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Unveiling Collaborative Trends in Fuzzy Delphi Method (FDM) Research: A Co-Authorship Bibliometrics Study

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ABSTRACT

The Fuzzy Delphi Method (FDM) employs fuzzy logic to address uncertainty and ambiguity in expert judgments, facilitating consensus in complex decisions. Recent years have witnessed a surge in FDM publications, indicating its increasing popularity as a versatile decision-making tool across various domains, owing to its adept handling of uncertainty and complexity. However, there remains a limited understanding of collaborative dynamics among researchers in this field. This research aims to bridge this gap by examining co-authorship patterns and trends in FDM research literature, contributing to a deeper understanding of collaborative networks and their impact on the advancement of FDM methodologies and applications. A comprehensive examination was conducted on FDM research documents retrieved from the Scopus database spanning 1991 to 2022. Using the keyword "Fuzzy Delphi method," 766 papers underwent further scrutiny. Various tools, including Microsoft Excel for frequency analysis, VOSviewer for data visualization, and Harzing's Publish or Perish for citation metrics and analysis, were employed. The study's findings were presented using bibliometric indicators, encompassing document type, sources, language, subject area, publication trends by year, top countries, influential institutions, leading authors, active journals, co-authorship analysis, citation analysis, and highly cited recent articles. While the total number of publications shows a general increasing trend over the years, the total citation trend does not demonstrate a consistent pattern of increase. Taiwan emerged as the top contributor to FDM research, followed by Malaysia. Robust collaboration exists among authors and countries. The evolution of FDM research benefits by providing a structured approach to decision-making processes, facilitating consensus-building among stakeholders, and enhancing strategic planning in curriculum development and educational policy formulation.

1. Introduction

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Seeking expert opinions is a common method in the early phases of new product development. The Fuzzy Delphi Method (FDM) is one of the research methodologies that is frequently used to gain expert consensus on certain subjects. As a systematic process for collecting the opinions of numerous experts to obtain a consensus decision, FDM has been used in a variety of fields, such as humanities, management, business, physical science, and engineering [1,2]. The FDM is essentially a modified and improved version of the classic Delphi method (DM). The combination of the classical DM with a fuzzy set theory has resulted in an upgraded FDM, whereas the vagueness of this DM is intended to be improved [2].

Historically, Dalkey and Helmer [3] developed the classic DM in 1963 for a RAND Corporation study to analyse the direction of scientific advances, population control, automation, space advancement, war prevention, and missile defense systems. In Delphi studies that respect to the original argument, the objective is often to establish consensus, based on the assumption that agreement within a group of experts for better decision [4]. Delphi studies have proved effective in educational contexts for developing guidelines, standards, and forecasting trends [5]. Meanwhile, the idea of a fuzzy set theory, as introduced by Zadeh in the 1960s, appears to play a crucial role in human cognition, particularly for concept generation, pattern recognition, and decision-making as well as in getting quantitative values from high-uncertainty linguistic judgments while retaining qualitative attributes [6-8]. FDM studies have expanded since Kaufman and Gupta [9] introduced the FDM's applicability for forecasting and Ishikawa *et al*., [10] pioneered the Delphi method with triangular fuzzy numbers.

1.1 Co-Authorship Studies

Currently, bibliometric analysis studies have been extensively accepted as an alternative way for evaluating academic issues and demonstrating the trends of study [11]. Bibliometrics is described as a statistical approach used to analyze the quality and number of published scientific literature quantitatively [12]. Research trends, publication impact, citation analysis, authorship, journal analysis, and international collaboration between countries in a certain discipline may all be explored using bibliometric analysis. However, according to Eck and Waltman [13], the most prevalent studies are citation-based analysis, keyword co-occurrence analysis, and co-authorship analysis. Co-authorship analysis is the connection of authors when they co-author a work, and the study can show evidence of the collaboration as well as the social structure [14].

There have been various research undertaken focused on co-authorship analysis (Table 1). Köseoglu *et al*., [15] and Kılıc *et al*., [16] conducted bibliometric analyses of authorship and co-authorship in lodging studies and the accounting discipline, respectively. Both studies ranked authors based on network centrality metrics, including degree centrality, Bonacich's power index, closeness centrality, and betweenness centrality. Another study by Sadatmoosavi *et al*., [17] and Higaki *et al*., [18] performed bibliometric studies and network analysis on co-authorship to identify the foremost researchers in cardiovascular studies employing machine learning. These studies utilized the Social Network Analysis method to uncover the structural aspects of the co-authorship network through the Web of Science database. In our study, we focus on research related to FDM due to the limited understanding of collaborative dynamics among researchers in this field using the Scopus database. Therefore, this research aims to bridge this gap by examining co-authorship patterns and uncovering the evolution structure, research trends, and key contributors to the development of FDM research. Consequently, this article aims to reveal collaborative trends in FDM through co-authorship bibliometric analysis by addressing three main research questions (RQs): RQ1: What is the evolution

and publication trend in FDM?; RQ2: Who has made substantial contributions to FDM research?; and RQ3: What is the trends of collaborations among countries and authors on FDM?.

Table 1
Comparison of previous studies on co-authorship analysis with our study

Basis for comparison	Data Source & Time period	Focus of the study	Methodology
Sadatmoosavi *et al*., [17]	Web of Science 2008 to 2010	to determine the macro-topological structure and the relationship between citation performance and centrality measures of co-authorship social networks of countries in the field of Nuclear Science and Technology	A bibliometric and network analysis (citation performance and co-authorship)
Köseoglu *et al*., [15]	Web of Science 1990–2016	To evaluate authorship trends, collaboration patterns, and co-authorship networks in lodging studies	A bibliometric and network analysis (authorship and co-authorship)
Kılıc *et al*., [16]	Web of Science 2000–2016	to explore co-authorship structures in the accounting discipline	A bibliometric and network analysis (authorship and co-authorship)
Higaki *et al*., [18]	Web of Science 2009 – 2019	To assess the characteristics of co-authorship networks and identify the leading investigators in cardiovascular research utilizing machine learning	A bibliometric and network analysis (co-authorship)
Our study	Scopus (all years excluded 2023)	to examine co-authorship patterns, the evolution structure, the research trends and key contributors on the FDM study	A bibliometric and network analysis (co-authorship)

2. Methodology

The research was designed following to the modified PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [19,20] and bibliometrics methods standard [14]. The Scopus database was used to collect bibliographic data for the study since it is a high-quality data source that established internal review protocols to continually monitor preidentified areas of high efficiency [21]. By removing publications published in 2023, the keyword “Fuzzy Delphi method” was included in the title, abstract (ABS), and keywords (KEY). The extraction of data from the Scopus database was performed on January 3, 2023. The preliminary search yielded 766 scholarly papers. All of the publications found in the initial search had their titles and abstracts thoroughly examined for relevance to the FDM. Because of the screening procedure, 766 papers on FDM-related articles remained in the final database, with no record removed (Figure 1).

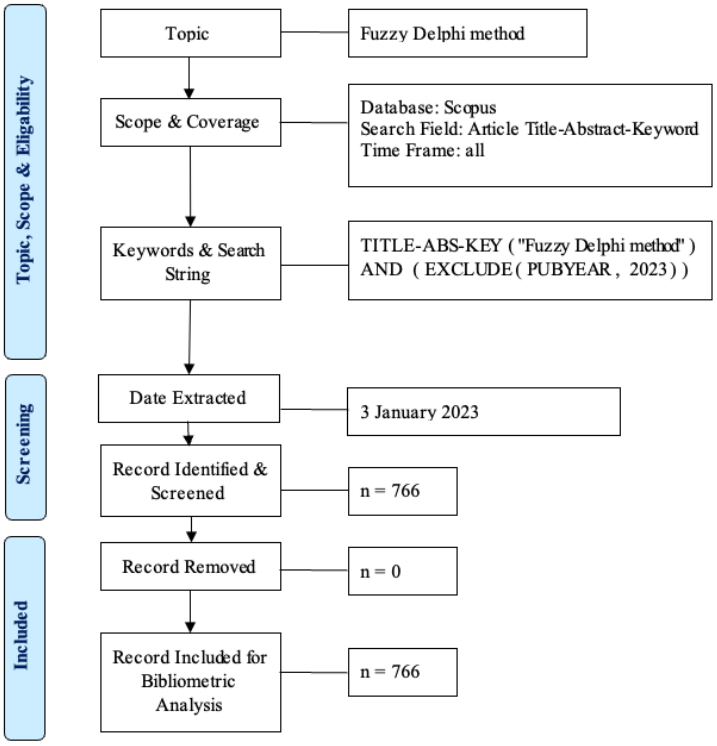


Fig. 1. Illustration outlining the search strategy

3. Results and Discussion

3.1 What is the Evolution and Publications Trend on the FDM?

In this study, a total of 766 records related to the FDM were identified. Initially, we organized and examined the statistical data from the included studies, drawing preliminary conclusions. Figure 2 illustrates the distribution of document types identified in the study, presenting the number of documents classified into various types and their respective percentages. The predominant document type is articles, constituting 80.0% of the total, followed by conference papers at 16.3%. Reviews, book chapters, conference reviews, books, and notes form smaller proportions of the document types. Figure 3 depicts the distribution of source types included in the study. The majority of documents emanate from journals, making up 82.0% of the total. Conference proceedings account for 11.8% of the sources, while book series and individual books contribute smaller proportions of 5.5% and 0.8%, respectively. Simultaneously, Figure 4 showcases the distribution of languages observed in the study, listing the languages found in the documents. The predominant language is English, comprising 97.3% of the total. Other languages, including Chinese, Croatian, Malay, Persian, and Portuguese, contribute to smaller proportions of the documents.

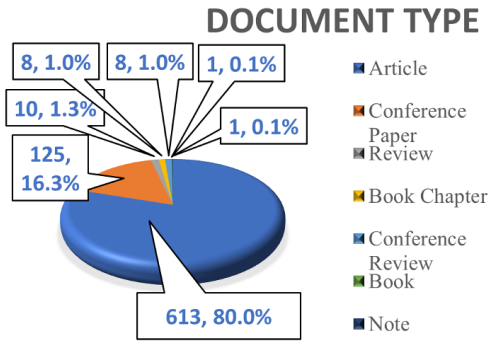


Fig. 2. Document type for FDM research

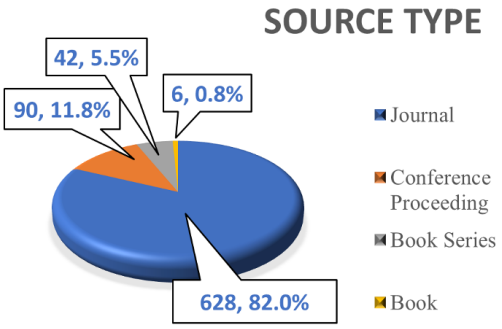


Fig. 3. Sources for FDM research

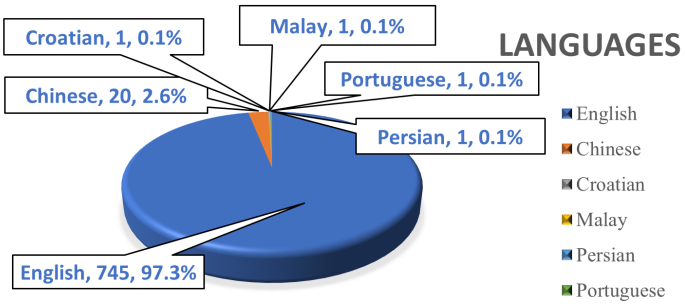


Fig. 4. Languages for FDM research

Figure 5 provides an overview of the distribution of publications across various subject areas. The figure highlights the prominence of Engineering, Computer Science, and Social Sciences in terms of the highest number of publications, with Engineering accounting for the largest share at 279 publications (36.4%), followed by Computer Science at 230 publications (30.0%), and Social Sciences at 206 publications (26.9%). It also shows the diversity of subject areas covered in the FDM research, with varying levels of representation across different disciplines.

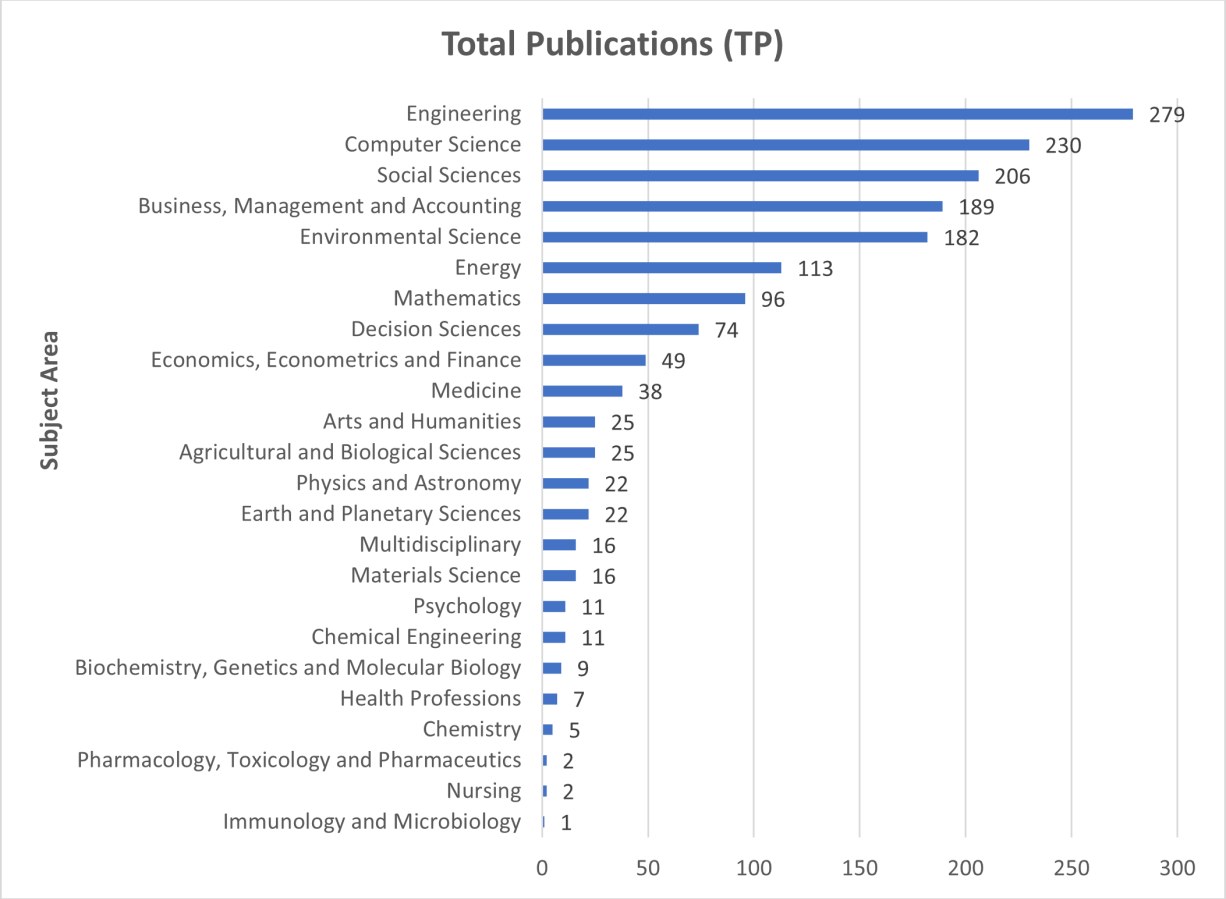


Fig. 5. Subject area for FDM research

Analyzing documents according to their publication years enables researchers to monitor the evolution and research trends in specific topics across time. The highest productivity occurred in 2022, with 149 documents, while the highest citation count was in 2018, with 1148 citations (Table 2 and Figure 6). Although there was a rise in the number of published documents over the years, the trend in total citations does not consistently show an increase. The rising number of publications related to the FDM indicates a burgeoning interest among researchers, scholars, and practitioners, underscoring a widening scope of FDM knowledge within this domain.

Table 3 offers insights into the distribution of authorship in publications related to the FDM, shedding light on prevalent collaborative research practices within this domain. The data reveals that a considerable portion of publications (29.0%) involves three authors, followed closely by those with two authors (22.3%). Additionally, publications featuring four authors constitute a significant proportion, amounting to 20.0%. Conversely, publications authored by a single individual or without any specified author are less frequent, representing 5.4% and 1.0% respectively. Notably, some conference review documents are presented without any listed author.

Table 2
Number of FDM research publications by year

Year	TP	NCP	TC	PCP	CCP	*h*	*g*
1991	1	1	1	1.00	1.00	1	1
1993	2	2	575	287.50	287.50	2	2
1995	1	1	89	89.00	89.00	1	1
1996	1	0	0	0.00	0.00	0	0

1997	1	1	12	12.00	12.00	1	1
1999	3	3	38	12.67	12.67	2	3
2000	1	1	148	148.00	148.00	1	1
2001	3	3	10	3.33	3.33	2	3
2002	1	1	373	373.00	373.00	1	1
2003	1	0	0	0.00	0.00	0	0
2004	1	1	97	97.00	97.00	1	1
2005	3	3	64	21.33	21.33	3	3
2006	7	4	61	8.71	15.25	4	7
2007	6	6	220	36.67	36.67	5	6
2008	13	10	393	30.23	39.30	7	13
2009	14	9	288	20.57	32.00	6	14
2010	17	17	911	53.59	53.59	9	17
2011	25	23	774	30.96	33.65	11	25
2012	26	21	475	18.27	22.62	8	21
2013	23	22	385	16.74	17.50	10	19
2014	28	21	225	8.04	10.71	8	14
2015	29	26	704	24.28	27.08	11	26
2016	38	33	1007	26.50	30.52	16	31
2017	41	36	702	17.12	19.50	16	26
2018	56	48	1148	20.50	23.92	17	33
2019	67	53	916	13.67	17.28	16	28
2020	90	66	816	9.07	12.36	15	26
2021	118	99	1021	8.65	10.31	17	28
2022	149	70	341	2.29	4.87	11	14
Total	**766**						

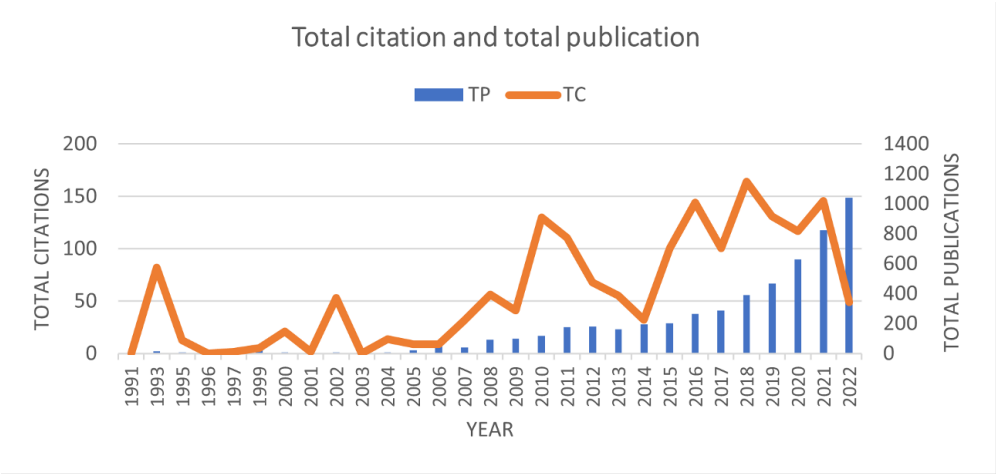


Fig. 6. Total publications and citations by year

Table 3
Number of Author(s) per document

Author Count	Total Publications (TP)	Percentage (%)
0*	8	1.0%
1	41	5.4%
2	171	22.3%
3	222	29.0%
4	153	20.0%
5	99	12.9%
6	43	5.6%

7	22	2.9%
8	2	0.3%
9	1	0.1%
10	1	0.1%
11	1	0.1%
15	2	0.3%
Total	766	100.00%

*Conference review document. No author is listed

Citation metrics, such as impact factor and h-index, are relied upon by the scientific community to gauge the reputation of a journal [22]. Table 4 presents the citation metrics of publications related to the FDM spanning from 1991 to 2022. The data indicates a total of 766 papers published during this period, accumulating 11,794 citations by the end of 2023. On average, these publications received approximately 368.56 citations per year and 15.4 citations per paper. Remarkably, each author associated with these papers garnered an average of 4,102.43 citations, with an average of 269.61 papers per author. The h-index, a measure of both productivity and citation impact, is calculated at 54, indicating that 54 of the publications have each received at least 54 citations. Similarly, the g-index, which takes into account the distribution of citations among papers, is determined to be 87. These metrics collectively provide a comprehensive overview of the scholarly impact and influence of research utilizing the FDM over the specified timeframe.

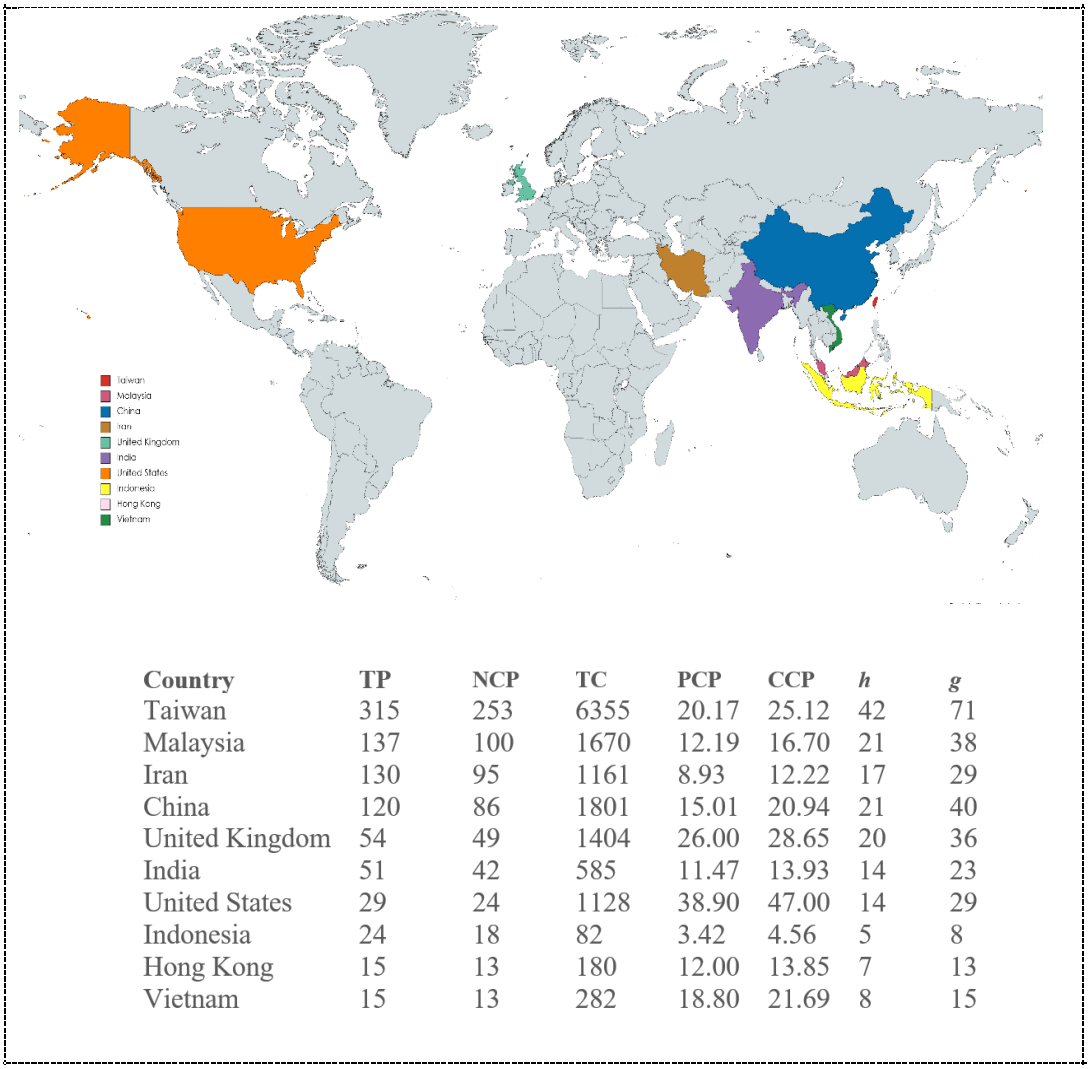
Table 4
Citations metrics

Metrics	**Data**
Publication years	1991-2022
Citation years	32 (1991-2023)
Papers	766
Citations	11794
Citations/year	368.56
Citations/paper	15.4
Citations/author	4102.43
Papers/author	269.61
h-index	54
g-index	87

3.2 Who Made the Substantial Contributions to FDM Research?

Figure 7 presents the top countries that have made substantial contributions to FDM research, along with their corresponding metrics for performance analysis. The citation metrics included, besides TP and TC, encompass the number of cited publications (NCP), proportion of cited publications (PCP), citations per cited publication (CCP), h-index, and g-index. NCP refers to the number of publications from a research constituent that are cited, while PCP is calculated by dividing NCP by TP. Meanwhile, CCP represents the total citations for NCP. According to Donthu *et al*., [23], the h-index represents the number of publications cited at least h times for influence measurement, while the g-index, an impact measurement, refers to the number of publications receiving at least g^2 citations. For instance, a g-index of 10 indicates that the top 10 publications of a country have been cited at least 100 times (10^2). The figure illustrates that Taiwan has the highest number of FDM research publications with 315 publications, followed by Malaysia with 137 publications and Iran with 130 publications. Taiwan also leads in NCP with 253, contributing significantly to TC with 6355. However, when considering PCP and CCP, the United States ranks highest with 38.9% PCP and 47.00 CCP, indicating a high impact of their publications. Regarding h-index and g-index, Taiwan has the

highest values with 42 and 71 respectively, reflecting its strong influence and productivity in FDM research. Malaysia, Iran, and China also demonstrate notable contributions to FDM research based on their h-index and g-index values. These substantial contributions highlighted by countries provide insights into the global landscape of FDM research and the impact of publications from different countries.



Country	TP	NCP	TC	PCP	CCP	*h*	*g*
Taiwan	315	253	6355	20.17	25.12	42	71
Malaysia	137	100	1670	12.19	16.70	21	38
Iran	130	95	1161	8.93	12.22	17	29
China	120	86	1801	15.01	20.94	21	40
United Kingdom	54	49	1404	26.00	28.65	20	36
India	51	42	585	11.47	13.93	14	23
United States	29	24	1128	38.90	47.00	14	29
Indonesia	24	18	82	3.42	4.56	5	8
Hong Kong	15	13	180	12.00	13.85	7	13
Vietnam	15	13	282	18.80	21.69	8	15

Notes: TP=total number of publications; NCP=number of cited publications; TC=total citations; PCP=proportion of cited publications; CCP=citations per cited publication; h=h-index; and g=g-index.

Fig. 7. Top 10 countries contributed to the articles on FDM

Table 5 presents information on the top 15 influential institutions in FDM research. Notably, institutions from Taiwan, Malaysia, Iran, and the United Kingdom feature prominently in this list. For example, Asia University in Taiwan leads with 49 publications and 823 total citations, underscoring the significant impact of its research. Universiti Kebangsaan Malaysia from Malaysia and China Medical University in Taiwan closely follow with 41 and 35 publications, respectively, showcasing their substantial contributions to FDM research. Coventry University in the United Kingdom stands out with a high PCP and CCP, indicating the strong influence of its publications in the field.

Table 5
Top 15 influential institutions

Affiliation	Country	TP	NCP	TC	PCP	CCP	*h*	*g*
Asia University	Taiwan	49	43	823	16.80	19.14	14	27
Universiti Kebangsaan Malaysia	Malaysia	41	37	662	16.15	17.89	12	25
China Medical University	Taiwan	35	30	617	17.63	20.57	13	24
China Medical University Hospital	Taiwan	35	32	580	16.57	18.13	13	23
Chung Hua University	Taiwan	26	21	374	14.38	17.81	8	19
University of Tehran	Iran	24	19	259	10.79	13.63	9	15
Coventry University	United Kingdom	22	21	617	28.05	29.38	11	22
National Taiwan University of Science and Technology	Taiwan	22	20	285	12.95	14.25	7	16
Ming Chuan University	Taiwan	21	19	230	10.95	12.11	8	14
Universiti Teknologi MARA	Malaysia	20	15	61	3.05	4.07	4	6
National Taipei University of Technology	Taiwan	20	16	341	17.05	21.31	9	18
Islamic Azad University	Iran	20	14	48	2.40	3.43	4	6
Universiti Pendidikan Sultan Idris	Malaysia	18	12	163	9.06	13.58	6	12
Chaoyang University of Technology	Taiwan	17	12	91	5.35	7.58	5	9
Universiti Malaya	Malaysia	17	11	83	4.88	7.55	4	9

Furthermore, Table 6 presents information on the most productive authors in FDM research. The table highlights the contributions of specific authors to FDM research based on their publication output and citation impact. Notable author from Asia University in Taiwan, Tseng, M.L. lead the list with 50 publications and 1352 total citations, demonstrating a significant influence in the field. Other authors, including Lim, M.K. from the University of Glasgow in the United Kingdom and Bui, T.D. from Asia University in Taiwan, also exhibit substantial productivity and impact in FDM research.

Table 7 findings indicate that the majority of documents related to FDM were published in Sustainability Switzerland, accounting for 55 publications, followed by Elsevier-published journals: Journal of Cleaner Production, Expert Systems with Applications, and Resources, Conservation and Recycling with 27, 15, and 10 publications respectively. However, Expert Systems with Applications was the journal with the highest total citation count: 1479. Interestingly, despite the high publication count, Sustainability Switzerland did not exhibit the highest values in two key indicators: SCImago Journal Rank (SJR) and Source Normalized Impact per Paper (SNIP). SJR evaluates the prestige of a journal's citations based on the citing journal's status, while SNIP calculates citation frequency within the past three years relative to the total publications in that period [24][25]. In 2022, the International Journal of Production Economics had the highest SJR, suggesting that citations from this source held relatively more weight than those from sources with lower SJRs. Conversely, Expert Systems with Applications Journal exhibited the highest SNIP in 2022, indicating frequent citations relative to its publication volume, demonstrating significant influence within FDM research.

Table 6
Most productive authors

Author's Name	Affiliation	Country	TP	NCP	TC	PCP	CCP	*h*	*g*
Tseng, M.L.	Asia University	Taiwan	50	47	1352	27.04	28.77	19	36

Lim, M.K.	University of Glasgow	United Kingdom	27	25	685	25.37	27.40	12	26
Bui, T.D.	Asia University	Taiwan	22	21	600	27.27	28.57	10	22
Chang, K.L.	Ming Chuan University	Taiwan	16	15	159	9.94	10.60	7	12
Wu, K.J.	Hainan University	China	15	14	437	29.13	31.21	11	15
Mahdiyar, A.	Universiti Sains Malaysia	Malaysia	13	12	305	23.46	25.42	7	13

Table 7
Top 10 active journals

Source Title	**TP**	**TC**	**Publisher**	**Cite Score**	**SJR 2022**	**SNIP 2022**
Sustainability Switzerland	55	393	Multidisciplinary Digital Publishing Institute (MDPI)	5	0.664	1.31
Journal of Cleaner Production	27	906	Elsevier	15.8	1.921	2.444
Expert Systems with Applications	15	1479	Elsevier	12.2	2.07	2.985
Resources Conservation and Recycling	10	531	Elsevier	17.9	2.589	2.943
Mathematics	8	39	Multidisciplinary Digital Publishing Institute (MDPI)	2.9	0.538	1.162
Communications in Computer and Information Science	7	6	Springer Nature	0.9	0.209	0.286
International Journal of Advanced Computer Science and Applications	7	15	Science and Information Organization	1.8	0.284	0.528
International Journal of Logistics Research and Applications	7	80	Taylor & Francis	7.7	1.056	1.556
International Journal of Production Economics	7	307	Elsevier	14.3	2.808	2.877
Mathematical Problems in Engineering	7	94	Hindawi	2.1	0.327	0.638

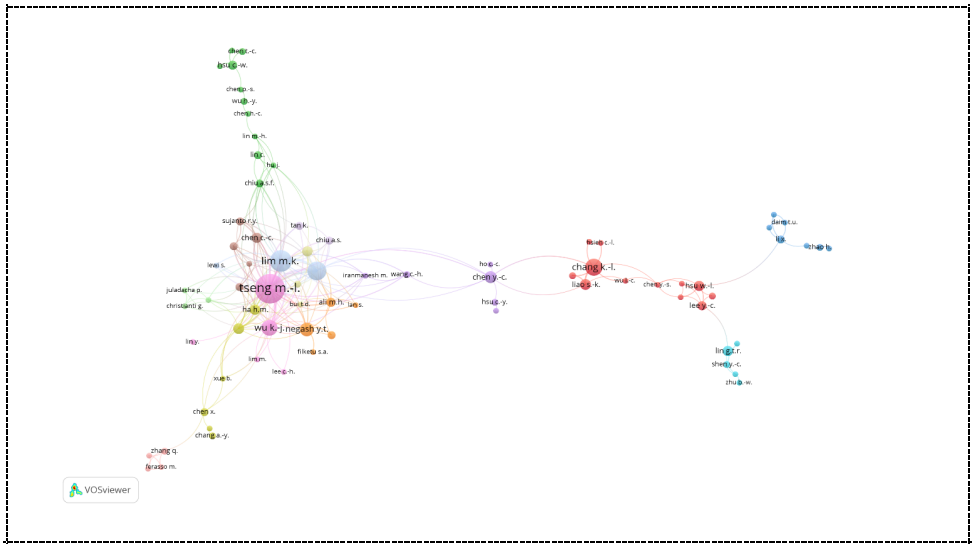
3.3 What is the Trends of Collaborations among Countries and Authors on FDM?

Bibliometric analysis plays a crucial role in measuring co-authorship by providing quantitative insights [26] into various aspects of scientific collaboration [27]. According to Ponomariov and Boardman [28], co-authorship serves as a clear indication of genuine research collaboration. Additionally, they emphasized that any scientists engaged in collaboration automatically assume the role of co-authors. In co-authorship, two common weight attributes are known as the 'Links' attribute and the 'Total link strength' attribute. The 'Links' attribute signifies the count of co-authorship links of a particular researcher with others, while the 'Total link strength attribute represents the total strength of these co-authorship links with other researchers [29].

3.3.1 Co-authorship authors network

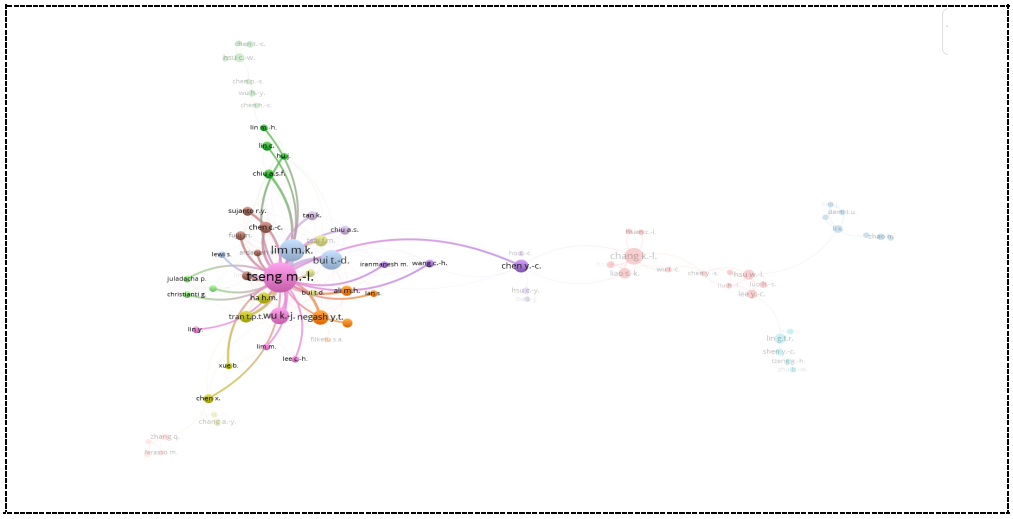
Figure 8 displays the network visualisation map of the co-authorship in FDM studies. The co-authorship network, as sourced from the Scopus database, and excluding data from 2023, comprised 1831 authors. To prioritize substantial contributions, articles with over 25 co-authors were omitted.

Applying a threshold of at least 2 published articles per author, each with a minimum of 2 citations, 348 authors meet the criteria. However, Figure 8 visually depicted only 77 authors due to the absence of links among some authors in the network. These authors were grouped into 14 clusters, with the node size indicating the number of their published documents in FDM research. Notably, Tseng M. L., who had the largest node in Cluster 9 (shown in Magenta color in Figure 9), emerged as the most prolific collaborator with other researchers, boasting 35 links and a total link strength of 154. Detailed information regarding the number of published documents, clusters, link count, total link strength, and average publication year for the 27 authors out of the total 77 is presented in Table 8.



Note: Unit of analysis = Authors; Counting method: Full counting; Minimum number of documents of an author = 2; Minimum number of citations of an author = 2

Fig. 8. Network visualisation map of the co-authorship in FDM research



Note: Unit of analysis = Authors; Counting method: Full counting; Minimum number of documents of an author = 2; Minimum number of citations of an author = 2

Fig. 9. Network visualisation map of the co-authorship (Author: Tseng M. L.) in FDM research

Table 8
Co-authorship involving 27 from 77 authors, each with a minimum of 2 documents and 2 citations

Authors' Name	Clusters	Total Number of Documents	Total Citations	Links	Total Links Strength	Average Publication Year
Tseng M. L.	9	49	1363	35	154	2020.29
Lim M. K.	12	27	691	26	95	2020.78
Bui T. D.	12	20	505	20	69	2021.15
Chang K. L.	1	17	160	7	19	2016.35
Wu K. J.	9	15	440	23	48	2019.80
Negash Y. T.	7	11	65	11	23	2021.18
Chen Y. C.	5	8	100	8	10	2013.88
Liao S. K.	1	7	77	4	12	2017.00
Tran T.P.T.	4	7	151	14	31	2021.57
Chen C. C.	8	6	35	10	19	2021.17
Ha H.M.	4	6	162	10	26	2021.83
Hsu W. L.	1	6	26	6	9	2017.67
Lin G.T.R.	6	6	229	4	6	2012.67
Tsai F.M.	13	6	310	9	24	2020.50
Ali M.H.	7	5	218	10	17	2020.60
Hsu C.-W.	2	5	243	4	6	2012.20
Lee Y.C.	1	5	27	5	6	2016.20
Chen X.	4	4	22	6	6	2021.25
Chiu A.S.	14	4	131	7	17	2019.50
Chiu A.S.F.	2	4	206	9	13	2017.50
Fujii M.	8	4	43	8	15	2021.25
Hassan A.M.	7	4	39	4	7	2020.75
Li X.	3	4	110	5	8	2017.75
Lin C.	2	4	95	4	4	2012.50
Lin C. W.	8	4	11	9	15	2021.75
Sujanto R.Y.	8	4	27	7	15	2021.25
Tan K.	14	4	112	6	12	2018.50

Meanwhile, Table 9 showcases the author with the most recent articles with the highest citation counts within the domain of FDM research. The list encompasses a range of topics, reflecting the diversity of applications within this field. Topping the list is the article by Bui et al. [6], which delves into the "Opportunities and challenges for solid waste reuse and recycling in emerging economies: A hybrid analysis", accumulating 23 citations since its publication in 2022. This article shows the collaboration of the first author, Bui T.D. from Taiwan, with Tseng, J. W., Tseng M. L., and Lim M. K. from China, Taiwan, and the United Kingdom, respectively. Following closely behind are articles addressing Fuzzy Delphi in various themes such as green mining, sustainability through innovation adoption in manufacturing, causal analysis of construction site accidents, decision-making for COVID-19 applications, and sustainable supply chain management in different industries. Notably, these articles have received commendable citation rates, ranging from 11 to 23 citations per year, indicating their significant impact and relevance within the research community. Each article contributes uniquely to the advancement of knowledge in its respective area, showcasing the breadth and depth of research utilizing the FDM.

Table 9
The most recent article title with the most citations

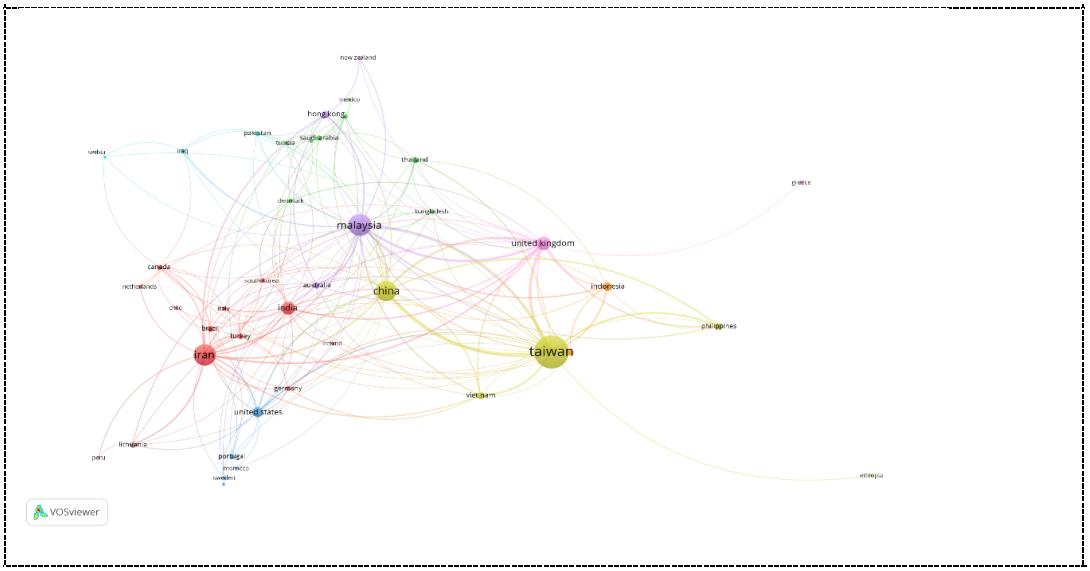
Authors	Title	Year	Cites	Cites per Year
Bui *et al*.,[6]	Opportunities and challenges for solid waste reuse and recycling in emerging economies: A hybrid analysis	2022	23	23
Jiskani *et al*., [30]	An integrated fuzzy decision support system for analyzing challenges and pathways to promote green and climate smart mining	2022	21	21
Ullah, Khan, and Ahmad [31]	Promoting sustainability through green innovation adoption: a case of manufacturing industry	2022	19	19
Mohandes *et al*., [32]	Causal analysis of accidents on construction sites: A hybrid fuzzy Delphi and DEMATEL approach	2022	16	16
Alamoodi *et al*.,[33]	Multi-criteria decision-making for coronavirus disease 2019 applications: a theoretical analysis review	2022	15	15
Tseng, Bui, Lim, Fujii, *et al*., [34]	Assessing data-driven sustainable supply chain management indicators for the textile industry under industrial disruption and ambidexterity	2022	15	15
Tseng, Ha, Wu, *et al*.,[35]	Healthcare industry circular supply chain collaboration in Vietnam: vision and learning influences on connection in a circular supply chain and circularity business model	2022	15	15
Joshi *et al*., [36]	Assessing Effectiveness of Humanitarian Activities against COVID-19 Disruption: The Role of Blockchain-Enabled Digital Humanitarian Network (BT-DHN)	2022	12	12
Tseng, Ha, Lim, *et al*., [37]	Sustainable supply chain management in stakeholders: supporting from sustainable supply and process management in the healthcare industry in Vietnam	2022	12	12
Mahdiraji *et al*., [38]	Analysing the voice of customers by a hybrid fuzzy decision-making approach in a developing country's automotive market	2022	11	11
Rathore and Gupta [39]	A fuzzy based hybrid decision-making framework to examine the safety risk factors of healthcare workers during COVID-19 outbreak	2022	11	11
Tseng, Phuong, Tran, Wu, *et al*., [40]	Exploring sustainable seafood supply chain management based on linguistic preferences: collaboration in the supply chain and lean management drive economic benefits	2022	10	10

3.3.2 Co-authorship countries network

VOSviewer, a tool developed in the Java programming language by Nees Jan van Eck and Ludo Waltman, offers three types of visual representations: network, overlay, and density [29]. The network and density visualizations highlight the significance of items within clusters through weight attributes like links, total link strength, citations, and normalized citations. In contrast, the overlay visualization considers score attributes such as average publication year, average citations, and average normalized citations, with items colored accordingly. For example, in Figure 11, colors ranging from blue (oldest publications) to yellow (latest publications) indicate the chronological distribution of documents published by different countries. The distance between two countries in the visualizations approximates their co-authorship linkages [29].

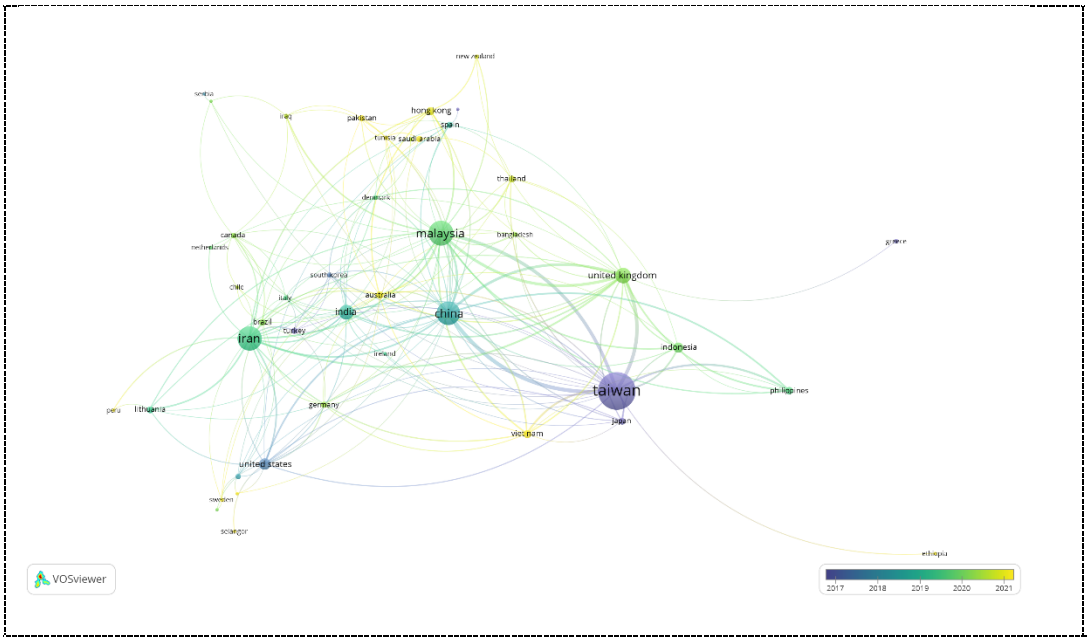
The co-authorship network among countries in FDM-related publications from 1997 to 2022 involved 67 countries. Applying a threshold requiring each country to have published at least 2 documents with a minimum of 2 citations, 34 countries met the criteria. These countries were then categorized into 9 different clusters (refer to Figure 10). According to Figure 10, the clusters are

represented by the colors red, green, blue, yellow, purple, turquoise, orange, brown, and magenta for Cluster 1, Cluster 2, Cluster 3, Cluster 4, Cluster 5, Cluster 6, Cluster 7, Cluster 8, and Cluster 9, respectively. Taiwan, belonged in Cluster 4 ranked first in both the total number of documents (315) and total link strength (166), although it did not lead in terms of the number of links. Conversely, Malaysia emerged as the top country with the highest number of links (26).



Note: Unit of analysis = Countries; Counting method: Full counting; Minimum number of documents of an author = 2; Minimum number of citations of an author = 2

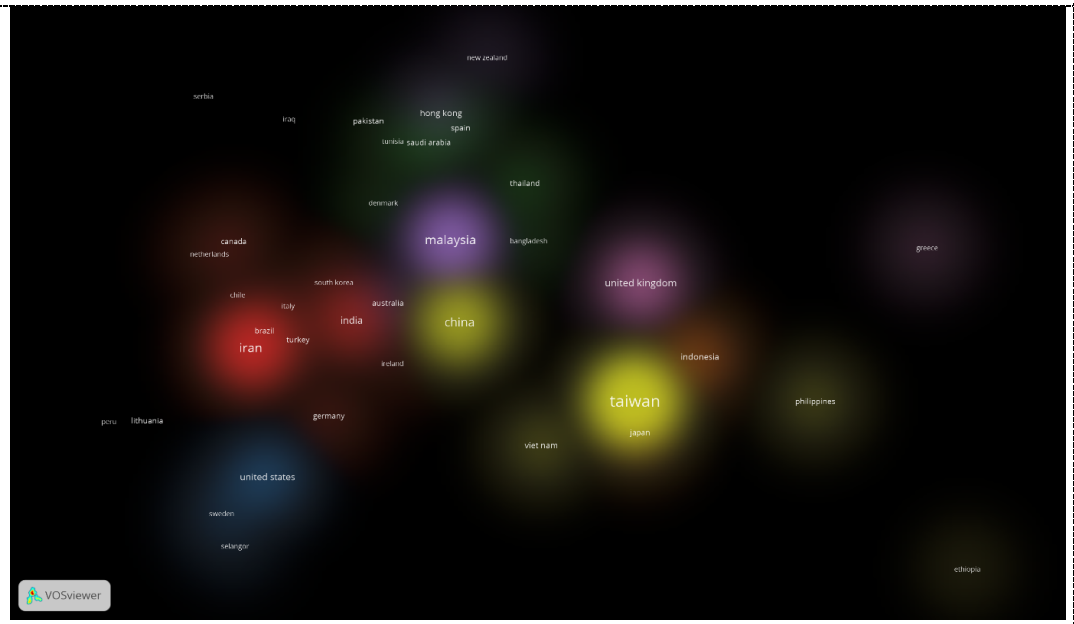
Fig. 10. Network visualisation map of the co-authorship in FDM research



Note: Unit of analysis = Countries; Counting method: Full counting; Minimum number of documents of an author = 2; Minimum number of citations of an author = 2

Fig. 11. Network visualisation map of the co-authorship in FDM research

Regarding citations, Taiwan also holds the highest position with a total of 6374 citations. However, focusing on recent publications (indicated by the yellow color in Figure 11), Ethiopia, Morocco, Pakistan, Vietnam, Tunisia, Peru, Malaysia, and Sweden emerged as the top eight countries, with average publication years ranging from 2021 to 2022. Lastly, Figure 12 displayed the density visualization, enabling viewers to promptly identify dense areas [13], notably Taiwan (highlighted in yellow), where numerous nodes are closely located.



Note: Unit of analysis = Countries; Counting method: Full counting; Minimum number of documents of an author = 2; Minimum number of citations of an author = 2

Fig. 12. Density visualisation map of the co-authorship in FDM research

4. Conclusion

The evolution and publication trends of the FDM were comprehensively analyzed in this study to answer RQ 1. By examining 766 records from the Scopus database spanning 1991 to 2022, the study revealed insights into document types, sources, languages, and subject areas. The predominant document type was articles, comprising 80.0% of the total, with journals being the primary source type, contributing 82.0% of the documents. English was the predominant language, representing 97.3% of the total publications. Engineering, Computer Science, and Social Sciences emerged as the prominent subject areas, indicating a diverse range of applications for the FDM across various disciplines. While there was a general increasing trend in the number of publications over the years, the total citation trend did not consistently reflect this pattern, suggesting variations in the impact of FDM research across different publication years.

The RQ 2 of this study aimed to identify the countries, institutions, authors and source titles making substantial contributions to FDM research. Taiwan emerged as the top contributor with 315 publications, followed by Malaysia and Iran. However, the United States demonstrated the highest impact based on citation metrics such as PCP and CCP. Taiwan exhibited the highest h-index and g-index values, reflecting its strong influence and productivity in FDM research. The top influential institutions included Asia University in Taiwan and Universiti Kebangsaan Malaysia, located in Malaysia. Additionally, notable authors such as Tseng M.L. from Asia University in Taiwan and Lim

M.K. from the University of Glasgow in the United Kingdom demonstrated significant productivity and impact in FDM research. Regarding source titles, Sustainability Switzerland and Expert Systems with Applications emerged as the most active journals with the highest TP and TC, respectively, for publishing FDM-related research.

Furthermore, the third RQ of this study explored collaborative trends among authors and countries in FDM research. A co-authorship network analysis revealed robust collaboration among authors, with Tseng M.L. emerging as the most prolific collaborator. The most recent article with the highest citation count belongs to Bui et al. [6], titled “Opportunities and challenges for solid waste reuse and recycling in emerging economies: A hybrid analysis”. Meanwhile, the co-authorship network among countries involved 67 countries, categorized into 9 different clusters based on collaboration patterns. Taiwan ranked first in both the total number of documents and total link strength, indicating its central role in collaborative networks. Interestingly, recent publications showed emerging collaborations among countries such as Ethiopia, Morocco, Pakistan, Vietnam, Tunisia, Peru, Malaysia, and Sweden, highlighting the evolving landscape of international collaboration in FDM research. Overall, the study has shown collaborative dynamics and trends in FDM research, contributing to a deeper understanding of its global impact and interdisciplinary applications.

While the study provides valuable insights into collaborative trends in FDM research, several limitations should be considered. Firstly, the analysis is based on data retrieved from the Scopus database, which might not encompass all relevant publications in the field. Other databases or sources of information could provide additional insights into FDM research collaborations. Secondly, the study focuses primarily on quantitative bibliometric analysis, which may not capture qualitative aspects of collaboration such as the nature of interactions among researchers or the quality of collaborative outputs. Incorporating qualitative methods such as interviews or surveys could provide a more comprehensive understanding of collaborative dynamics in FDM research. Lastly, the study's analysis is limited to co-authorship patterns and citation metrics, neglecting other forms of collaboration such as joint research projects or collaborative grants, which could offer further insights into collaborative networks in the field.

To address these limitations and enhance future research in this area, several recommendations can be made. Firstly, researchers should consider employing a multi-method approach that combines quantitative bibliometric analysis with qualitative methods to provide a more holistic understanding of collaborative dynamics in FDM research. By integrating qualitative and quantitative data, this approach leverages the advantages of both research while mitigating the limitations of each method [41]. Qualitative methods such as interviews or focus groups could help elucidate the motivations, challenges, and benefits of collaboration among researchers in the field. Interviews become essential when our focus is on past events that cannot be replicated [42]. Secondly, efforts should be made to expand the scope of data collection beyond traditional bibliometric indicators to include other forms of collaboration such as co-citation, joint research projects, collaborative grants, or co-development of tools or methodologies. This would provide a more comprehensive picture of collaborative networks and their impact on the advancement of FDM methodologies and applications. Lastly, future studies could explore the role of interdisciplinary collaboration in FDM research, considering the potential contributions of researchers from diverse fields such as engineering, computer science, social sciences, and others to address complex real-world problems effectively. Furthermore, exploring AI-driven investigations pertaining to FDM among students could be beneficial, as students represent the future workforce capable of advancing and enhancing the industry further [43].

In conclusion, this study addresses the aim of exploring co-authorship patterns and trends in FDM research literature to enhance our comprehension of collaborative networks and their influence on

the progression of FDM methodologies and applications. The findings illuminate collaborative trends in FDM research, underscoring the diverse contributions of countries, institutions, and authors to the field. Despite providing valuable insights into co-authorship patterns and citation metrics, it's crucial to acknowledge the study's limitations. By implementing the recommended strategies, future research endeavors can deepen our understanding of collaborative networks and their role in advancing FDM methodologies and applications across various domains.

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