-based models [2]. Over the years, the quest has grown into one of the hottest computational science areas. As a result, DL has resulted in the growth and development of various techniques that collect, process, and utilise data for various applications. Given this, numerous researchers have proposed numerous definitions of the concept based on various theoretical and empirical perspectives in the scientific literature. According to Mitchell and Mitchell [3], DL broadly speaking is any field of research dedicated to the full comprehension of knowledge based on developed techniques that learn or leverage data to enhance the performance of some designated tasks.

In general, DL has been described as a field of study that employs computational algorithms to transform experimental data into usable models [2]. Likewise, DL has been defined as a multi- and interdisciplinary field adapted from AI principles with the objective of "teaching" computers how to seek relationships in data [4, 5]. In principle, DL can be defined as the capacity of any computer-based system to obtain and incorporate knowledge through extensive observations [6]. According to Woolf [6], the definition extends to the system's independent capability to enhance and expand the frontiers of the acquired knowledge through the process of learning new knowledge as opposed to being programmed. Furthermore, the definition highlights DL as an integrated process or procedure that collects, and processes large volumes of data typically utilized to generate models.

Given the broad definitions, DL has been developed and implemented for various applications, particularly in the current global era of big data and analytics. For example, DL is used for detecting, understanding, and predicting irregular behaviour or patterns in various cyber-based phenomena, processes, and systems around the globe [2]. It is also used to leverage modern platforms for processing parallel data [7]. In addition, DL provides an integrated structure for establishing intelligent domains for making informed decisions [8]. The concept is also widely applied in forecasting, quality assessments, or performance optimization employing different algorithms [4, 5]. With the use of DL, computers can also be trained to perform varied tasks such as calculations, clustering, and identifying trends in data. In addition, DL can be used for problem-solving tasks and processes such as collecting, classification, regression, and determination of association rules [9].

Given its versatility, DL has created novel opportunities for various innovations in academia, industry, as well as policy and governance. One such area in that DL has shown great promise in recent times is the areas of economics, energy, and finance. The application of DL in finance has been widely reported in the literature. For example, DL has been widely applied in the finance related topics and areas such as signal processing and portfolio selection [10], criteria identification and classification [11], and scenario (e.g., supply chain finance, credit risk assessments) prediction and forecasting [12-15]. Other researchers have employed DL in quantitative finance topics and areas such as fast pricing, hedging, and fitting of derivatives [16], as well as asset management [17], and developing various financial products [18]. DL algorithms deployed with quantum computers have also been applied to portfolio optimization [19], whereas Boughaci and Alkhawaldeh [20] demonstrated the applicability of DL for credit scoring and predicting bankruptcy in finance. With the growing calls for the integration of sustainability strategies in all spheres of human endeavour, DL has also been applied to the area of carbon finance. The study by Nguyen et. al., [21], sought to examine the corporate carbon footprints for risk analysis in climate finance using DL. The study demonstrated the applicability of DL in predicting the carbon emissions of corporations to enhance risk analyses by potential stakeholders.

Further review of the literature on deep learning in finance (or DLAF) research showed that the research landscape on the subject area is broad with numerous publications on the theories/foundations, themes, and applications existing in various databases. For example, the search on the Elsevier database revealed 2,418 documents based on the "TITLE-ABS-KEY" search criteria. Despite a large number of published documents on the subject area, there have been just two thematic reviews on the subject by Kumar et. al., [22] and Goodell et. al., [23]. In the study by Kumar et. al., [22], the application of DL in digital credit scoring in rural finance was examined using a systematic literature review. The findings also showed that the study is focused on the application of DL in a branch of finance and its application in agriculture. In contrast, Goodell et. al., [23] presented a bibliometric analysis (BA) of the application of DL (as a branch of AI) in finance with a focus on highlighting the fundamental themes and research clusters on the subject area. In the study, the authors adopted co-citation and coupling analyses to examine the DLAF research but excluded vital BA analysis techniques such as co-author (CA), keyword occurrence (KO), and citation (CT) analyses. The absence of CA, KO, and CT, creates a research gap which limits comprehensive analysis of the research landscape on DLAF research.

As a result, the primary goal of this work is to critically assess the DLAF research landscape using published materials on the topic that were indexed in the Elsevier Scopus database from 2007 to 2021. Additionally, a thorough analysis of the topic's primary stakeholders, funding sources, and publication trends will be done. The evolution, development, and implementations of DLAF research will also be examined using a comprehensive literature review.

The responses to these relevant issues will offer crucial understandings of the research landscape, scientific growth, and technological developments in DLAF research. The findings will also significantly benefit current and future researchers by offering an overview of the current status and future developments in the subject area of DLAF research.

II. METHODOLOGY

The objective of this paper is to examine the current and future trends in the application of Deep Learning in Finance (DLAF) through bibliometric analysis. Consequently, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach [24, 25] was adopted to detect, select, and assess the data on the published documents on the DLAF topic from the Scopus website. Figure 1 presents the schematic diagram for the PRISMA scheme used for the identification, screening, and analysis of DLAF and related documents on the topic in the scientific literature. First, the search query "Deep Learning" AND "Finance" was developed based on the title keywords before executing the search in the Scopus database to recover related publications from 2007 to 2021. A period of 15 years was selected to obtain sufficient related documents, typically >5 published documents per year and >200 publications in total, which is required for conducting a complete bibliometric analysis [26].

The executed search results recovered a total of 1,925 document results based on the TITLE-ABS-KEY search criterion, which was subjected to screening to remove irrelevant documents. The selected screening procedure was executed using the "LIMIT-TO" and "EXCLUDE" search query functions and Boolean operators "AND" and "OR" as shown in the Search query code below:

TITLE-ABS-KEY ("deep learning" AND "Finance") AND PUBYEAR > 2006 AND PUBYEAR < 2022 AND (LIMIT-TO (PUBSTAGE,"final")) AND (LIMIT-TO (DOCTYPE,"cp") OR LIMIT-TO (DOCTYPE,"ar") OR LIMIT-TO (DOCTYPE,"re")) AND (LIMIT-TO (LANGUAGE, "English")) AND (EXCLUDE (LANGUAGE,"Chinese")) AND (LIMIT-TO (SRCTYPE,"p") OR LIMIT-TO (SRCTYPE,"j"))

As can be seen, the screening process limited the final search results to the Document types (Conference Proceedings, Articles, and Reviews), Source type (Conference Proceedings, and Journal), and Language (English). 1,518 documents were ultimately released following screening; these documents were subsequently examined to determine the DLAF 's

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publication tendencies. Next, a bibliometric analysis was done to look at the networks of co-authorship (CA), keyword occurrence (KO), and citation trends (CT) for the subject. The selected conditions for CA, KO, and CT analyses are defined in section V of the paper.

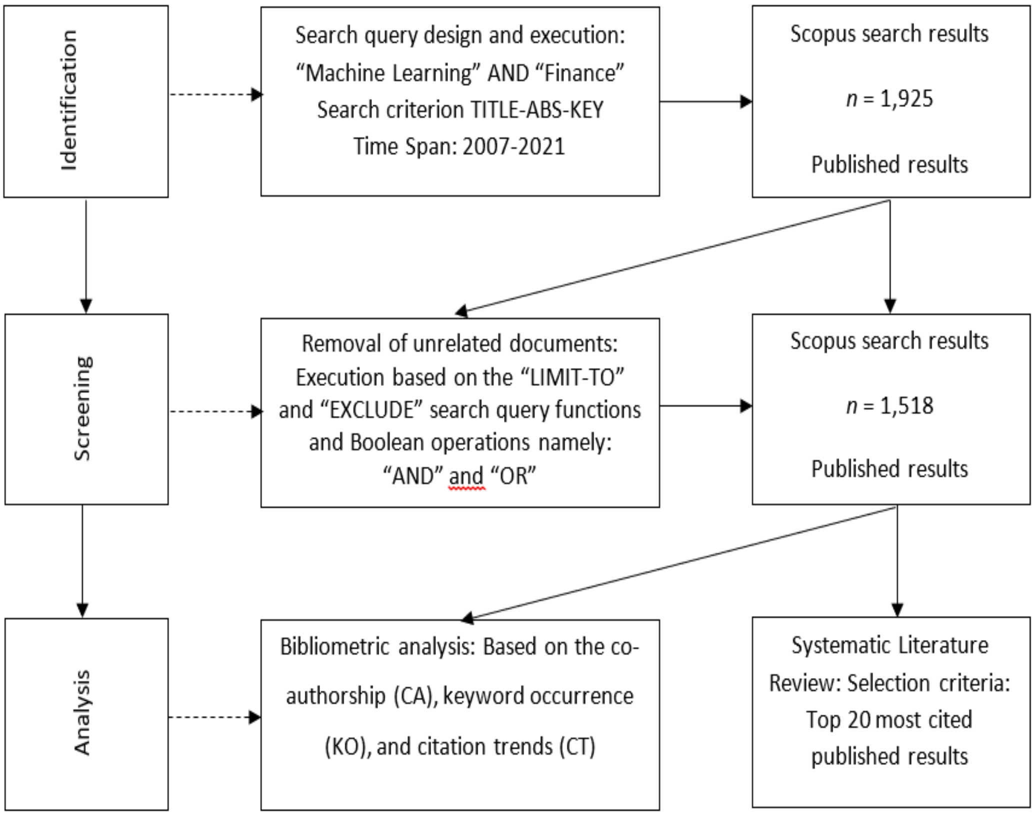

Fig. 1 Design for gathering, screening, and analyzing DLAF Research articles

III. Result and Discussion

A. Publication Trends

The degree of output on the topic over time was examined using a rigorous study of the publication trends on DLAF research from 2007 to 2021. Figure 2 displays a plot of the total annual published document output for the 15 years under consideration. As seen in the gradually rising curve, the number of published documents climbed steadily from 5 to 398 between 2007 and 2021. The data reveals that there was a 7,860% increase in the number of publications on the subject, which signals an enormous increase in scientific interest in the topic. However, a more critical analysis of the publication trends data based on 5-year intervals was carried out. The findings show that interest in the topic was rather low in Phase I (2007-2011) based on the low total number of publications (n = 70). In contrast, the total number of publications is 208 and 1,240 for Phase II (2012-2016) and Phase III (2017-2021), respectively. The observation shows that there was a 197.14% and 1,671.43% increase from PI to PII and PI to PIII, respectively, show interest in the topic increased considerably from 2007 to 2012 and 2017.

The steep rise in the number of published documents on DLAF after 2017 could be accredited to several factors notably the growing global importance of big data (BD). In principle, BD is defined as large sets or volumes of complex data that have been generated at various speeds and ambiguity and as such cannot be processed through conventional algorithms or programmes for data processing [27]. BD can be derived from numerous sources ranging from traffic cameras, weather satellites, and Internet of Things (IoT) devices to social media [28]. It is characteristically comprised of three important factors or 3 V's namely, variety, volume, and velocity – a definition that is largely based on the early definition proposed by Doug Laney in the early 2000s [28].

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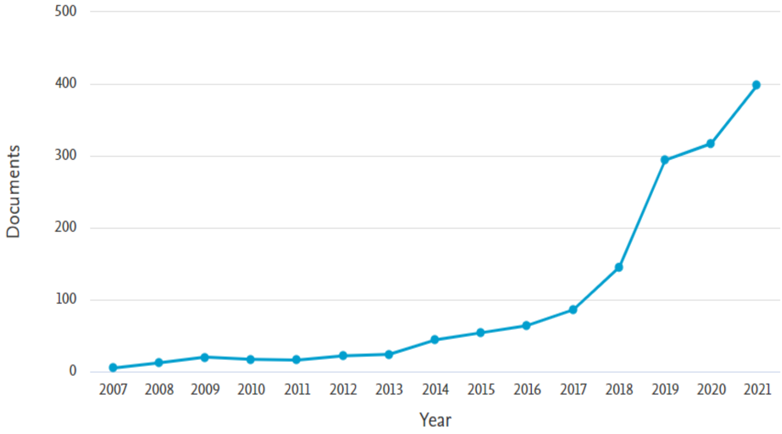

Fig. 2 Published documents per year on DLAF Research (2007-2021)

In current times, BD has become an important tool for utilizing large volumes of data to detect patterns and analyse problems [29]. According to SAP, big data is used by many companies to improve processes, products, and policy decisions worldwide [28]. Given its importance, the world of finance has also embraced BD to drive the growth and development of businesses around the world. Likewise, the rising prominence of BD has prompted increased research interest in the application of DL in finance, which is evident in a large number of publications on the subject as shown in **Error! Reference source not found.**. Further analysis also shows that the increase in published documents is also evident in the variety of document types on the subject. Figure 3 displays the breakdown of DLAF document types in the Scopus database over the study's time frame.

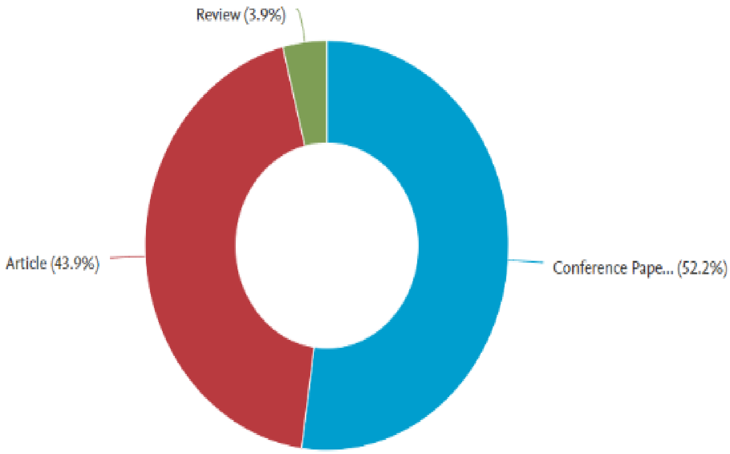

Fig. 3 Distribution of document types on DLAF research (2007-2021)

As can be seen, "Conference proceedings" (CP) which represent 793 published documents account for the largest share of the total publications. The lead of CP is closely followed by "Articles" (AR), which account for 666 published documents compared to 59 for "Reviews". Based on the results, it can be perceptively deduced that CP is the most preferred document type for researchers working on DLAF research topics worldwide. The reason for this observation may be due to the relative ease and speed of disseminating scholarly findings at conference meetings or workshops organised by peers in any field when compared to the publishing of articles. Typically, the process of publishing scientific findings in articles requires peer review, which although a crucial step in the scholarly process, could be rather lengthy and arduous for the researchers/scientists working in the industry [30].

Nonetheless, the publication of scholarly findings as articles in journals is still considered *de rigueur* for researchers and scientists in academia. Hence, the objective is to publish in peer-reviewed, prestigious, and high-impact journals, which are typically associated with academic excellence and scholarly prestige in the selected subject area. Similar to this, DLAF researchers frequently publish their findings in specialized journals or reference works. Based on information from the Scopus database, Table 1 lists the top 10 journals that academics in the subject of DLAF find most useful.

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TABLE TOP 10 JOURNALS SOURCES FOR DLAF RESEARCH

Source Title	TP	%TP	Source Type
ACM International Conference Proceeding Series	55	3.62	Conference Proceedings
IEEE Access	43	2.83	Journal
Expert Systems with Applications	32	2.11	Journal
Procedia Computer Science	26	1.71	Conference Proceedings
Ceur Workshop Proceedings	18	1.19	Conference Proceedings
Journal of Physics Conference Series	17	1.12	Conference Proceedings
Applied Soft Computing Journal	13	0.86	Journal
Neurocomputing	13	0.86	Journal
Proceedings of the ACM SIGKDD International Conference on Knowledge Discovery and Data Mining	11	0.72	Conference Proceedings
European Journal of Operational Research	9	0.59	Journal

TP – Total publications; %TP – Percentage total publications

As seen, the top 10 journal sources that publish works on DLAF largely comprise Conference Proceedings and Journals each accounting for 50% of the total. Further analysis shows that the top 10 journal sources account for 237 published documents or approximately 15.61% of the total publications on the subject area, which is significant considering that 115 sources have published at least 2 published documents. Hence, the sources in Table 1 can be considered the most prolific and by extension the most prestigious on the subject considering the high preference to publish in them. In particular, the *ACM International Conference Proceeding Series* (ACM-ICPS) and the *IEEE Access* are the most sought-after conference proceedings and journals, on the subject area respectively. The ACM-ICPS is published by the Association for Computing Machinery headquartered in New York, USA. According to its 2021 Scopus metrics, the ACM-ICPS has a CiteScore 1.0, SJR 0.232 and SNIP 0.310, while it is grouped into various Computer Science categories (e.g., software, Computer Vision and Pattern Recognition, and Human-Computer Interaction). However, the *IEEE Access* journal is published by the Institute of Electrical and Electronics Engineers headquartered in New York, USA. Based on its 2021 Scopus metrics, the journal has Citescore 6.7, SJR 0.927, and SNIP 1.326 while it is grouped into Engineering, Computer Science, and Material Science categories in the Scopus database.
The analysis shows that the prestige and reputation of the source type are critical factors for researchers seeking to publish their works. Hence, the more prestigious a source title, the higher the likelihood of the researchers particularly the top players in the field to publish in them. Likewise, the reputation of the source types also plays a crucial role in the future citation rates as well as the research impact of the published documents. To further examine this submission, the top 10 most cited published documents on the DLAF research were examined as shown in **Error! Reference source not found.**. The selection criterion was the retrieval of published documents with over 100 citations to date.

The findings show that the top 10 most cited published documents on the DLAF have a combined 5249 citations (or 142.22 on average). The most cited is "Identifying nonlinear dynamical systems sparsely to find governing equations from data" by [31], whereas the most cited is "Mining corporate annual reports for intelligent detection of financial statement fraud – A comparative study of deep learning methods" by [77]. Further analysis showed that the most common document type is articles with 32 published documents (or 54% of the top 10 most cited), whereas conference proceedings and reviews each account for 9 each (or 21% of the top 10 most cited). The analysis of the source type revealed that the top sources are *Expert Systems with Applications* (6 published documents), *European Journal of Operational Research* (4 published documents), *Applied Soft Computing Journal* (3 published documents), and *Neurocomputing* (2 published documents). The findings confirm the earlier submission (*see* **Error! Reference source not found.**) that Expert Systems with Applications is a top source for DLAF research studies, which may also explain its reputation, citation profile, and attraction by the top researchers in the subject area. Section II will identify and highlight the top researchers or scientists working in the subject area of DLAF Research based on data retrieved from the Scopus database from 2007 to 2021.

TABLEII TOP 10 MOST CITED PUBLISHED DOCUMENTS ON DLAF RESEARCH (2007-2021)

References	Title	Source Title	Cited by	Document Type
Brunton et. al., [31]	Identifying nonlinear dynamical systems sparsely to find governing equations from data	Proceedings of the National Academy of Sciences of the United States of America	1220	Article
Fischer and Krauss [32]	Deep learning using lengthy short-term memory networks to forecast financial markets	European Journal of Operational Research	719	Article
Hirschberg and	Natural language processing	Science	525	Review

Manning [33]	improvements			
Gabrel et. al., [34]	A review of recent achievements in robust optimization	European Journal of Operational Research	511	Review
Patel et. al., [35]	Forecasting stock and stock price index movement using machine learning and trend deterministic data preparation	Expert Systems with Applications	478	Article
Dwivedi et. al., [36]	Multidisciplinary perspectives on new issues, opportunities, and a research, practice, and policy agenda in artificial intelligence (AI)	International Journal of Information Management	436	Article
Nelson et. al., [37]	LSTM neural networks are used to anticipate the price movement on the stock market	Proceedings of the International Joint Conference on Neural Networks	352	Conference Paper
Tsai and Wu [38]	Utilizing neural network ensembles in credit scoring and bankruptcy prediction	Expert Systems with Applications	342	Article
Dosilovic et. al., [39]	A survey on explainable artificial intelligence	2018 41st International Convention on Information and Communication Technology, Electronics and Microelectronics, MIPRO 2018 - Proceedings	336	Conference Paper
Gunning and Aha [40]	DARPA's explainable artificial intelligence program	AI Magazine	330	Article

B. Top Authors and Institutions

The analysis of the top researchers and institutions on DLAF research was examined based on information retrieved from the Scopus database between 2007 and 2021. The objective is to analyse the research landscape on the subject area based on the major stakeholders. As can be seen, the top 10 authors on DLAF research have published ≥ 4 or 49 (or 4.9 on average or 3.23% of TP) documents over time. The top or most prolific author (defined as the researcher with the highest number of publications) on DLAF research is *Chihfong Tsai* (CT) with 7 published documents. CT is based at the National Central University (Taiwan) and has published notable works which have been cited a combined 894 times over the years. The most notable published work "Using neural network ensembles for bankruptcy prediction and credit scoring" published in *Expert Systems with Applications* has gained 342 citations to date. The 2nd most prolific author on DLAF is *Chienfeng Huang* (CH) who is also based in Taiwan. The National University of Kaohsiung-based author has 6 published documents on DLAF research which have a combined 226 citations. The most cited published document by CH with 161 citations is "A hybrid stock selection model using genetic algorithms and support vector regression". In contrast, Stephen P. Boyd who is the 3rd most prolific researcher on DLAF has 5 published documents on DLAF research. The works of the Stanford University (Palo Alto, United States) based researcher have gained a total of 282 citations, of which the most notable is "OSQP: an operator splitting solver for quadratic programs" published in *Mathematical Programming Computation* with 174 citations to date.

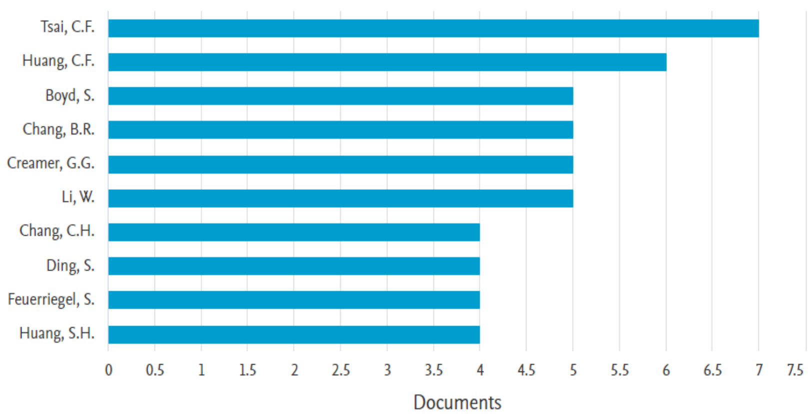

Fig. 4 Top 10 most active researchers on DLAF research (2007-2021)

In contrast, the top or most prolific institution (defined as the organisation with the highest number of publications) on DLAF research is Stanford University (United States) with 17 published documents which have gained 1298 citations today, as shown in **Error! Reference source not found.**. The leadership of Stanford University ((SU), (USA)) on DLAF research can be largely attributed to the productivity of researchers such as Julia Hirschberg, Christopher D. Manning, Woongki Baek, Trishul M. Chilimbi, Stephen S. Boyd and their co-workers. The leadership of SU is closely followed by the Chinese Academy of Sciences (China) and Tsinghua University (China) with 16 and 15 published documents, respectively. Overall, the analysis showed that DLAF research is generally dominated by researchers and institutions based on three continents North America, Europe, and Asia. This observation may indicate that the productivity of these researchers and institutions could be ascribed to factors ranging from access to research funding, and other forms of academic resources to institutional or national research policies.

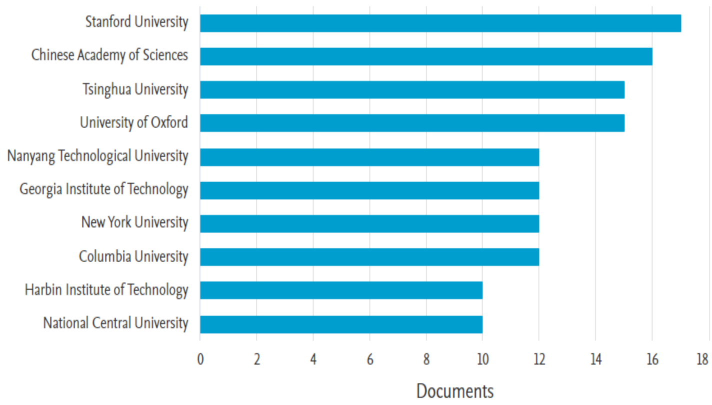

Fig. 5 Top 10 most active research institutions on DLAF research (2007-2021)

The bibliometric study will be used to evaluate the level of technological and collaborative research between the top countries engaged in DL in finance research on a variety of issues and themes. The findings of the bibliometric study of DLAF research based on co-authorship, keywords, and citations on published papers in the topic area are presented in Section III.

C. Bibliometric Analysis (BA)

BA is a popular numerical technique for analyzing the state of research in various fields, as well as scientific and technical advancements [82]. Likewise, BA is depicted as an information-based methodology for the mapping and interpretation of published materials such as conference proceedings, articles, reviews, and books among others related to any field of study [82, 83]. It has also been used to quantitatively identify, filter, and assess information on published research materials on various topics or subject areas [26, 84]. In general, the BA process is obtaining, classifying, and looking through the bibliographic information on published articles recovered from scientific databases like Elsevier Scopus, Web of Science, CrossRef, PubMed, and PubMed, to name a few. The recovered data is subsequently analysed using bibliographic software such as VOSviewer, Bibliometrix, Bibexcel, Pajek, Gephi, SciMat, Sci2, and UCINET among others [86, 87]. The BA technique has been successfully adopted to examine the research landscape on numerous subject areas ranging from energy, climate change, business, medicine, and management to mention but a few. In order to analyze the study landscape on the topic, the co-authorship, keywords, and citation networks on DLAF research are examined in this report using BA.

***Co-authorship Analysis*:** The CA analysis is regarded as a useful technique for evaluating the degree of connection amongst authors, institutions, and nations actively engaged in any field of research [88]. Additionally, the degree of cooperation between diverse players and stakeholders plays a crucial role in the expansion and growth of any field of study or scientific endeavor [89, 90]. Therefore, it is crucial to examine the levels of co-authorships, or collaboration by extension, on any given area of research to ascertain the level of research growth and scientific development. In this paper, the author- and country-based co-authorship networks on DLAF were developed using VOSviewer based on published documents data from Scopus. The network visualisation maps of the author- and country-based co-authorships on DLAF research between 2007 and 2021 are shown in Figures 6 and 7. The study of co-authors based on authors was done using a minimum of two documents per author, each with at least 50 citations. The findings revealed that 4,152 authors in total had published at least one document on the DLAF, but that only 150 of them had met the requirements for further investigation. The analysis's final findings, which are displayed in Figure 6, reveal that throughout the study's time period, 67 writers collaborated on publications on the topic. Furthermore, the highest number of co-authored published documents (15) and total link strength (TLS) (33) is by Chen Y. (blue cluster), whereas the highest number of citations is by Brunton S.L. and Kutz J.N. both with 1207 citations. The results also showed that there are 8 clusters, 67 connected researchers, 168 links and a TLS of 209. The largest cluster of co-authors consists of researchers such as Gao H., Han D., and Wand and S. among others, while the smallest cluster is made up of Chen K., Shi Y., Zhou Y. Based on the co-authored outputs, links, and TLS recorded, Chen Y. (blue cluster) who is based at Anhui University, Hefei (China) is the most influential collaborator on DLAF research worldwide. Overall, the co-authorship analysis showed that there is a high level of collaboration between the various authors involved in DLAF research worldwide. This observation may be due to the growing relevance of DLAF as an important tool for the

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comprehensive analysis of big data, which is required for various uses such as enhanced decision-making, process efficiency, and performance in many organizations and countries worldwide.

Given its growing importance, many nations around the world have set up programmes, schemes, and strategies to explore and exploit the use of DL and related tools such as IoT for the analysis of complex (big) data for applications in many aspects of policy and governance. Hence, the mandate has been placed on the academia and industry in these countries, which has resulted in significant research over the years. To this end, numerous researchers, scientists, and academics within and outside the borders of many nations have sought to collaborate and explore solutions to numerous problems related to DLAF. The resulting product has been numerous co-authored published documents, which not only serve as a measure of collaboration but also the level of growth and development of the field. To further examine this, the country-based co-authorship networks on DLAF were examined, as shown in **Error! Reference source not found.**7.

Likewise, the country-based co-author analysis was performed based on the minimum number of 2 documents per country each with 50 or more citations. The results showed that a total of 130 countries have published 2 or more papers although only 50 fulfilled the set criteria for co-authorship analysis. In addition, the largest set of connected items, which indicates the highest number of co-authorship links between countries is 48, which generated 9 clusters, 226 links and a TLS of 494. Based on the analysis, the country with the highest number of co-authored published documents, highest citations, and TLS is the United States. The next subsection of the study looks at how keyword occurrence can be used to assess the research effect of any field.

Keyword Analysis**:** The keyword occurrence is another important aspect of the BA process that examines the research impact of the level of relevance of any given subject area. In addition, the process helps researchers to map the hotspots, current and potential areas of interest for future research on any given subject area [92, 93]. In this study, the keyword occurrence analysis of DLAF was carried out using the designated feature in VOSviewer using the title keywords. The study was based on a minimum of 50 occurrences of a keyword, yielding 9,023 results, 43 of which met the established requirements for further investigation. Following that, the visualisation map of keyword occurrences on DLAF Research was created, as shown in Figure 8.

As expected, the most occurrent keywords are "deep learning" and "finance" which occurred 855 and 694 times respectively. However, the TLS of "finance" (3,431) was found to be higher when compared to DL (3,242). The results also show a total of 5 clusters, the largest (red) of which consists of keywords such as Classification, Crime, Decision Trees, Finance, and Risk assessment to mention but a few.

Furthermore, the results showed the keyword occurrence map has 865 links and a TLS of 17,819. Overall, the findings indicate that DLAF has an extensive network of core keywords which are linked to several secondary keywords, which invariably indicates the field has a high research impact. In addition, the diversity of the keywords deduced during the analysis indicates DLAF is highly multidisciplinary, which could provide an important foundation for the growth and development of the subject area.

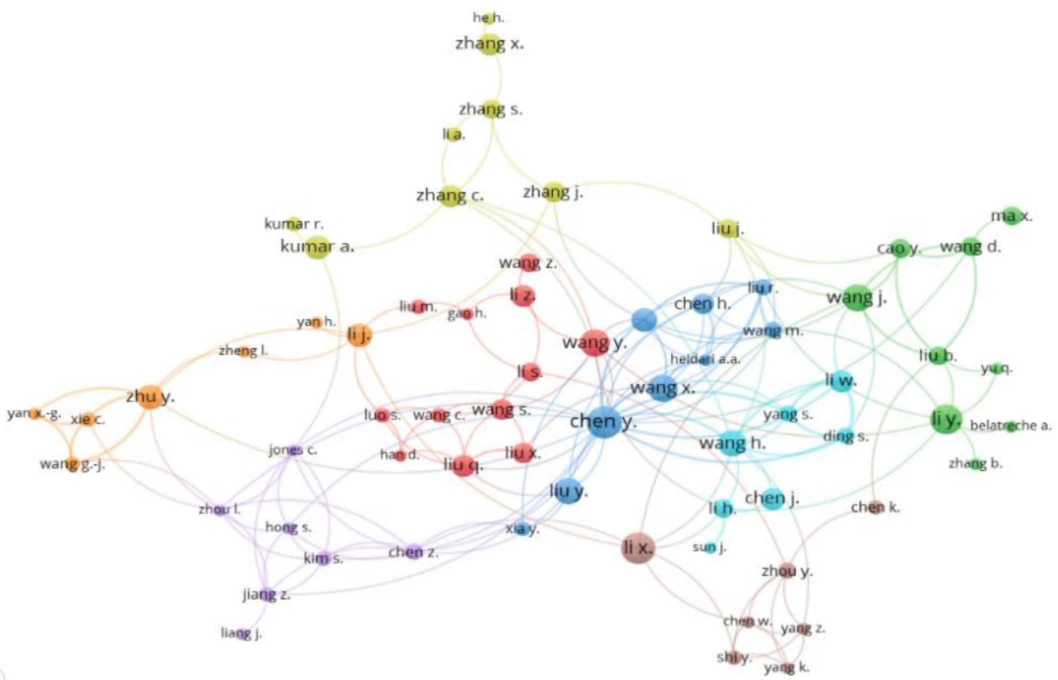

Fig. 6 Visualisation map of the author-based co-authorship network on DLAF Research (2007-2021)

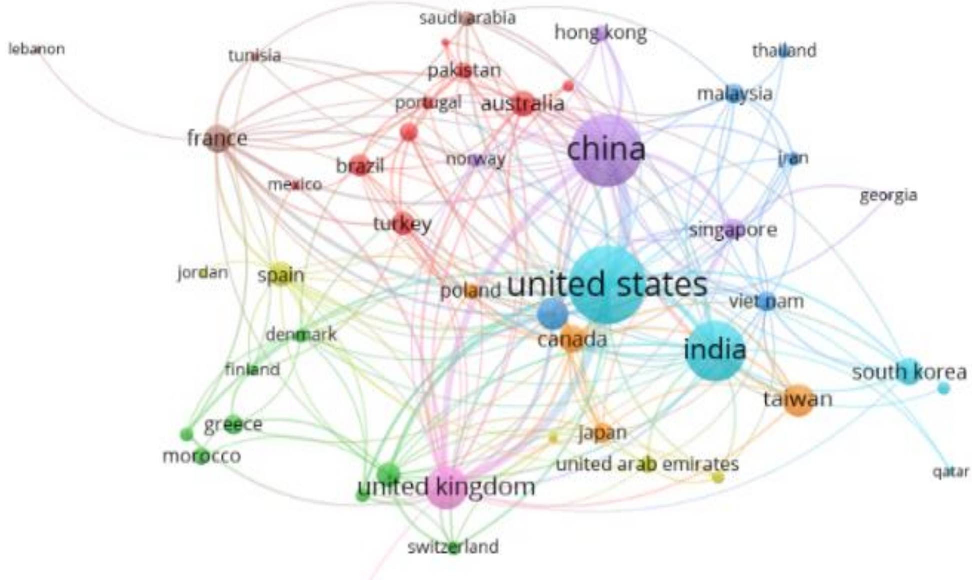

Fig. 7 Visualisation map of the country-based co-authorship network on DLAF Research (2007-2021)

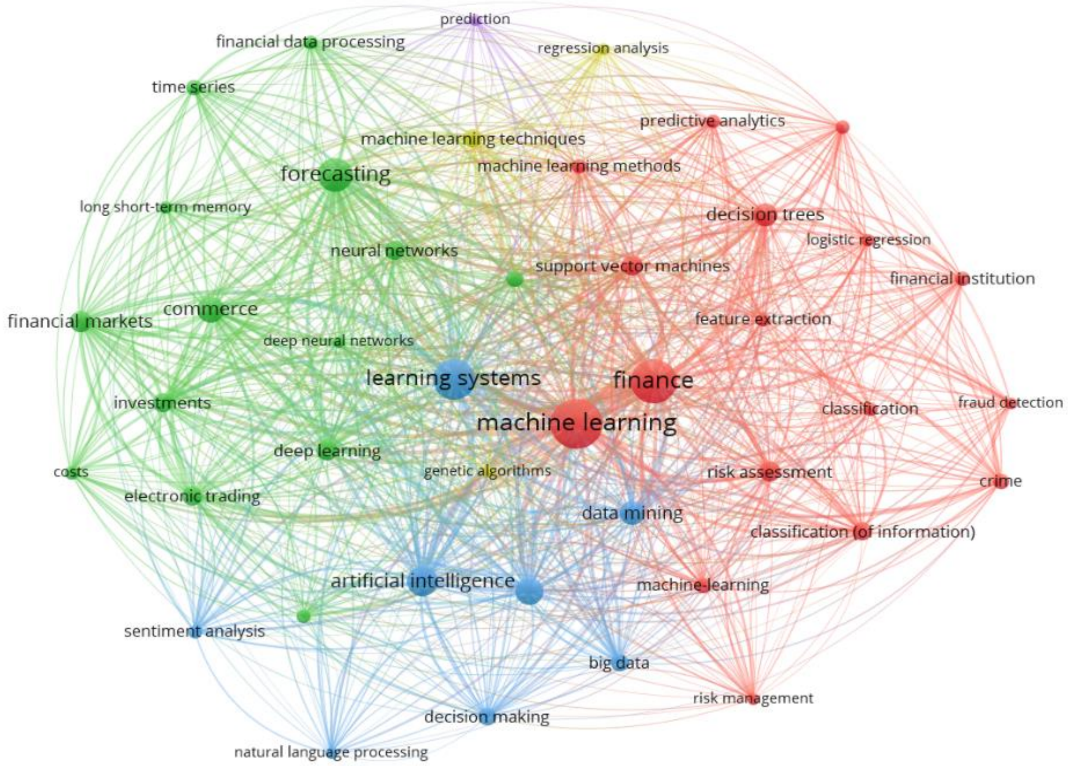

Fig. 8 Visualization map of the keyword occurrences on DLAF Research (2007-2021)

D. Systematic Literature Review

The research landscape on the current developments in DLAF research was also examined through a systematic literature review of the benchmark publications on the subject area. The document selection for SLR was based on the criteria; (i) Published documents with 5 or more citations; (ii) published documents with the keywords "deep learning" and "applications" and "finance" in their TITLE only; (iii) indexed in Scopus between 2007 and 2021; (iv) document type (articles and conference proceedings). Table 3 presents a summary of the major findings of the benchmark papers (*n* = 13), on DLAF research from 2007 to 2021.

TABLE III SUMMARY OF FINDINGS OF BENCHMARK PUBLICATIONS ON DLAF RESEARCH

References	Study Objectives	Summary of Study findings
Kim and Boyd [10]	Propose a minimax-based formula for applying DL in finance.	The study demonstrated the potential use and applications of DL in finance using hybrid concepts of robust Fisher linear discriminant and robust portfolio selection. The authors demonstrated that saddle points exist that can be efficiently used for convex computing and optimization.
Xu et. al., [11]	Proposes a novel approach for identifying Chinese language text in finance through DL.	The study proposed an innovative approach for the selection of feature items that could be applied to enhance the identification of financial texts using DL. The results showed that the use of the SVMs classifier on the real-world *corpora* improves selection, which validates the efficacy of LR (likelihood ratio) as a dependable metric for selecting informative features. The findings also showed higher performance that ensured 80% removal of unrelated terms.
Zhu et. al., [12]	Demonstrate the use of DL in forecasting SME credit risk in supply chain finance using DL.	The study demonstrated that the proposed combined or collective DL approach comprising Random Subspace-Real AdaBoost (RS-RAB) for forecasting credit risk displayed excellent performance. Hence the approach was deemed appropriate for predicting credit risk in supply chain finance particularly small and medium-sized enterprises (SMEs) in China.
Zhu et. al., [13]	Presents a comparative study of DL techniques applied in forecasting credit risk in supply chain finance for SMEs in China.	The study demonstrated the effectiveness of utilising 6 DL techniques for predicting credit risk in SMEs in China. The findings showed that IEDL (integrated ensemble DL) methods acquire better performance than IML (individual DL) and EML (ensemble DL) methods.
De Spiegeleer et. al., [16]	Proposes DL as a tool for rapid derivative pricing, fitting, and hedging in quantitative finance.	The study showed a practical approach for deploying DL approaches for problem-solving in quantitative finance. Hence, Gaussian regression-based DL was deployed for rapid analysis and resolution of classical finance problems although the approach resulted in a loss of accuracy.
Zhu et. al., [14]	Proposes an enhanced hybrid ensemble DL method for predicting credit risk in supply chain finance of SMEs.	The results showed that the enhanced hybrid ensemble DL method (termed RS-MultiBoosting) is effective for predicting SMEs credit risks for small sample sizes. Furthermore, the findings showed that an even better performance for assessing the financing ability can be obtained by using “traditional factors” like the current or quick ratio of SMEs. Likewise, the use of specific factors like trade goods features could greatly improve SCF.
Ma and Lv [15]	Proposes the use of DL to predict credit risk in internet finance	The study adopted three archetypal test functions to simultaneously compare the performance of DL IA and logic-based prediction algorithms based for financial credit risk prediction and assessment. The results showed that DL algorithms can be utilised and improved for application in predicting credit risk in the financial sector.
Cai et. al., [94]	Examined the potential for using DL and expert judgement for the analysis of emergent themes in accounting and finance research.	The study demonstrated the comparative use of two DL algorithms for keyword detection as an effective approach for qualitative data analysis and systematic literature reviews. The results showed that automated analysis is effective for large quantities of text and provides a standardized and non-biased method way of examining the literature. Yet, the human researcher or manual approach showed better results for analysing current issues and future trends in the literature.
Gan et. al., [18]	Examined the application of DL solutions to problems such as financial product pricing in finance.	The paper proposed an innovative and model-free DL approach for quickly and accurately determining the price arithmetic and geometric average options in finance.
Alcazar et. al., [19]	Investigated the application of classical and quantum models of DL in finance.	The study constructed scenarios from the probabilistic version of the popular problem of portfolio optimization in finance using time-series data for pricing from asset subsets of the S&P 500 index of the stock market. The objective was also to solve questions related to real-world classical data sets using quantum performance model approaches. The results showed that the quantum models showed superior performance on typical instances (when compared to classical approaches) even with recognised RBMs (restricted Boltzmann machines) training and under similar resources and parametric terms.
Boughaci and Alkhawaldeh [20]	Examined the application of suitable DL techniques predicting bankruptcy and for credit scoring in banking and finance.	In the study, DL methods for predicting bankruptcy and credit scoring were examined for applications in banking and finance using various real-life datasets. The results showed that the DL techniques were able to successfully generate credit scores for applicants, which could help banks and other financial institutions make informed decisions.

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Nguyen et. al., [21]	Investigated an DL technique for forecasting the carbon footprint for the analysis of the climate finance risk of corporate entities.	This paper adopted DL to enhance the forecasting of corporate carbon emissions for enhanced risk assessments by investors. The two-step framework proposed by the authors was aimed at combining projections from multiple base learners as the safest approach for emission prediction. The findings showed an accuracy gain of about 30% based on mean absolute error when associated with present models. However, the accuracy of the prediction could be further enhanced by integrating extra predictors and firm discoveries in specific areas.
Hansen and Borch [95]	Examined the uncertainty of absorption and multiplication using DL-based finance.	The study examined the potential of using DL for analysing and translating uncertainty into controllable risk. The findings showed that DL could also be used to establish a novel and powerful kind of uncertainty (termed critical model uncertainty, CMU) in addition to absorbing uncertainty in finance. The CMU is defined as the incapacity to describe DL models (e.g., neural networks) or how and why they reach their projections and conclusions. Lastly, the authors recommended that the discussion about the ambiguity of absorption and multiplication associated with DL models required further investigation in the subject area of finance.

IV. CONCLUSION

A comprehensive literature assessment of all articles published on the subject between 2007 and 2021 that were indexed in the Scopus database, as well as an examination of publishing trends and bibliometric data, were used to critically assess the research landscape on deep learning applications in finance (DLAF). From 2007 to 2021, there was a staggering 7,860% growth in the number of papers published on the subject, according to the publishing trends analysis. It is possible that the increasing demand for powerful algorithms to efficiently handle and analyze large or complicated data sets is driving the substantial interest in DLAF research shown by the results. Businesses are using big data into their operations to enhance processes, goods, and services, and governments throughout the world are using it to make better policy decisions and pass more effective laws. After delving further, it became clear that there are a plethora of writers and organizations dedicated to studying DL in Finance from all angles. The results of the bibliometric study demonstrated that the institutions and writers involved in this field work together extensively, and that they produce a great deal of published work and citations. Analysis of keyword occurrences showed a wide variety of terms and research hotspots/themes, suggesting that DLAF encompasses a wide range of disciplines. However, citation analysis revealed that researchers' choice of source title (i.e., journal or proceedings) for publishing their research works is significantly influenced by the publications metrics. Expert Systems with Applications, IEEE Access, and the ACM International Conference Proceedings Series (ACM-ICPS) are the most well-known and esteemed publications for DLAF research. The systematic literature review concluded that DLAF research will likely keep expanding and improving in the future. Its themes will likely expand into and make use of a wide range of areas and applications, including but not limited to: data mining, artificial intelligence, supply chain management, carbon trading, credit assessment, financial data analytics, and risk management. Research into the use of DL in the financial sector is vast, interdisciplinary, and influential; this paper's results demonstrate that this field will continue to be significant for the foreseeable future.

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