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Review

Recent Advances in Yttrium Iron Garnet Films: Methodologies, Characterization, Properties, Applications, and Bibliometric Analysis for Future Research Directions

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Abstract: Due to recent advances in communication systems, dielectric and magnetic ceramics (ferrites) are attractive for use in devices. Spinel-type ferrites were the first material utilized in microwave devices; however, yttrium iron garnet (YIG) has low dielectric losses and is exploited in many applications. Owing to its high Faraday rotation, YIG films are utilized in magneto-optical applications. This study intends to examine the research trends and scientific research progress on highly cited papers discussing YIG films published between 2012 and 2022 using a bibliometric method. A comprehensive review of 100 scientific papers about YIG was performed from the Scopus database. The assessment of these highly cited papers was highlighted based on the following factors: publication trends and performance, limitations/research gaps, keywords, sub-fields, methodology journal evaluations, document type evaluation, issues, difficulties, solutions, and applications as well as guiding future YIG research. The majority of publications (99%) comprise experimental analysis, whereas 1% provide a based state-of-the-art overview. Ninety-one percent of articles focused on magnetization characterization. This bibliometric survey indicates that YIG film research is an expanding and developing field. The results of the data analysis can be utilized to improve the researchers' understanding of YIG research and to encourage additional study in this area.

Keywords: yttrium iron garnet (YIG); thin film; bibliometric analysis; highly cited papers; methodology; statistical analysis

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1. Introduction

Magnetic garnets are essential components in a variety of bulk and thin film devices that require magnetic insulators. Initial experiments in magnonics were inspired by radar and microwave applications and were conducted with bulk yttrium iron garnet (YIG) crystals [1,2]. In the past, bulk YIG crystals were utilized to explore magnonics on the micrometer to millimeter length scales required for microwave devices [3]. Presently, yttrium iron garnet ($Y_3Fe_5O_{12}$, YIG) has been used for spintronics [4–7]. Spintronics applications that employ yttrium iron garnets emerged in 2010 and 2011 [8]. This interest is based on the fact that YIG materials have two important characteristics; namely, they have relatively low intrinsic damping $a_o = 3 \times 10^{-5}$ [6,9] and electrically insulating [6,8]. Low damping in YIG is essential for the construction of magnonic logic devices to transport, store, and process microwave and digital information. This minimal damping is very desirable for a variety of applications, such as spin-torque oscillators and spin-wave-based logic circuits [8]. Recent spintronics research has emphasized the transfer of spin information through spin-wave or magnon excitations in magnetic insulators [10]. Spintronic phenomena generate, manipulate, and detect spin-polarized charge carriers [2]. Additionally, YIG has the low infrared absorption, high Verdet constant, and extremely low damping that needed for applications such as Faraday rotators, isolators, and sensors [7].

The development of YIG-based spintronics necessitates YIG thin films with a nanometer-scale thickness and minimal damping. Unlike bulk crystal applications, thin film devices rely on interactions across the interface; consequently, surface properties (such as topology and magnetism) are crucial [7]. Extensive attention has been paid to the formation of micron or submicron-thick YIG films and the growth of nanometer-thick YIG films in the context of YIG research development [6]. In addition, the production of YIG films with superior structural and magnetic properties has the potential to be utilized to integrate spintronic, magnonic, and magneto-optical systems [2]. For magneto-optical activity, YIG is very transparent at near-IR communication wavelengths [11]. For magneto-optical devices, the Y is partly substituted by rare earth, which can boost the Faraday rotation by an order of magnitude [11,12]. For example, cerium-doped YIG is a promising 1550 nm isolator material due to its high magneto-optical properties, indicated by the Faraday rotation divided by the optical absorption, and this is similarly observed in optical isolators comprised of Ce:YIG [12]. YIG can be synthesized using several techniques, including pulsed laser deposition (PLD) [2,8,11–17], molecular beam epitaxy (MBE) [18,19], liquid phase epitaxy (LPE) [17,20–25], radio frequency (RF) magnetron sputtering [6,26–28], ion beam sputtering [29,30], chemical vapor deposition (CVD) [31], sol-gel [32–34], metal–organic decomposition (MOD) [35], etc. Pulsed laser deposition (PLD) is a typical method for the development of oxide thin films [7]. Nevertheless, systematic studies of YIG development and the association between the structural and magnetic properties are limited [7]. High-quality YIG thin films can be fabricated on a gadolinium gallium garnet (GGG), yttrium aluminum garnet (YAG) single crystal, silicon (Si), and gallium arsenide (GaAs) and be doped with rare earth elements to control the ferrimagnetic resonance (FMR) linewidth and for other applications [36,37]. GaAs substrate is popular in conventional complementary metal-oxide-semiconductor (CMOS) applications because it has excellent charge carrier mobility and a broad band gap. In the example of germanium epitaxial films on GaAs substrates, the electrons recombine with valence band holes at a 0.8 eV energy level [38]. YIG structures on GaAs substrates are promising for magnonic and spintronic element integration [30]. There are reports that have been presented in leading scholarly publications with discussion on these subjects.

YIG thin film has enormous potential applications in numerous sectors, but there is not enough literature in this area of research compared to the world's research capability. Reviewing the literature is an important way to refine the outcomes of past investigations so that current knowledge may be used efficiently, promoting research and offering evidence-based perspectives on evaluation, expertise, and management. Bibliometrics provided a reproducible, systematic, and straightforward numerical analysis of scientific performance [39]. Bibliometrics is a type of research strategy that utilizes library and information science to provide information and analysis concerning specific research, such as statistics and a quantitative approach [40,41]. Bibliometrics is a significant subject of study because it provides specific and historical data that may be utilized to forecast future research trends. When applying bibliometric techniques, researchers assess, illustrate, and evaluate the theme of scientific research and further establish the links between the authors, frameworks, methodologies, journals, countries, and research institutions and practices in numerous scientific study domains [42–44]. Bibliometrics is frequently used to rank academic positions and evaluate the performance of publications, nations, and organizations. In addition, it plays a significant part in scientific decision-making. Bibliometric results may also serve as a foundation for the establishment of applicable policies and the theoretical underpinning of scientific research in connected areas [45].

In recent years, many researchers have utilized bibliometric techniques [39,40,42–50] to determine the development of various subjects or disciplines. To the best of our knowledge, no bibliometric research in YIG has been reported. The Scopus database reveals that this YIG research began in 1956 based on the keywords used. It was noted that YIG film has been widely utilized for many applications in recent times. As a result, the number of articles discussing the growth of high-quality magnetic garnet thin films and the implementation of innovative technology frameworks relying on these thin films is rapidly increasing. To highlight the important findings in these disciplines and to direct future research, we have analyzed the recent and top cited literature in the field of YIG. Utilizing the Scopus database, this research presents a bibliometric survey of YIG with the current top 100 most cited works in the years between 2012 and 2022. The paper summarizes the data and analysis of the top 100 cited YIG articles. Based on the information from the literature, some insights into the peculiarities of YIG films are provided and explored. Specific objectives of the analysis include the determination of the scientific research trend, evaluating the subject, methodology, keywords, and document type, and assessing the authorship in the field of YIG films. This study also employed a qualitative method to evaluate YIG thin film techniques, film properties, and applications. This work's bibliometric approach is intended to establish the evolution and research perspective of YIG thin films. It will aid researchers by offering a thorough background to direct their work as it covers important studies about this topic and includes important discussions.

This paper is organized as follows: Section 2 presents the data source and surveying methodology using the Scopus database. Section 3 provides an overview of the state-of-the-art YIG and introduces the top 100 articles as identified by Scopus. Section 4 of the paper proceeds with an analysis of the publication trends and country performance, top 10 articles (discussing their rank, methodology, number of authors, methodology, film characterization, scope/outcome/advantages, and application), subject categories evaluation methodology evaluation for the top 100 articles (discussing their preparation, substrates, film characterization, and applications), keywords assessment, and document type evaluation. In Section 5, the issues and recommendations are described, and Section 6 provides a summary of the conclusion and pertinent future directions that are relevant to the topics.

2. Data Source and Surveying Methodology

The methodology used to analyze this study is a bibliometric analysis, a scientific method that is widely accepted and used worldwide. Bibliometrics is a scientific method that uses mathematical techniques and statistics to evaluate a given scientific output [51]. Numerous databases, including PubMed, Web of Science, Scopus, Web of Science, Google Scholar, and Baidu Scholar can be searched for articles containing strategy in research [52–54]. The statistical analysis for this study was conducted using the Scopus database. Scopus was chosen rather than other databases because it contains a broader range of publications throughout almost all research disciplines [55]. Therefore, it was an easy choice for this analysis. The first publication of the yttrium iron garnet was recorded in the year 1957. Our study examined research publications on yttrium iron garnet (YIG) thin films that were published solely between 2012 and 2022. The data for yttrium iron garnet were collected from the Scopus database in the third week of July 2022.

The primary objective of this research is to update the summary section of the publications in the Scopus database and to evaluate the development advancements in the fields of yttrium iron garnet thin film over the last ten years. This is to shed light on the state of the research in this area of publication. This study analyzes the most cited research in YIG as well as the top citation journals, publishers, authors, and nations. The methodologies, limitations/research gaps, keywords, challenges, difficulties, and solutions, as well as suggestions for future YIG research, were highlighted in the evaluation of the publications with the highest citation counts.

2.1. Selection Method

The technique for performing this study was determined through a top-down review of the top 100 papers in the Scopus database. Certain criteria for selecting highly cited papers from the 100 publications were established based on the following: chosen keywords (yttrium iron garnet, thin film, magnetic properties), publication years (2012–2022), subject area (physics and astronomy, materials science), document type (article), source type (journal), language (English), and relevance and significance to practical topics. The review of evaluating survey methods in the Scopus database is shown as follows:

1. Evaluation Selection method
    - During the initial search (first step) of the Scopus database, a total of 5429 papers on yttrium iron garnet were discovered. Due to the large number of papers, the sample size was too large for an exhaustive search and analysis. As a consequence, the articles were chosen and filtered based on a variety of criteria to define the data search.
    - In Step 2, 1428 papers were identified using the keywords "thin film" and "magnetic properties".
    - In Step 3, 896 papers were discovered between the years 2012 and 2022 in the specified subject areas of physics, astronomy, and materials science.
    - In Step 4, 799 papers were chosen based on the journal source type, article document type, and English proficiency, considering that English is the international language spoken at the United Nations and at majority of international conferences.
    - In Step 5, 100 papers were identified for final analysis based on their title, abstract, content relevancy, and contribution to practical topics. All shortlisted publications were the research published in international journals between 2012 and 2022. The papers were sorted from highest to lowest by citation count. The data obtained from the 100 scholarly papers on YIG constitute a sufficient evaluation of the literature on the topic.

The 100 articles chosen to explore a wide range of topics: (a) state-of-the-art discussion of the top articles with the highest citation counts; (b) publishing performance and trends (include citation structure and the countries involved and leading the research areas); (c) top 10 articles evaluation; (d) subject categories evaluation; (e) evaluation techniques based on methodologies, substrate types, and film characterization and applications; (f) favorable keyword evaluations; and (g) document evaluations, which may contain journal articles and their impact factors. For future directions, applications of YIG-based literature, difficulties, and recommendations were described.

2. Review discussions and findings
    - Data sources and surveying methodology include selection method and yearly trends in scientific publications.
    - State-of-the-art YIG based on the top 10 articles were discussed, including the methodologies, scope, findings, and research gaps.
    - The analytical discussion concentrated on publication performance and trends, subject categories and evaluation, methodological journal evaluation, keyword assessment, document type evaluation, and evaluation of the most prominent authors.
    - Future directions and conclusions emphasize the applications, challenges, and solutions underlying YIG. General recommendations for promoting YIG research were provided.

2.2. Annual Trends in Scientific Publication

The global annual number of YIG publications from 1961 to 2022 is depicted in Figure 1. The patterns were collected using the "thin film" and "magnetic properties" keyword selection method. As the graph demonstrates, the annual number of articles and annual growth rate fluctuated over time. According to the Scopus archives in 1961, an article was written by Banks et al. [56] and published in the *Journal of Applied Physics*. Four authors were from the United States. This research reported the fabrication and properties of thin ferrite films using vacuum evaporation. These ferrites films attained high magnetizations of up to 2200 gauss, which enables optical transmission investigations of the material and should permit the observation of spin-wave resonances to determine magnetic exchange constants. From 1961 to 2000, a total of 233 papers were published; 239 papers were between 2001 and 2011, and 941 papers were between 2012 and 2022. Until the year 2000, the growth rate of papers was approximately 1%, which is fairly modest. Since then, the number of published papers has increased by approximately 1.6% per year until 2011. The highest growth rate was then observed in 2020, with a 9.66% increase in the total percentage of articles represented. During the selected period, the number of publications in YIG research quickly expanded, from a low of 233 papers from 1961 to 2000 (29 years) to a high of 941 papers from 2012 to 2022 (10 years). During recent years, there has been discernible growth. The highest number of papers was recorded in 2020, when 138 were published, marking a 9.66% growth rate in publications.

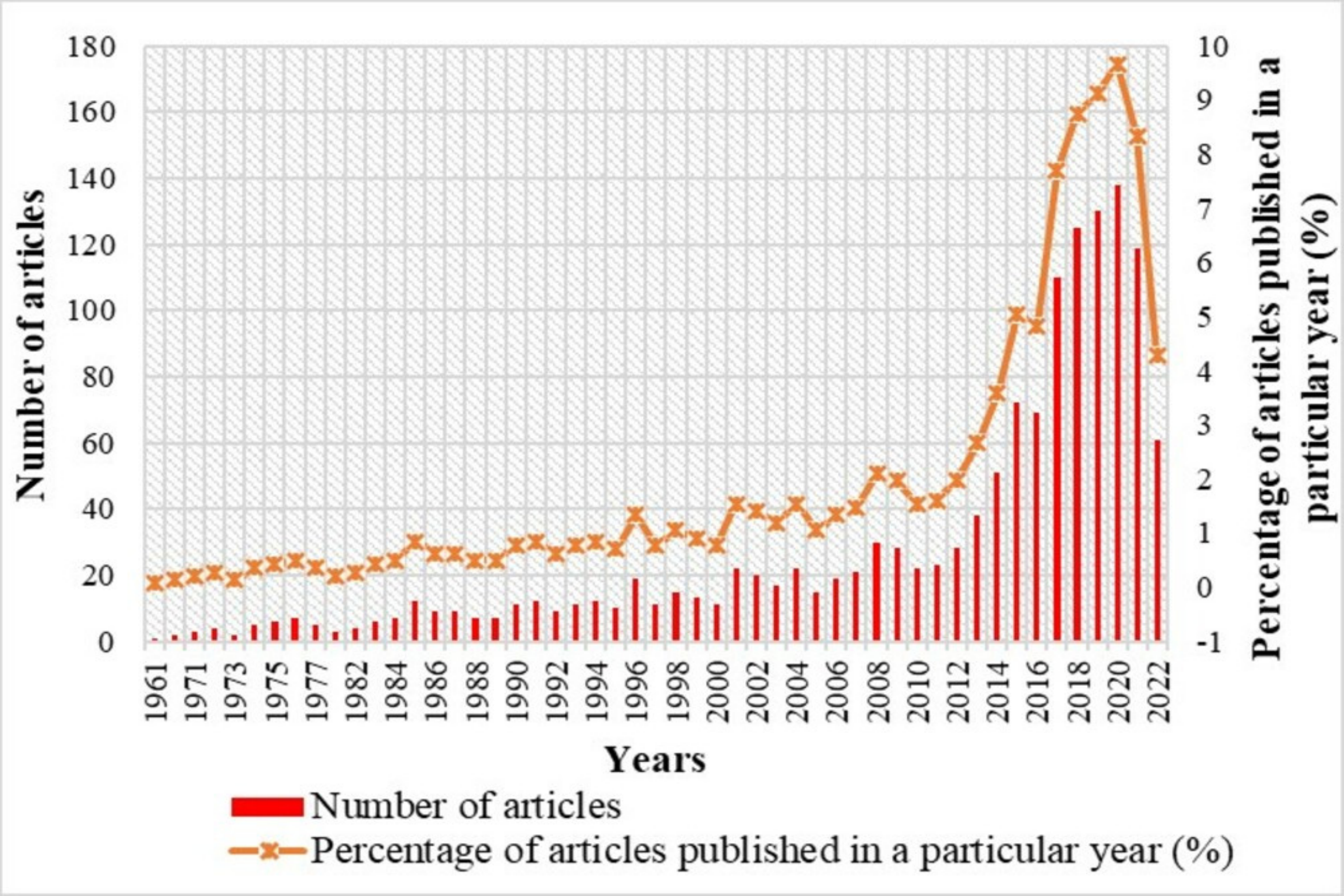

Figure 1. Global annual trend of YIG from 1961 to 2022.

YIG materials are employed in phase shifters, isolators, and circulators [57]. This is due to YIG having small magnetic damping. Currently, YIG materials are popular for spintronic and magnon device applications. YIG-based devices may provide faster domain wall motion, magnetization switching with lower currents, and more energy-efficient information transfer than metal-based devices [58]. This paper discusses YIG film development for future research in the area.

3. State-of-the-Art of YIG

Yttrium iron garnet ($Y_3Fe_5O_{12}$, YIG) is a versatile ferromagnetic insulator with low magnetic damping and outstanding magneto-optical characteristic that has been widely utilized in electrical and microwave devices, including oscillators, filters, antennas, phase shifters, and magnetic field sensors [59].

In 1957, the first publication of YIG [60] was published. Geller and Gilleo's publication [60] garnered 250 citations. In their study, the crystal structure and ferrimagnetism of YIG are described. The distance between tetrahedral iron and oxygen is 1.88 $\acute{\text{Å}}$, the distance between octahedral iron and oxygen is 2.00 $\acute{\text{Å}}$, and the lengths between yttrium and oxygen are 2.37 $\acute{\text{Å}}$ and 2.43 $\acute{\text{Å}}$. Interionic lengths and angles are essential for magnetic ion interaction. Fe^{3+} in the 16(a) and 24(d) places had the strongest magnetic interactions. Figure 2 depicts the crystal structure of YIG as described by Geller and Gilleo in their publication [60]. YIG exhibits a cubic symmetry, defined composition, trivalent metal ions, large Faraday constant, and minimal magnetic damping. These qualities make it ideal for studying spin-waves, magneto-optical phenomena, and magnetic insulator-based spintronics [9].

YIG films and films of other iron garnets were the topics of intensive research. Perspectives for the development of a variety of microwave filters, delay lines, and magneto-optical devices for information storage and processing, such as magneto-optical transparencies, displays, deflectors, optical insulators, read heads, and integrated magneto-optical devices, have sparked interest in these films. The use of YIG in these investigations was necessitated by the material's superior magnetic, optical, and magneto-optical properties, including incredibly low spin-wave damping, great transparency in a broad spectrum range, and a strong Faraday effect [61].

There has also been a growing interest in the production of metamaterials having simultaneously negative permittivity and permeability, known as double negative materials (DNMs), exhibiting "reversed" electromagnetic properties and innovative potential applications [59,62–64]. Because of its superior negative permeability features, YIG is the most promising candidate for the realization of negative permeability [65]. YIG can generate negative permeability in the absence of an external magnetic field. When a magnetic field is provided, the negative permeability of YIG can become adjustable [66]. With YIG's potential for use in the construction of metamaterials, its magnetic properties had been exhaustively investigated to tune for either negative permittivity or negative permeability [59,65,66]. This is significant, as ferrimagnetic YIG with simultaneously negative permittivity and negative permeability have excellent metamaterial performance and become an effective alternative for ordered metamaterials in wave-transparent, solar energy harvesting fields and microwave-absorbing [64].

In recent years, magnetic heterostructures with nanoscale YIG layers have gained popularity. The latest innovations in magnonics and oxide spintronics have sparked interest in transporting information via spin-wave packets instead of current carriers [61].

Using the Scopus database, only papers published between 2012 and 2020 were listed among the top articles. The dataset covers 100 of the most cited papers from 2012 to 2020, as shown in Table 1. The data are organized in Table 1 according to rank, author name, publication year, number of authors, journal, publisher, impact factor, country, and research methodology. Impact factor values for the most recent year of article publication have been determined. According to the findings in Table 1, the number of publications annually produced in the YIG field has varied throughout the period. The data from Table 1 will be statistically and graphically analyzed using VOS viewer, Microsoft Excel, and Microsoft PowerPoint software. The gathered information is described in Section 4.

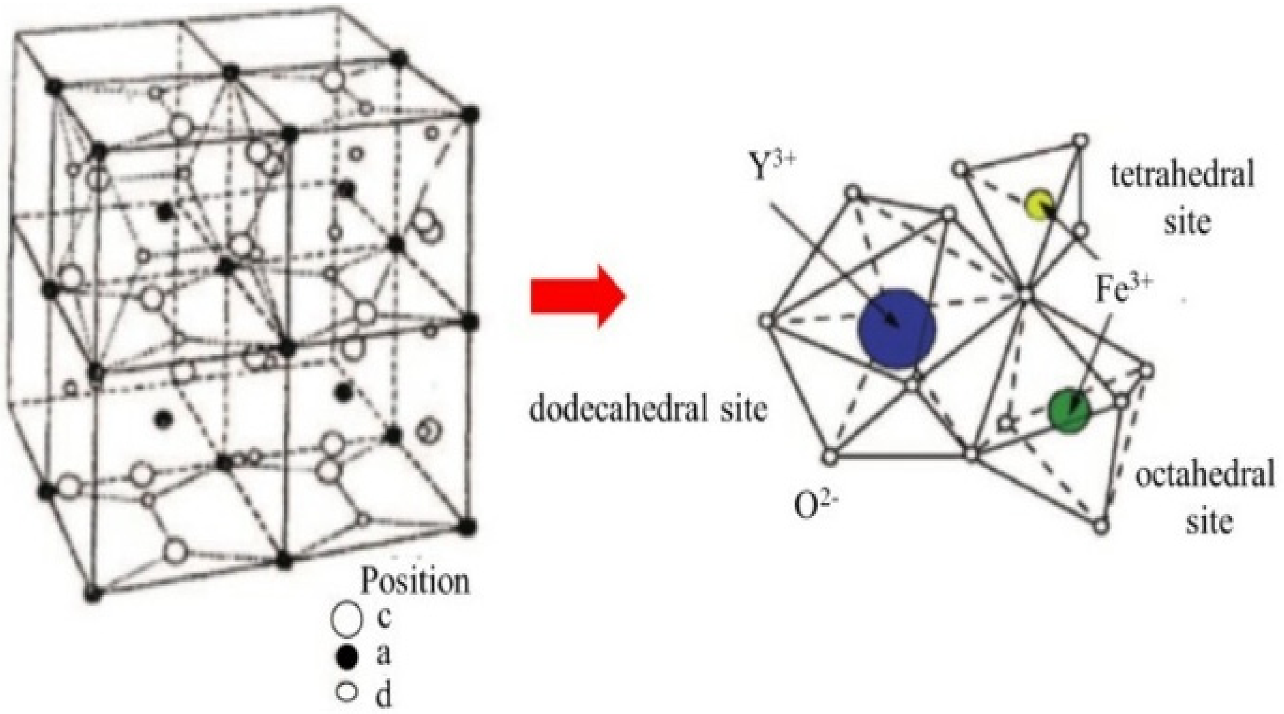

Figure 2. Unit cell YIG with three cation sub-lattices [67].

Table 1. The top 100 papers in the field of yttrium iron garnet, ranked from highest to lowest by number using the Scopus database.

Ref	Rank	Authors	Years	NC	No. of Authors	Journal	Publishe	IF	Country	Methodology
[13]	1	Wang et al.	2015	383	5	*Physical Review Letters*	APS	9.185	USA	PLD
[36]	2	Huebl et al.	2013	377	8	*Physical Review Letters*	APS	9.185	Germany	-
[18]	3	Althammer et al.	2013	349	21	*Physical Review B*	APS	3.908	Germany	MBE
[68]	4	Rezende et al.	2014	227	8	*Physical Review B*	APS	3.908	Brazil	-
[8]	5	Sun et al.	2012	202	9	*Applied Physics Letters*	AIP	3.971	USA	PLD
[14]	6	Sun et al.	2013	201	14	*Physical Review Letters*	Aps	9.185	USA	PLD
[69]	7	Cornelissen et al.	2016	193	5	*Physical Review B*	APS	3.908	UK	-
[20]	8	Lu et al.	2013	185	8	*Physical Review Letters*	APS	9.185	China	LPE
[15]	9	D'Allivy et al.	2013	179	16	*Applied Physics Letters*	AIP	3.971	France	PLD
[5]	10	Chang et al.	2014	171	7	*IEEE Magnetics Letters*	IEEE	1.549	USA	Sputtering deposition
[16]	11	Schreier et al.	2013	169	7	*Physical Review B*	APS	3.908	Germany	PLD
[19]	12	Lang et al.	2014	153	19	*Nano letters*	ACS	11.19	USA	PLD
[2]	13	Onbasli et al.	2014	147	8	*APL Materials*	AIP	6.635	USA	PLD
[17]	14	Kehlberger et al.	2015	143	12	*Physical Review Letters*	APS	9.185	Germany	PLD and LPE
[70]	15	Mendes et al.	2014	143	8	*Physical Review B*	APS	3.908	Brazil	Magnetron sputtering

Table 1. *Cont.*

Ref	Rank	Authors	Years	NC	No. of Authors	Journal	Publishe	IF	Country	Methodology
[6]	16	Liu et al.	2014	123	8	*Journal of Applied Physics*	AIP	2.877	USA	RF sputtering
[71]	17	Boona and Heremans	2014	114	2	*Physical Review B*	APS	3.908	USA	-
[21]	18	Goennenwein et al.	2015	113	7	*Applied Physics Letters*	AIP	3.971	Germany	LPE
[72]	19	Yu et al.	2016	110	9	*Nature Communications*	Nature Research	17.69	Germany	Magnetron sputtering
[22]	20	Mendes et al.	2015	104	9	*Physical Review Letters*	APS	9.185	Brazil	LPE
[23]	21	Holanda et al.	2108	96	4	*Nature Physics*	Nature Publishing Group	19.68	Brazil	LPE
[73]	22	Jin et al.	2015	93	5	*Physical Review B*	APS	3.908	USA	-
[74]	23	Giles et al.	2015	91	4	*Physical Review B*	APS	3.908	USA	-
[75]	24	Jungfleisch et al.	2015	91	9	*Physical Review B*	APS	3.908	Germany	PLD
[76]	25	Meyer et al.	2017	90	12	*Nature Materials*	Nature Publishing Group	47.66	Germany	PLD
[26]	26	Marmion et al.	2014	90	5	*Physical Review B*	APS	3.908	UK	RF magnetron sputtering
[11]	27	Goto et al.	2012	89	3	*Optic Express*	Optica	3.833	USA	PLD
[24]	28	Seifert et al.	2018	88	12	*Nature Communications*	Nature Research	17.69	Germany	LPE
[77]	29	Jiang et al.	2015	88	6	*Nano letters*	ACS	11.19	USA	PLD
[25]	30	Dubs et al.	2017	81	6	*Journal of Physics D: Applied Physics*	IOP	3.207	Germany	LPE
[78]	31	Klingler et al.	2018	80	12	*Physical Review Letters*	APS	9.185	Germany	-
[79]	32	Rückriegel et al.	2014	79	5	*Physical Review B*	APS	3.908	Germany	-
[66]	33	Shi et al.	2013	79	8	*Journal of Materials Chemistry C*	RCS	8.067	China	Solid state reaction method
[80]	34	Chen et al.	2018	77	8	*Physical Review Letters*	APS	9.185	China	Magnetron sputtering
[81]	35	Quindeau et al.	2017	76	12	*Advanced Electronic Materials*	Wiley-VCH Verlag	7.633	USA	PLD
[82]	36	Jiang et al.	2016	76	8	*Nature Communications*	Nature Research	17.69	USA	PLD
[12]	37	Sun et al.	2015	74	8	*ACS Photonics*	ACS	7.15	USA	PLD
[59]	38	Cheng et al.	2019	72	9	*Journal of Materials Chemistry C*	RCS	8.067	China	-

Table 1. *Cont.*

Ref	Rank	Authors	Years	NC	No. of Authors	Journal	Publishe	IF	Country	Methodology
[83]	39	Collet et al.	2017	72	12	*Applied Physics Letters*	AIP	3.971	France	PLD
[37]	40	Meyer et al.	2014	70	5	*Applied Physics Letters*	AIP	3.971	Germany	not mention
[30]	41	Sadovnikov et al.	2019	68	9	*Physical Review B*	APS	3.908	Russia	Sputtering deposition
[84]	42	Rezende et al.	2016	68	5	*Journal of Magnetism and Magnetic Materials*	Elsevier	2.993	Brazil	LPE
[85]	43	Flebus et al.	2017	65	8	*Physical Review B*	APS	3.908	Netherlanc	-
[86]	44	Kehlberger et al.	2015	65	11	*Physical Review Applied*	APS	4.931	Germany	PLD
[87]	45	Evelt et al.	2016	63	12	*Applied Physics Letters*	AIP	3.971	Germany	PLD
[88]	46	Bhoi et al.	2019	58	7	*Physical Review B*	APS	3.908	South Korea	Not mention
[89]	47	Du et al.	2014	58	4	*Physical Review Applied*	APS	4.931	USA	Sputtering deposition
[90]	48	Christofi et al.	2018	57	4	*Optics Letters*	Optica	3.56	USA	-
[91]	49	Kimling et al.	2017	57	8	*Physical Review Letters*	APS	9.185	USA	PLD
[92]	50	Wesenberg et al.	2017	56	5	*Nature Physics*	Nature Publishing Group	19.68	USA	Sputtering
[93]	51	Maier et al.	2016	56	5	*Physical Review B*	APS	3.908	Germany	LPE
[31]	52	Dushenko et al.	2016	55	9	*Physical Review Letters*	APS	9.185	Japan	CVD
[94]	53	Howe et al.	2015	55	9	*IEEE Magnetics Letters*	IEEE	1.549	USA	PLD
[95]	54	Meyer et al.	2014	52	7	*Applied Physics Letters*	AIP	3.971	Germany	PLD
[96]	55	Haigh et al.	2015	52	4	*Physical Review B*	APS	3.908	UK	-
[97]	56	Jermain et al.	2017	50	9	*Physical Review B*	APS	3.908	USA	Sputtering
[98]	57	Zare et al.	2015	50	3	*Physical Review B*	APS	3.908	Iran	-
[99]	58	Cornelissen et al.	2017	48	8	*Physical Review B*	APS	3.908	UK	LPE
[100]	59	Mruczkiewicz et al.	2014	48	6	*Physical Review B*	APS	3.908	UK	Chemical etching
[101]	60	Bozhko et al.	2017	47	9	*Physical Review Letters*	APS	9.185	Germany	-
[65]	61	Shi et al.	2015	47	7	*Journal of the European Ceramic Society*	Elsevier	5.302	China	Wet chemical technique
[102]	62	Maier et al.	2017	46	8	*Physical Review B*	APS	3.908	Germany	-
[7]	63	Tang et al.	2016	46	9	*Applied Physics Letters*	AIP	3.971	USA	PLD

Table 1. *Cont.*

Ref	Rank	Authors	Years	NC	No. of Authors	Journal	Publishe	IF	Country	Methodology
[27]	64	Li et al.	2020	45	12	*Physical Review Letters*	APS	9.185	USA	Magnetron sputtering
[103]	65	Fanchiang et al.	2018	44	10	*Nature Communications*	Nature Research	17.69	Taiwan	Sputtering
[104]	66	Sharma and Kuanr	2018	44	2	*Journal of Alloys and Compounds*	Elsevier	5.316	India	Solid state reaction method
[105]	67	An et al.	2020	43	12	*Physical Review B*	APS	3.908	France	LPE
[61]	68	Sokolov et al.	2016	43	12	*Journal of Applied Physics*	AIP	2.877	Russia	PLD
[106]	69	Streib et al.	2019	40	4	*Physical Review B*	APS	3.908	UK	-
[92]	70	Tian et al.	2015	39	5	*Applied Physics Letters*	AIP	3.971	USA	RF magnetron sputtering
[107]	71	Haidar et al.	2015	39	6	*Journal of Applied Physics*	AIP	2.877	Sweeden	PLD
[108]	72	Onbasli et al.	2014	39	5	*Optics Express*	Optica		USA	PLD
[109]	73	Jiang et al.	2016	38	6	*AIP Advances*	AIP	1.697	USA	PLD
[110]	74	Rezende et al.	2014	38	4	*Physical Review B*	APS	3.908	Brazil	-
[111]	75	Stenning et al.	2013	38	8	*Optics Express*	Optica		UK	PLD
[112]	76	Aakansha et al.	2017	37	4	*Ceramics International*	Elsevier	4.527	India	Solid-state reaction method
[113]	77	Matatagui et al.	2015	37	5	*Nanoscale*	RCS	8.307	Mexico	-
[114]	78	Lin et al.	2013	37	3	*Applied Physics Letters*	AIP	3.971	USA	PLD
[115]	79	Dulal et al.	2016	36	7	*ACS Photonics*	ACS	7.15	USA	Sputter epitaxy
[116]	80	Rückriegel and Kopietz	2015	36	2	*Physical Review Letters*	APS	9.185	Germany	Equation-based experiment
[117]	81	Qin et al.	2018	35	6	*Nature Communications*	Nature Research	17.69	Finland	PLD
[118]	82	Cramer et al.	2018	35	8	*Nano Letters*	ACS	11.19	Germany	LPE
[119]	83	Jiang et al.	2014	35	6	*Applied Physics Letters*	AIP	3.971	USA	PLD
[120]	84	Davies et al.	2015	34	6	*Applied Physics Letters*	AIP	3.971	UK	-
[121]	85	Saiga et al.	2014	34	7	*Applied Physics Express*	IOP	2.895	Japan	Sputtering
[122]	86	Gruszecki et al.	2015	33	7	*Physical Review B*	APS	3.908	Poland	-
[34]	87	Aldbea et al.	2014	33	3	*Applied Surface Science*	Elsevier	6.707	Malaysia	Sol-gel
[123]	88	Wimmer et al.	2019	32	8	*Physical Review Letters*	APS	9.185	Germany	-
[28]	89	Li et al.	2016	30	6	*Nanoscale*	RSC	8.307	USA	Magnetron sputtering

Table 1. *Cont.*

Ref	Rank	Authors	Years	NC	No. of Authors	Journal	Publishe	IF	Country	Methodology
[124]	90	Fakhrul et al.	2019	28	6	*Advanced Optical Materials*	Wiley-VCH	10.05	USA	PLD
[125]	91	Vasili et al.	2017	28	11	*Physical Review B*	APS	3.908	Spain	-
[126]	92	Sposito et. al.	2013	28	5	*Optical Materials Express*	Optica	3.074	UK	PLD
[127]	93	Cooper et al.	2017	27	10	*Physical Review B*	APS	3.908	UK	Magnetron sputtering
[128]	94	Gallagher et al.	2016	27	14	*Applied Physics Letters*	APS	3.971	USA	-
[129]	95	Thiery et al.	2018	27	18	*Physical Review B*	APS	3.908	France	LPE
[35]	96	Jesenska et al.	2016	27	9	*Optical Materials Express*	Optica	3.074	Japan	MOD
[33]	97	Ibrahim and Arsad	2016	26	2	*Journal of Magnetism and Magnetic Materials*	Elsevier	2.993	Malaysia	Sol-gel
[130]	98	Schmidt et al.	2020	26	5	*Physica Status Solidi (B)*	Wiley-VCH	3.277	Germany	PLD
[131]	99	Zhu et al.	2017	26	8	*Applied Physics Letters*	AIP	3.971	USA	RF magnetron sputtering
[132]	100	Gomez-Perez et al.	2018	26	11	*Physical Review Applied*	APS	4.931	Spain	PLD

NC is the number of citations, APS is the American Physical Society, AIP is Applied Physics Letters, ACS is American Chemical Society, CVD is chemical vapor deposition, IEEE is Institute of Electrical and Electronics Engineers, IOP is Institute of Physics, LPE is liquid phase epitaxy, MBE is molecular beam epitaxy, RF is radio frequency, MOD is metal–organic decomposition, PLD is pulsed laser deposition, and RCS is Royal Society of Chemistry.

4. Analytical Discussion

This section contains the findings of a bibliometric study of the 100 selected and most cited papers. A bibliometric analysis is dependent on a methodology of statistically analyzing scientific publications. The bibliometric analysis method has attracted the interest of organization studies academics from a variety of academic areas [133]. This bibliometric analysis utilizing Scopus was conducted in the third week of July 2022. The analysis was carried out using papers with a high citation ranking. The scope of the papers was limited to physics and astronomy and materials science, and all papers were based on journal articles that were published in English. The bibliometric results were based on the statistical data analysis. The graphical visualization output from VOS viewer software is also presented.

4.1. Publications Trends and Country Performance

From the available statistics in this new bibliometric database, Figure 3 displays the total number of papers per year in the YIG field over the last ten years. As shown in Figure 3, the number of papers published has fluctuated throughout the past ten years. The maximum number of publications occurred in 2015. After 2016, fewer papers were published. Within 2021 and 2022, no citations for top cited papers have been documented. This study examines the recently published papers with the highest citation counts. Articles published in the past often receive more citations than those that were more recently published. This is apparent from Table 1, where the first top paper [13] was published in 2015 and the next six were published before 2015. Figure 1 illustrates that in the last ten years (2012–2022), the number of published papers has increased the most compared to the preceding year (1961–2011). This fact indicates that YIG research is experiencing a rapid expansion, which is anticipated to result in a massive market deployment in the near future.

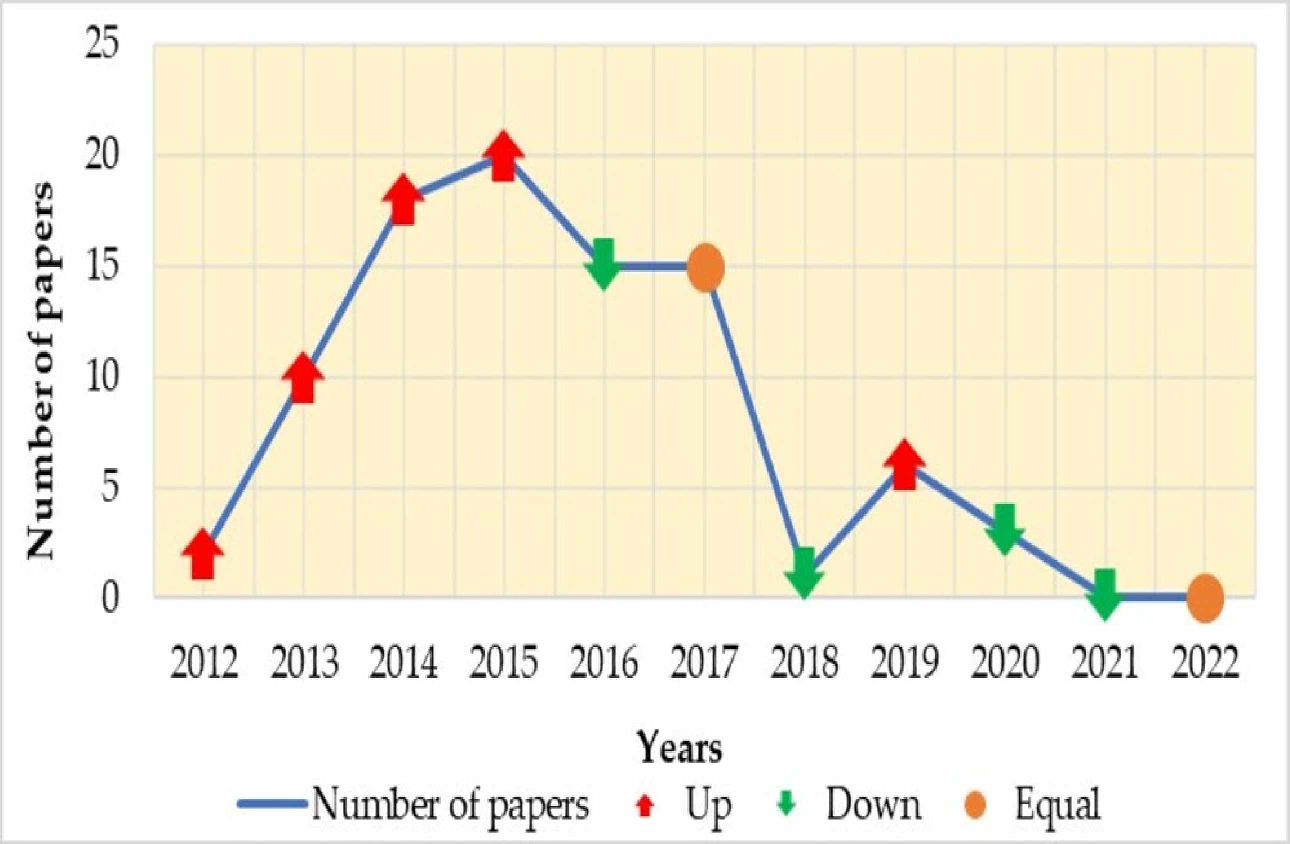

Figure 3. The top 100 most cited YIG papers during the last ten years.

Figure 4 depicts the analysis of one country's contribution to the highest citation count of YIG papers. The contribution of one country is based on the first author's affiliation. The United States of America (USA) published the most papers (33) and is the leading publishing country in the world, followed by Germany (23), the United Kingdom (UK) (10), Brazil (6), China (5), and Japan (3). Furthermore, two papers were contributed by the countries Russia, India, Malaysia, and Spain. The remaining nations, including the Netherlands, South Korea, Iran, Taiwan, Mexico, Poland, Finland, and Sweden, each contributed a single paper. From 2012 to 2020, the United States has displayed a continuous publishing of top papers. The first-ranked paper is [13] from the USA. Germany and the UK have also contributed to paper growth, but less than the US has. Even though Germany is ranked second for its expanding contribution of top papers, the country has produced two top-ranked citation papers placed second [36] and third [18] (refer to Table 1). These top three productive countries (the USA, Germany, and the UK) should collaborate with other countries to provide high-quality YIG research.

4.2. The Top 10 Most Cited Papers

This analysis analyzed the top ten articles with the highest number of citations from 2012 to 2020 to identify the current strongest research projects in YIG development. Early papers typically have more citations than articles more recently published. Regardless of their overall quality, earlier articles are more frequently cited. Table 2 reveals that the top ten most cited papers are the most important YIG works to date, indicating the general interests and trends within the field. Table 2 summarizes the rank, author, citation, number of authors, methodology, sample characterization, scope/outcome/advantages, and application. According to Table 2, the citing of the top ten papers range from 171 to

383 between 2012 and 2015. This study revealed that the paper contains various methods for producing high-quality YIG film for the intended application. The growth film was characterized by various measuring parameters to gather information for the application. The top 10 publications contribute a variety of aims, scope, outcomes, and advantages, all of which contribute to the research's advantages. The papers from [5,8,13–15,18,20,36,68,69] published the top 10 papers, which had citation counts of 383, 377, 349, 227, 202, 201, 193, 185, 179, and 171, respectively.

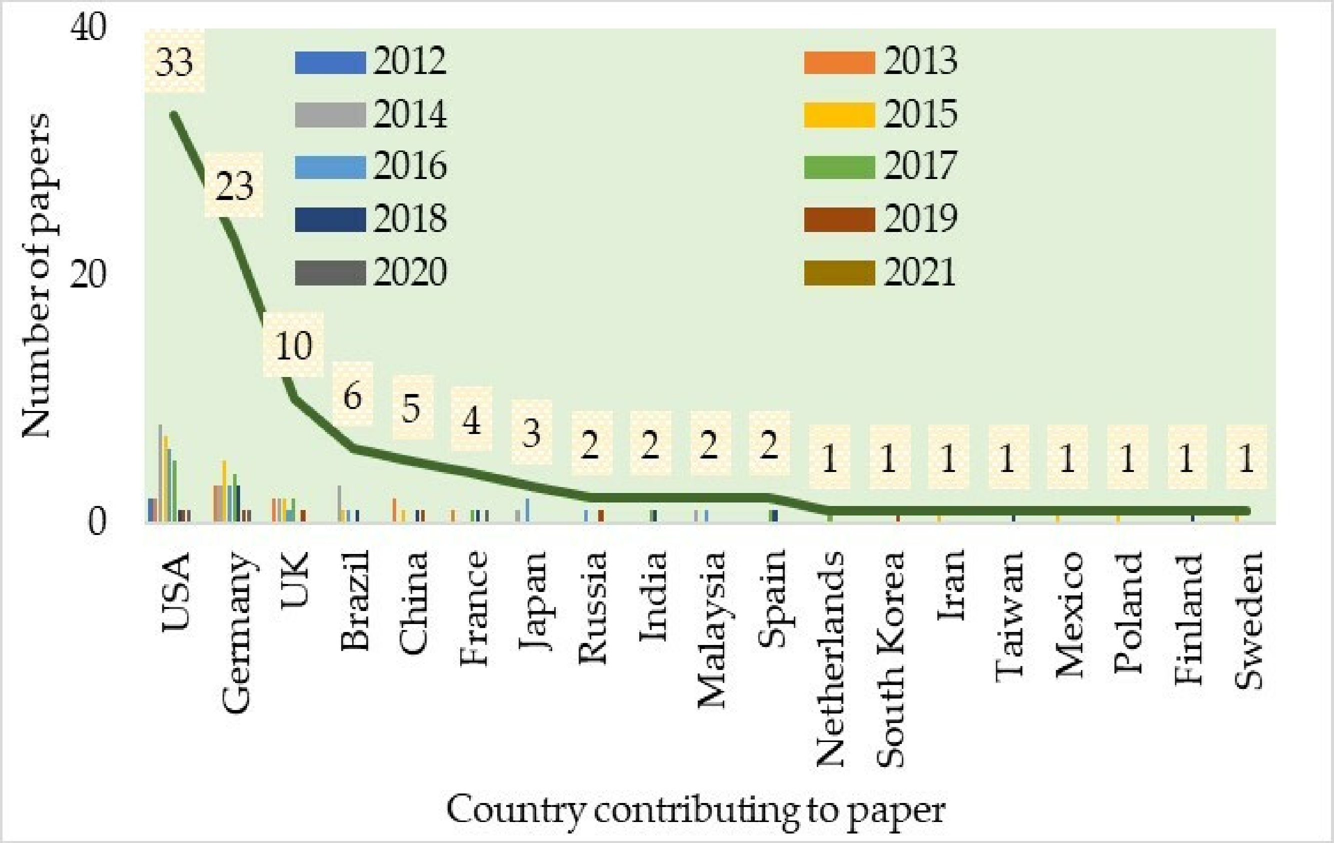

Figure 4. Publishing countries that have contributed to YIG papers during the last ten years.

Wang et al. [13] received 383 citations, making it the most-cited paper in the analysis of the previous ten years. The study indicates the anomalous Hall effect (AHE) in single-layer graphene exchange coupled to an atomically flat YIG ferromagnetic thin film. The proximity-induced ferromagnetic order in graphene potentially rises to unique transport phenomena such as quantized AHE, which can be beneficial for spintronics. With 377 citations, Huebl et al. [36] produced the second most cited paper. The research reports a significant coupling between exchange-coupled YIG spins and a superconducting microwave resonator. Exchange-coupled gallium-doped YIG film is ideal for cavity quantum electrodynamics (QED) experiments and microwave applications. Althammer et al. [18] received 349 citations in their third-ranked paper. The research analyses the spin Hall magnetoresistance effect in pulsed laser-deposited YIG/platinum (PLD). SMR is a novel, easy to measure magnetoresistance effect that enables new spin-current research, the appropriate film for use in spintronics. Based on Tables 1 and 2, the top three papers were published by the American Physical Society (APS), with *Physical Review Letters* [13,36] and *Physical Review* [18] having an IF of 9.185 and 3.908, respectively.

In summary for the top 10 papers, preparation methods of YIG film using PLD [8,13–15], MBE [18], LPE [20], and sputter deposition [5] were reported. The impact factors for the top 10 papers range between 1.54 and 3.971 (refer to Table 1). In the top ten papers, more than five authors collaborated to generate high-quality publications, with the most authors contributing to the ninth-ranked paper (sixteen authors in total) [15]. Most papers [8,13,15,18,20,68,69] grew YIG film for spintronic device development, whereas a few papers [5,14,36] grew YIG for microwave applications.

Table 2. The top ten most-cited papers in the field of YIG.

Rank	Ref	NC	No. of Authors	Methoc	Characterization of Sample	Scope/Outcome/Advantages	Application
1	[13]	383	5	PLD	AHE, AFM	Proximity-induced YIG ferromagnetic in graphene can lead to novel transport phenomena.	Spintronic
2	[36]	377	8	-	FMR	Exchange-coupled gallium-doped YIG film is excellent for cavity QED investigations.	Microwave
3	[18]	349	21	MBE	SMR	This allows SMR to measure spin diffusion length and spin Hall angle in NMs. SMR is a novel, simple magnetoresistance effect that enables new spin current investigations.	Spintronic
4	[68]	227	8	-	ISHE voltage measurement	Provides a different mechanism for the LSSE that arises from the flow of magnons through the thickness of the ferromagnetic insulator (FMI) film.	Spintronic
5	[8]	202	9	PLD	XRD, XPS, AFM, FMR	PLD growth of low FMR linewidth YIG nanofilms and their linewidth in FMR characteristics. Linewidth correlates with surface roughness and surface Fe deficiency, indicating that surface defect-associated two-magnon scattering contributes significantly.	Spintronic
6	[14]	201	14	PLD	FMR	Damping phenomena may be caused by ferromagnetic ordering in Pt atomic layers near the YIG=Pt interface	Microwave
7	[69]	193	5	-	SMR	YIG's magnon chemical potential is vital for energy and spin transport in magnetic insulators.	Spintronic
8	[20]	185	8	LPE	SQUID	Strong proximity effects in Pt on magnetic insulators and their contribution to spin-related studies.	Spintronic
9	[15]	179	16	PLD	FMR, XRD, SQUID,	Identify spin waves using Pt's inverse spin-Hall effect (ISHE)	Spintronic
10	[5]	171	7	Sputteri deposition	AFM, XRD, X-ray reflectivity, AFM, SQUID, FMR	Presented sputters nm-thick YIG films with low damping.	Microwave

AFM = atomic force microscopy, AHE = anomalous Hall effect, SMR = spin Hall magnetoresistance, FMI = ferromagnetic insulator, FMR = ferromagnetic resonance, LSSE = longitudinal spin-Seebeck effect, ISHE = inverse spin-Hall effect, MBE = molecular beam epitaxy, NC = number of citations, NMs = nonferromagnets, PLD = pulsed laser deposition, QED = quantum electrodynamics experiments, SMR = spin Hall magnetoresistance, SQUID = superconducting quantum interference device, XRD = X-ray diffractometer and YIG = yttrium iron garnet.

4.3. Papers with Various Subfields

These bibliometric studies also explore the subject areas covered by the most cited papers. The classification of the highest-ranking articles for various subject subfields and years is presented in Table 3. The subject subfields of magnetization characterization with a citation range of 26–383 achieved the highest frequency percentage (91%) of citations.

Preparation/Fabrication of YIG is in the second position with a citation range of 26–383 and frequency weight of 56%, followed by magnon with a citation range of 26–227 and frequency weight of 54%. The subject categories in nanomaterials were ranked fourth with a citation range of 26–202 and frequency weight of 53%. Ferromagnetic/Ferrimagnetic resonance (FMR) (39%), magnetic anisotropy (39%), spintronic (32%), and spin-wave (31%), were among the remaining subjects, with a frequency weight of above 30%. Below is a summary of the categorized subjects observed in Table 3:

- Among all magnetic materials, yttrium iron garnet (YIG) has contributed the most significant role to understanding the dynamics of high-frequency magnetization. Bulk YIG crystal was the prototypical material for ferromagnetic resonance (FMR) experiments in the middle of the twentieth century due to its unique characteristics [15]. Attractive characteristics of YIG include a high Curie temperature, ultra-low damping (the lowest among all materials at room temperature), electrical insulation, strong chemical stability, and simple synthesis in the single crystalline form [18,22,81]. YIG's low magnetic damping makes it perfect for hybrid spintronic devices with graphene [22,81]. Nowadays, ferromagnetic insulators (FMI) are extensively utilized. FMI enables the clear separation of spin-current and charges current effects. YIG is one of the prototype models of an FMI substance [16–18,22]. By altering the ferrimagnetic insulator thickness and interface quality, the paper [17] reported the detection of a spin-Seebeck effect (SSE) characteristic: the SSE signal increases with the increase in YIG film thickness.
- In fundamental device application research, a film with low damping is required. The nanometer-thick YIG film can generate minimal damping phenomena. For the deposition of submicron-thick films, pulsed laser deposition (PLD) and sputtering are the preferred methods [8]. Numerous top cited papers have described various YIG film preparation procedures to achieve high-quality film [25], including pulsed laser deposition (PLD) [8,11,13–15,17,75–77], laser molecular beam epitaxy (MBE) [18,19], liquid phase epitaxy (LPE) [17,20,22,24,25,84], sputtering [89,92,97,103] and sol-gel methods [33,34]. Gadolinium gallium garnet ($Gd_3Ga_5O_{12}$, GGG), silicon, yttrium aluminum garnet (YAG), and quartz are some of the substrates that have been utilized to deposit films.
- Magnonics is a technology for low-power signal transmission and data processing based on the propagation of spin-waves (magnons) in magnetic materials [72,78,79,106]. They have spin angular momentum and are bosonic [106]. Due to the rapid development of nanotechnology, magnonics is currently undergoing an explosion [72]. Yttrium iron garnet (YIG) is particularly intriguing for this application due to its lengthy magnon propagation length [78] and relatively low damping ($\alpha < 10^4$) [106]. YIG also exhibits excellent magnetic and elastic properties [23]. In [72], the authors describe the inductive creation and detection of plane wave spin-waves in the low-power linear regime. In [106], both anisotropy and exchange-mediated magnon–phonon interactions are considered. Hence, YIG is used to study magnonic phenomena. YIG's centimeter-long magnon propagation length and graphene's excellent carrier mobility could lead to novel spintronic devices [22].
- The rise of this industry creates a demand for YIG films with nanometer-scale thickness and minimal damping, similar to YIG bulk materials and thick films. Nanofilms with such low damping properties are essential for both fundamental research, such as the study of spin pumping, and device applications, such as spin-torque oscillators [5,8]. YIG functional layers for practical magnonics should be nanometer-thin with ultrasmooth surfaces to maximize data processing efficiency and to reduce the energy consumption of sophisticated spin-wave devices [25]. According to Dubs et al. [25], developing YIG films with thicknesses below 100 nm using LPE remains a challenge for conventional thick film LPE process. The prior top cited paper, Chang et al. [5], successfully developed YIG film using sputtering with nanoscale (nm) thickness and achieved the lowest damping ($\alpha = (8.58 \pm 0.21) \times 10^5$ for spintronic development.

Table 3. Distribution of subject categories for the top 100 papers.

Subject Categories	Rank	References	Range Years	Citation Range	Frequency Percentage (%)
Magnetic characterization	1, 3–9, 11–59, 62–65, 67–78, 80–100	[2,6–8,11–28,30,31,33–35,37,59,61,68–89,91–100,102,103,105–112,114,116–132]	2012–2020	26–383	91
Preparation/Fabrication of YIG	1–2, 5–6, 8–12, 14, 16, 18, 21, 26–30, 32, 34–38, 41, 44, 53, 58, 61–63, 65–66, 68, 70–73, 75–76, 78–79, 81–82, 85, 87, 89, 90, 92–94, 96–100	[5–8,11–17,19–21,23–26,28,30,33–36,59,61,65,77,79–82,86,92,94,99,102–104,107–109,111,112,114,115,117,118,121,124,126–128,130–132]	2012–2020	26–383	56
Magnon	4–7, 9, 11–18, 21–24, 28, 30–34, 36, 39, 41–43, 45–46, 49–51, 55–60, 62, 64, 67–69, 71, 74, 80–81, 84, 88–89, 95, 98–100	[2,6,8,14–17,19,21,23–25,27,28,30,61,68–71,73–75,78–80,82–85,87,88,91–93,96–102,105–107,110,116,117,120,123,129–132]	2012–2020	26–227	54
Nanomaterials	5, 7, 9–14, 16, 18, 21, 26–30, 32, 34–38, 41, 44, 53, 58, 61–63, 65–66, 68, 70–73, 78–79, 81, 85, 87–91, 93–100	[2,5,6,8,11,12,15–17,19,21,22,25–28,30,31,33–35,61,65,69,72,76–78,81,82,84,90,92,94,95,99,104,107–109,114,115,117,121,123–125,127–132]	2012–2020	26–202	53
Ferromagnetic/Ferrimagnetic resonance (FMR)	2, 5–6, 9–10, 13, 15–16, 19, 20, 24, 30–31, 34, 41, 44, 46–47, 51–53, 55–57, 63, 65–68, 71, 75, 81, 84, 89, 91–92, 94, 98–99	[2,5–8,14,15,22,25,28,30,31,36,61,70,72,75,78,80,86,88,89,93,94,96–98,103–105,107,111,117,120,125,126,128,130,131]	2012–2020	36–377	39
Magnetic anisotropy	1–3, 5, 7–9, 12–15, 18, 21, 24, 26–27, 29–30, 34–35, 37, 44, 53, 56, 62, 65–69, 72–73, 86, 88, 91, 94, 98–100	[2,8,11–13,15,17–21,23,25,26,36,61,69,70,75,77,80,81,86,94,97,102–106,108,109,122,123,125,128,130–132]	2012–2020	26–383	39
Spintronic	1, 4–5, 7–8, 10, 12, 15–16, 20–21, 23, 25–26, 28–30, 35–36, 42, 44, 50, 65, 71, 73–74, 82, 89, 94, 99–100	[5,6,8,13,19,20,22–26,28,68–70,74,76,77,81,82,84,86,92,103,107,109,110,118,128,130–132]	2012–2020	26–383	32
Spin-wave	4, 7, 9, 11–12, 15, 17, 21, 23, 31–32, 34, 39, 41–45, 51, 57, 59, 64, 68–69, 77, 80–81, 84, 88, 98, 99	[15,16,19,23,27,30,61,68–71,74,78–80,83–87,93,98,100,106,113,116,117,120,123,130,131]	2013–2020	26–227	31
Spin Hall effect (SHE)	1, 3, 9, 11, 15, 18, 20, 23, 24–25, 28–29, 35, 42–43, 45, 50–52, 54–55, 65, 70, 73, 78, 82–83, 93, 100	[13,15,16,18,21,22,24,31,70,74–77,81,84,85,87,92,93,95,96,103,109,114,118,119,127,132]	2013–2018	26–383	29
Microwave	2, 6, 11, 13, 15, 19, 21, 31, 34, 51, 53, 55, 57, 59–62, 65–68, 75, 77, 81, 84	[2,14,16,23,36,61,65,70,72,78,80,93,94,96,98,100–105,111,113,117,120]	2013–2020	34–377	25

Table 3. *Cont.*

Subject Categories	Rank	References	Range Years	Citation Range	Frequency Percentage (%)
Spin-Seebeck effect (SSE)	3–4, 7, 9, 11, 14–15, 17, 22, 25, 28, 35–36, 42–43, 49, 58, 69–70, 74, 82, 85, 93	[15–18,24,68–71,73,76,81,82,84,85,91,92,99,106,110,118,121,127]	2013–2019	27–349	23
Dopant YIG	2, 27, 30, 37, 44, 48, 61, 65, 72, 76, 78, 83, 87, 90, 91, 96–97	[11,12,25,33–36,65,86,90,103,108,112,114,124,125]	2012–2019	26–377	16
Magneto-optical activity/device	27–28, 35, 37, 44, 48, 68, 72, 79, 90–91, 96	[11,12,24,35,61,81,86,90,108,115,119,124,125]	2012–2019	27–89	13
Magneto-optical (MO) materials	27, 37, 44, 48, 66, 72, 79, 87, 90–91, 96–97	[11,12,33–35,86,90,104,108,115,124,125]	2012–2019	26–89	12
Topological insulator	12, 29, 35–36, 65, 73, 83	[19,77,81,82,103,109,119]	2014–2018	35–153	7

The distribution of subject subfields over ten-year intervals of 100 top papers (displayed in Table 3) allows us to determine the amount of literature and citations devoted to a subject over a certain period and demonstrates that the subject has garnered more attention over time. Moreover, there appears to be a significant differentiation between subject groups, which demonstrates the evaluation and development of YIG research.

4.4. Methodology Journal Evaluation

This section described the developed methods utilized to grow the films along with the films' substrates YIG characterizations and applications. The film quality is dependent on the preparation methods, which include the deposition factors, annealing control parameters, and YIG substitution ions [9,33]. Based on the highly cited studies, the most favorable methodologies such as pulsed laser deposition (PLD), sputtering, and liquid phase epitaxy (LPE) have been developed with a frequency of 34, 17, and 13, respectively. Both the sol-gel and solid-state reaction methods have a frequency of two. Molecular beam epitaxy (MBE), metal–organic decomposition (MOD), and wet chemical techniques each have a frequency of one. Findings on the preparation of the YIG can be summarized based on a bibliometric analysis.

- Pulsed laser deposition (PLD) is the most common technique preparation employed by highly cited articles as indicated in Table 1. For oxide film epitaxy, PLD is the most versatile method [7]. The works [2,7,8,11–17,19,61,75–77,81–83,86,87,91,94,95,107–109,111,114,117,119,124,126,130,132] performed were used to prepare YIG films with the PLD method. Prior research demonstrated PLD processing of relatively low-damping YIG thin films [5]. Utilizing sputtering and PLD to prepare YIG enables precise control over layer thickness, stoichiometry, surface roughness, and magnetic properties [2]. Additionally, Haidar et al. [107] reported the growing of thin YIG films with bulk-like properties that had been obtained using the PLD technique.
- Sputtering is the most prevalent industrial technique [5]. The articles [5,6,26–28,30,70,72,80,89,92,97,103,121,127,131] discuss the sputtering growth of YIG films. This report [6] also indicates the viability of producing high-quality YIG nanofilms by the sputtering method. The papers have employed radio frequency (RF) magnetron sputtering, which is a well-established and reasonably inexpensive process for fabricating YIG film that would be excellent for usage in any potential industrial applications [26].
- Experiments to date have also utilized liquid phase epitaxy (LPE) to fabricate YIG films [17,20–25,84,93,99,105,118,129]. The LPE approach produces an excellent minority carrier lifetime, low damping value, and thick epitaxial layers. LPE produces thick, low-damping magnetic garnet films and high-quality magneto-optical material. In contrast to the PLD method, the LPE technique has low-cost equipment and operations [134].
- Additionally, it is shown that other various methodology processes including molecular beam epitaxy (MBE), wet chemical, sputtering, solid-state reaction, sol-gel, and metal–organic decomposition (MOD) techniques have been utilized in the production of garnet films.

Hence, it is shown that high-quality thin and ultra-thin YIG films were produced using the PLD, LPE, and sputtering techniques to research spin-wave phenomena and construct YIG waveguides and nanostructures for spin-wave excitation, modulation, and detection in magnonic circuits [25]. The PLD method is the most advantageous approach among highly cited articles that have been proven to produce high-quality films for magneto-optical devices. The LPE technique is the most established technology for microwave devices because of its ability to produce thicker films than other technologies. LPE can produce sub-micrometer YIG films with excellent crystallographic and magnetic characteristics for magnon spintronics [25]. YIG film deposition has also been performed using the sputtering method [135].

Substrates are required for the growth of the film. There were four types of substrates reported by the highly cited articles. According to the analysis of the most cited articles, YIG film growth has been demonstrated on gadolinium gallium garnet (GGG) (with a frequency of sixty-eight), yttrium aluminum garnet (YAG) (with a frequency of seven), silicon (with a frequency of five), and quartz (with a frequency of four) substrates. Before film deposition, substrates are initially cleaned. The substrate was cleansed using a different method. As detailed by Howe et al. [94], substrates were cleaned by rinsing them in ultrasonic baths of acetone, isopropyl alcohol, deionized water, and isopropyl alcohol, followed by drying them with dry nitrogen. The results of the substrates utilized for YIG growth are summarized below:

- YIG growth on GGG was recent and demonstrated by the majority of papers. GGG substrate was chosen among the most cited publications for growing YIG films because it matches the same crystal structure and lattice constant as YIG (12.383 Ǻ /12.376 Ǻ: GGG/YIG) and has similar thermal expansion coefficients [26,81]. Moreover, GGG substrates had the lowest lattice misfit (0.057%) for YIG/Ce-YIG thin film development [125]. Tang et al. [7] indicate that YIG film growth on GGG substrate prepared by PLD shows no negligible lattice misfit. Due to pseudomorphic development on substrates made of gadolinium gallium garnet ($Gd_3Ga_5O_{12}$, GGG), which has excellent lattice matching, the reported YIG films [94] have an incredibly high crystalline purity.
- In papers, the focus on YIG growth on YAG substrates has been presented in [16,18,37,95,111,126,127]. Researchers may favor YAG substrate due to its greater lattice mismatch compared with YIG on GGG, cheaper cost, and higher accessibility compared with GGG substrates. According to Sposito et al., [126] YIG/YAG samples have a narrower FMR linewidth than YIG films deposited on GGG under the same conditions, suggesting that lattice mismatch has a positive effect on the magnetic properties of the YIG films.
- To integrate this material into silicon photonic and spintronic devices, it is necessary to deposit phase-pure YIG films on Si substrates [131]. The attention on YIG growth on Si substrates is discussed in [11,12,92,115,124]. The lattice parameter of YIG (12.376 Ǻ) is significantly greater than that of Si (5.431 Ǻ) [12]. Due to a lattice mismatch between the silicon substrate and YIG, the synthesis of YIG on silicon or SOI substrates has been a challenge [136]. Growth of YIG on semiconductor substrates has been demonstrated using the PLD [11,12,124] and sputtering [92,115] techniques. By minimizing the impacts of heat processing on YIG layers, waveguides without cracks or delamination were demonstrated. The significant thermal mismatching coefficient necessitates a low growth temperature to avoid garnet film from cracking [12].
- Garnet films grown on quartz substrates are shown in [12,33,34,115]. Garnet films produced and crystallized on Si and quartz are polycrystalline due to the absence of an epitaxial bond with the substrate [12].

These applications demonstrate that the growth of YIG on substrates has altered their properties as a result of substrate effects.

The films were characterized by the different measurements summarized in Figure 5. The characterization of the films was obtained from the analysis of the top 100 cited articles. It demonstrates that there are six variables used to characterize films, including the structural, morphological, magnetic, magneto-optical, electrical, and optical properties. Table 4 displays the frequency of the film's categorization. Below is a summary of the film's characterization and measurements.

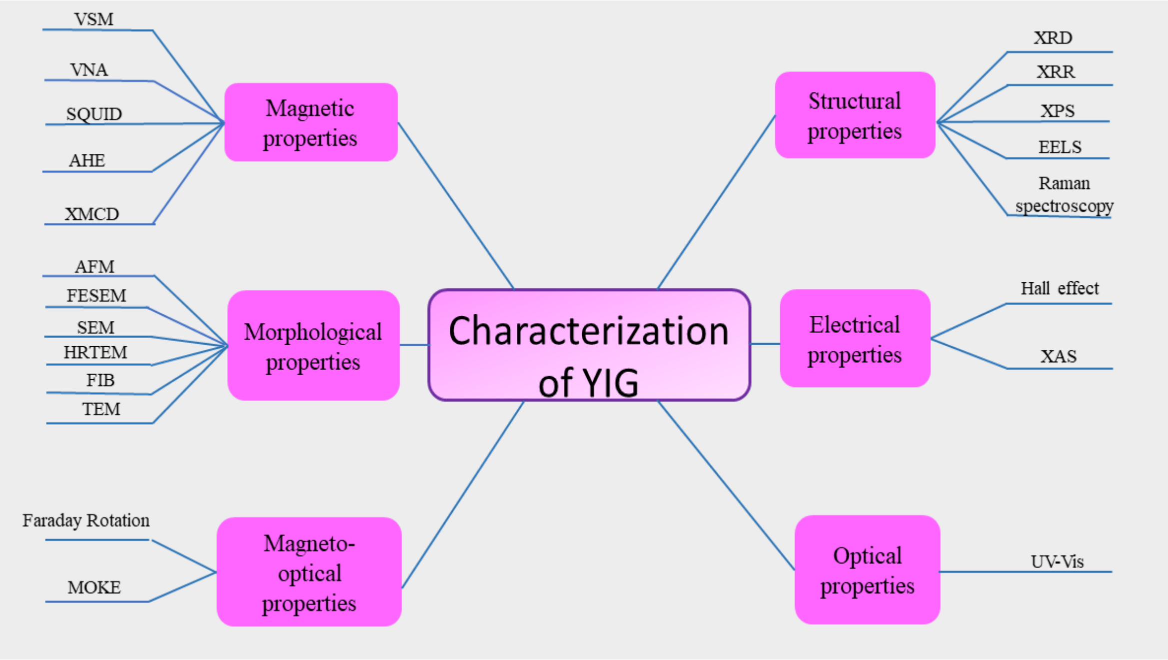

Figure 5. The characterization of YIG with the different measurements for the top 100 cited articles.

Table 4. Frequency of the film's characterization.

Characterization	Measurement	References	Frequency Percentage (%)
Structural properties	XRD	[5,6,8,11,15,19,28,33,34,59,61,65,66,75,77,80,82,86,89,92,94,95,104,108,109,112,117,124,126,128]	30
	XRR	[2,5,6,8,26,86,91]	7
	XPS	[8,25,104,130]	4
	ELS	[128]	1
	Raman spectroscopy	[22]	1
Morphological properties	AFM	[2,5–8,11–13,19,25,33,34,61,75,82,89,107–109,119,124]	21
	TEM	[12,26,35,94,103,108,117,120,121]	9
	SEM	[6,28,59,104,113,124,126,131]	8
	FESEM	[11,33,34,65,66]	5
	HRTEM	[26,104,124,132]	4
	FIB	[124]	1
Magnetic properties	VSM	[7,12,19,25,26,33,34,81,86,92,94,104,109,119,128,131]	16
	VNA	[2,7,25,28,75,78,86,102,117]	9
	SQUID	[5,15,20,78,92]	5
	XMCD	[20,81,125,132]	4
	AHE	[13]	1
Magneto-optical properties	MOKE	[19,35,81,86]	4
	Faraday rotation	[90,115,124]	3
Electrical properties	Hall effect	[18,68,82,101,114,119,127]	7
	XAS	[125]	1
Optical properties	UV-Vis	[33]	1

- Structural properties of the film were measured by X-ray diffraction (XRD), X-ray reflectometry (XRR), X-ray photoelectron spectroscopy (XPS), electron energy loss spectroscopy (EELS), and Raman spectroscopy analyses. Compared with other measurements, XRD reveals the greatest frequency (n = 30) of use in the 100 most cited papers. XRD is used to determine the crystalline structure, phase purity, and lattice parameters of YIG films [2]. In XRD analysis, lattice parameters and distribution strains were investigated based on symmetrical and asymmetrical reciprocal space mappings in peak diffractions [137].
- Using atomic force microscopy (AFM), transmission electron microscopy (TEM), scanning electron microscopy (SEM), field emission scanning electron microscopy (FESEM), high-resolution transmission electron microscopy (HRTEM), and focused ion beam (FIB), the morphological properties of the films were measured. The AFM method has the highest frequency at 21 compared with the other morphology-related measurements. AFM is a potent measuring device for quantitative surface measurements. AFM is utilized to measure the surface roughness of films with nanoscale precision.
- Magnetic properties were determined by a vibrating sample magnetometer (VSM), vector network analyzer (VNA), superconducting quantum interference device (SQUID), X-ray magnetic circular dichroism (XMCD), and anomalous Hall effect (AHE). VSM demonstrates the highest frequency of 16 compared with other magnetic measurements. A VSM was used to measure the magnetic properties of the films by exerting magnetic fields in the film plane [137].
- Magneto-optical Kerr effect (MOKE) and Faraday rotation were employed to measure magneto-optical properties. Using the Hall effect and X-ray absorption spectroscopy (XAS), electrical characteristics were determined. Employing ultraviolet-visible spectroscopy (UV-Vis), optical characteristics were characterized.

Therefore, it is evident that numerous characterization films have been measured by researchers, indicating that YIG films have the potential to be utilized in a variety of applications.

In terms of application, yttrium iron garnets are extremely valuable as electronic components, magneto-optical devices, and microwave devices. According to the ionic radii of these atoms, the garnet structure also contains sites that might be occupied by other cations, such as rare earth ions or even alkaline, earth alkaline, or other metal ions [138]. The magnetic, structural, optical, magneto-optical, and dielectric characteristics of the YIG structure can be modified via the synthesis of various preparation methods and substitution with other cations. Hence, a wide range of novel materials can be discovered, proposing the following possibilities:

- Nanodevices (e.g., spintronics) [8,13,20,36,68,69]
- Magneto-optical devices (e.g., Faraday rotators/isolators, and circulators) [11,12,86,90,126]
- Integrated microwave devices [5,14,16,36,126]
- New nanosystems [138]
- Sensing applications [122]

4.5. Keywords Assessment

The acquisition of keywords will aid in the development of new study topics and the evaluation of existing research. The co-occurrence of author keywords for the YIG field was determined. The keywords based on text data were described by the authors in the papers. The results are retrieved using the Scopus database, while the co-occurrence map was generated using VOS viewer software, as shown in Figure 6. This mapping method employing VOS viewer software is more advanced than the data counting method as it is more complex and allows for a greater interpretation [42]. VOS viewer is beneficial for visualizing big bibliometric maps in an easily interpretable approach [139]. According to VOS viewer, a total of 112 keywords were associated with the 799 publications of total articles. In the keyword co-occurrence map, the keywords are represented by colored nodes. The item's color nodes are determined by the cluster from which it was obtained.

Moreover, the map depicts the various items and linkages that correspond to a variety of keywords, as well as the connection line. The stronger connection line signifies the large frequency of the item cluster. The size of nodes is proportional to the frequency with which the keywords occur, and the lines between nodes show their co-occurrence relationship. In the analysis based on VOS viewer, Figure 6 depicts six clusters on the map. For example, cluster one contains eleven different items including an anomalous Hall effect, interface, inverse spin-Hall effect, magnetic anisotropy, magnetic insulator, spin-current, spin-Hall effect, spin-Hall magnetoresistance, spin pumping, spin-Seebeck effect, and spintronics. Cluster two contains nine items, including the Faraday effect, Faraday rotation, garnets, magneto-optical properties, magneto-optics, perpendicular magnetic anisotropy, pulsed laser deposition, and thin films. The nine items included in Cluster 3 are ferrites, magnetic materials, magnetic properties, magnetism, magnons, microstructure, optical properties, sol-gel, and thin film. The seven items included in Cluster 4 are ferromagnetic resonance, gilbert damping, magnetization dynamic, magnonics, microwave magnetics, spin waves, and yttrium iron garnet. Curie temperature, ferromagnetic resonance, garnet, linewidth, magnetic property, magnetization, and yttrium iron garnet are included in Cluster 5 (contains 7 items). Cluster 6 comprises the final four items: magnetic damping, nanoparticles, saturation magnetization, and sol-gel.

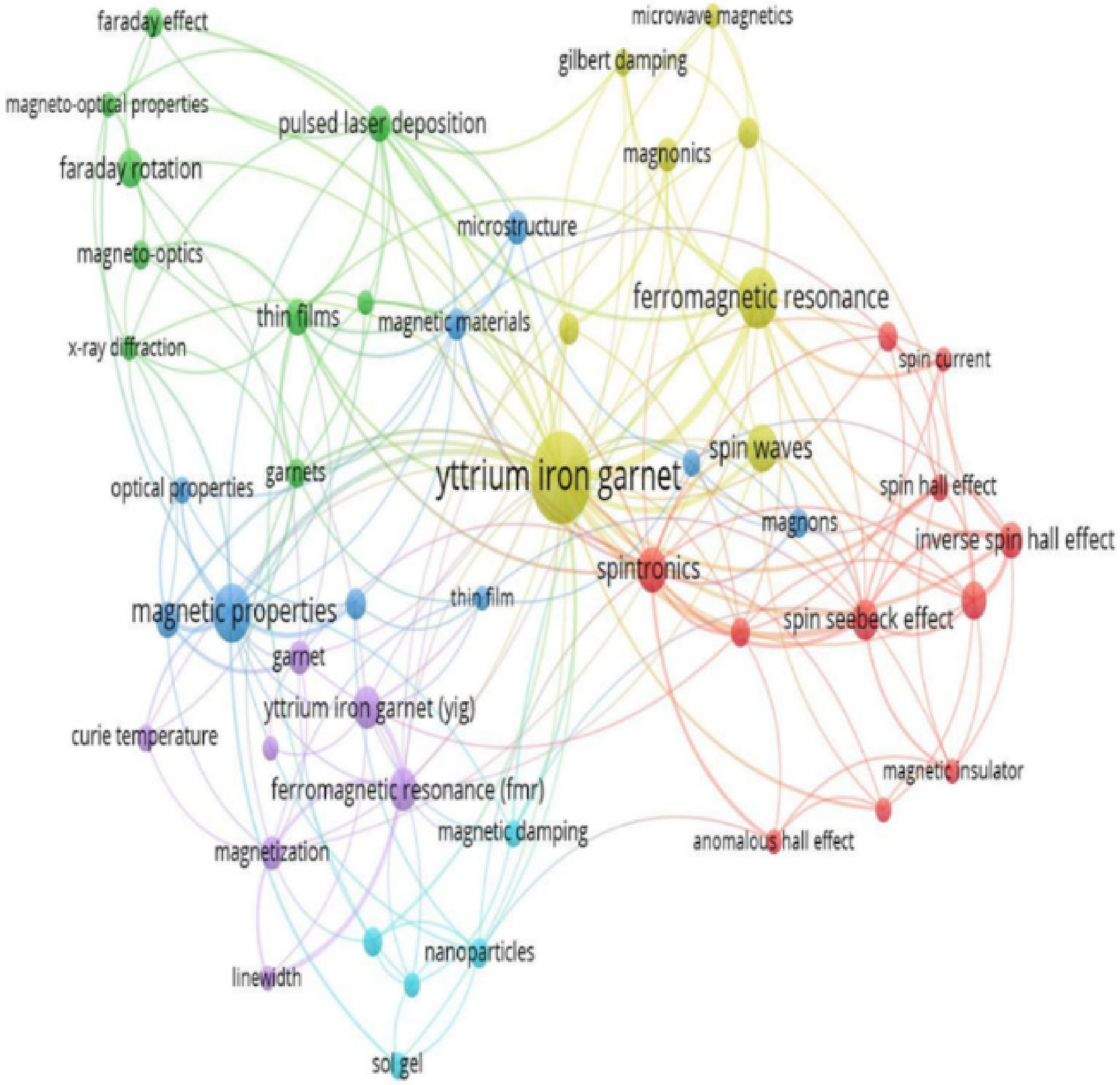

Figure 6. Co-occurrence of author keywords (number of occurrences 112 keywords).

According to Figure 6 which was analyzed from VOS viewer, the six clusters of keywords represent the groups of works that are closely related:

- Cluster 1: Recent spintronic phenomena such as the spin-Seebeck effect (SSE) and the spin-pumping effect have drawn substantial interest in magnetic garnets [16,18,35,84]. The most frequent approach to detect SSE spin currents is to measure the charge current caused by the inverse spin-Hall effect (ISHE) in a nonmagnetic metallic (NM) layer in interface with the magnetic material [84]. Furthermore, a study topic has emerged that employs YIG/platinum structures for spintronics [14,20]. Spintronics uses spin-polarized charge carriers for production, manipulation, and identification [20].
- Cluster 2: Magneto-optical devices require thin films with superior magnetic and structural properties [2]. The pulsed laser deposition (PLD) technique has been reported to provide superior control of layer thickness, surface roughness, stoichiometry, and magnetic characteristics for YIG thin film [2,124]. YIG is very transparent at near-infrared wavelength regions [86], but its magneto-optical performance is quite weak. For magneto-optical devices, the Y in YIG thin film is partially replaced with rare earth garnet elements such as bismuth, cerium, or other rare earth, which can boost the Faraday rotation by an order of magnitude [11,86,124].
- Cluster 3: Sol-gel technology was preferred to synthesize YIG film due to its inexpensive cost, simple preparation, and easy material composition control. Sol-gel provides exceptional uniformity microstructure, high purity, and nanocrystalline material [140,141]. In terms of optical properties, terbium- and aluminum-doped YIG films prepared by the sol-gel method were found to be between 76% and 92% transparent in the visible and infrared ranges [140]. According to the results reported by Ibrahim and Arsad [141], cerium-doped YIG films have exceptional qualities such as homogeneous structure, small nano grain size, high optical transparency (over 80%), and excellent magnetic properties. Having their best attributes, the films are more promising for use in magneto-optical devices.
- Cluster 4: The discovery of yttrium iron garnet (YIG) led to amazing advancements in microwave technology more than 50 years ago. YIG is suitable for microwave applications such as filters or sensors due to its band gap of 2.66 eV, low magnetic damping, and soft magnetization characteristics, which makes it a good insulator [86]. Yu et al. [72] developed configurable microwave-to-magnon transducers. Their solutions enabled integrating microwave electronics utilizing exchange-dominated spin-waves and improving magnonics-based technology.
- Cluster 5: YIG is a well-studied ferrimagnetic insulator with a Curie temperature that is above room temperature (Tc = 550 K). It has been explored as a prototype magnetic insulator for spinning waves and magnonic physics, involving spin-Hall and spin-Seebeck effects [19].
- Cluster 6: Onbasli et al. discovered that nanometer-thin films with thicknesses around 17 to 200 nm which are relatively close to the YIG bulk saturation moments at room temperature (135 emu cm) had low coercivity (<2 Oe) and low magnetic damping value as low as 2.2×10^{-4} [2]. These thin films are valuable for investigating the development of magnetization dynamics and innovative magnetic phenomena.

From the analysis of the cluster keywords, researchers can perform a more in-depth evaluation of the references and/or publications recognized as important in each network cluster [142]. Keyword co-occurrence maps make it easy to observe the keyword analysis relationship; therefore, it helps in assessing YIG thin film research terms. However, as discussed in the clusters section, not all keywords in each cluster are utilized. There may be other discussions that correlate to the cluster's keywords. Nevertheless, in some instances, as indicated by Shi et al. [143], it remains unclear why VOS viewer classified some keywords terms into the same category and established a new cluster rather than assigning them to other clusters with similar characteristics. This explanation must be investigated in future research.

This work provides a thorough manual examination (using Microsoft Excel) of the most effective keywords that frequently appeared in the top 100 citation publications. Figure 7 shows the top 15 most utilized keywords in the top 100 cited articles. The larger font size in letter words represents YIG papers' most favorable keywords. It is discovered that the popular keywords in the last ten years are iron (frequency = 64), yttrium iron garnet (frequency = 59), garnets (frequency = 45), film (frequency = 29), temperature (frequency = 22), ferromagnetic (frequency = 19), magnetism (frequency = 17), spin-waves (frequency = 14), pulse laser deposition (frequency = 13), damping (frequency = 12), spin-Hall effect (frequency = 11), ferrimagnetic (frequency = 11), magneto-optical (frequency = 11), gadolinium gallium garnet (frequency = 8) and microwave (frequency = 7). This analysis demonstrates that prevalent interest was attracted to the keywords "Iron", "yttrium iron garnet", "garnets", "film" and "temperature". The most popular keyword for "yttrium iron garnet" should be highlighted in YIG research, as it is given the greatest attention in the YIG study, as seen by the results displayed in Figures 6 and 7. However, "spin-Hall effect", "magneto-optical", and "ferrimagnetic" have the same frequency, with 11 occurrences.

Figure 7. Popular keywords in the top 100 cited articles.

After analyzing the information presented in Figures 6 and 7 about keywords, it is crucial to note that:

- In a garnet structure, three yttrium ions occupy the dodecahedra (c) site, two iron ions occupy the octahedral (a) site, and three iron ions occupy the tetrahedral (d) site. Trivalent Y^{3+} and Fe^{3+} ions make YIG ideal for magnetic research. The most important interaction in this structure is the superexchange interaction of YIG, given by the Fe ion in the tetrahedral site. This interaction is caused by the antiferromagnetic superexchange interaction between the iron ions in the tetrahedral and octahedral sites through the intervening oxygen ion [32]. Two iron ions from the d-site have their magnetic moments canceled by two from the a-site. Thus, the garnet's magnetic moment is due to the d-excess site's iron ion. Composition and homogeneity control is essential in garnet synthesis, as stoichiometry and microstructure determine the magnetic characteristics [144].
- Yttrium iron garnet $Y_3Fe_5O_{12}$ (YIG) has the most significant role in understanding high-frequency magnetization dynamics. YIG has a high Curie temperature, low damping (lowest among all materials at ambient temperature), electrical insulation, good chemical stability, and facile single-crystal production [15].
- For YIG film, it is vital to minimize the YIG's thickness with preserving its magnetic characteristics [15]. Reduce the YIG film thickness below the exchange length (10 nm) to better understand spin momentum transfer at the YIG/metal contact. Submicrometer-thick YIG films have generally been generated via LPE; however, the final thickness is 200 nm. Other growth strategies can diminish thickness. PLD is the most versatile oxide film epitaxy technique [15]. PLD-grown YIG has been developed by several researchers in these most cited articles [8,11,13–15,17,75–77]. In thin films, the temperature dependence of the longitudinal spin-Seebeck effect (LSSE) concerning YIG thickness has been studied [73].
- Other keywords that arise in the top-ranking papers, such as ferromagnetic, magnetism, spin-waves, pulse laser deposition, damping, spin-Hall effect, ferrimagnetic, magneto-optical, gadolinium gallium garnet, and microwave, are also significant as they play a remarkable role in assisting the researcher in tracking down and extracting data relevant to the YIG research. Upon this foundation of a summary of keyword analysis, researchers can obtain an overview of present research trends and potential future study directions in YIG research.

4.6. Document Type Evaluation

Figure 8 depicts the ranking of the most cited papers based on the number of publications provided by each journal and the impact factors. The selected 100 most-cited articles were published in 28 distinct journals that Scopus indexed. This demonstrates the diversity of publication distributions and widespread interest in YIG-related research. *Physical Review B* was the most influential journal, comprising 28 (28%) publications out of all the journals. *Physical Review Letters* and *Applied Physics Letters*, with 14 articles (14%), were the second-most-cited journals. The third most-cited journal is *Nature Communications*, with 5 articles (5%). The journals that had the fourth-highest number of papers (3%) were *Nano Letters*, *Journal of Applied Physics*, *Optic Express*, and *Physical Review Applied*. *Nature Physics*, *Journal of Materials Chemistry C*, *ACS Photonics*, *Journal of Magnetism and Magnetic Materials*, *Nanoscale*, *Optical Materials Express*, and *IEEE Magnetics Letters* correspond to the fifth-ranked journal, each of which had two articles featured in the list (2%). *APL Materials*, *Nature Materials*, *Journal of Physics D*, *Advanced Electronic Materials*, *Optics Letters*, *Journal of the European Ceramic Society*, *Journal of Alloys and Compounds*, *AIP Advances*, *Ceramics International*, *Applied Physics Express*, *Applied Surface Science*, *Advanced Optical Materials*, and *Physica Status Solidi (B)* were the sixth-ranked journals with one paper each (1%). The three most influential journals were *Physical Review B*, *Physical Review Letters*, and *Applied Physics Letters*, which had impact factors of 3.908, 9.185, and 3.971, respectively. The journal articles published in *Nature Materials* had the highest impact factor, which was 47.66. There was only one paper published in *Nature Materials* based on work done by Meyer et al. [76]. The paper [76] ranks 25th, with contributions from 12 authors who published work in 2017. The paper presents a spin Nernst effect observation for the optimization of spintronics. The impact factors of all top citation papers ranged between 1.54 and 47.66.

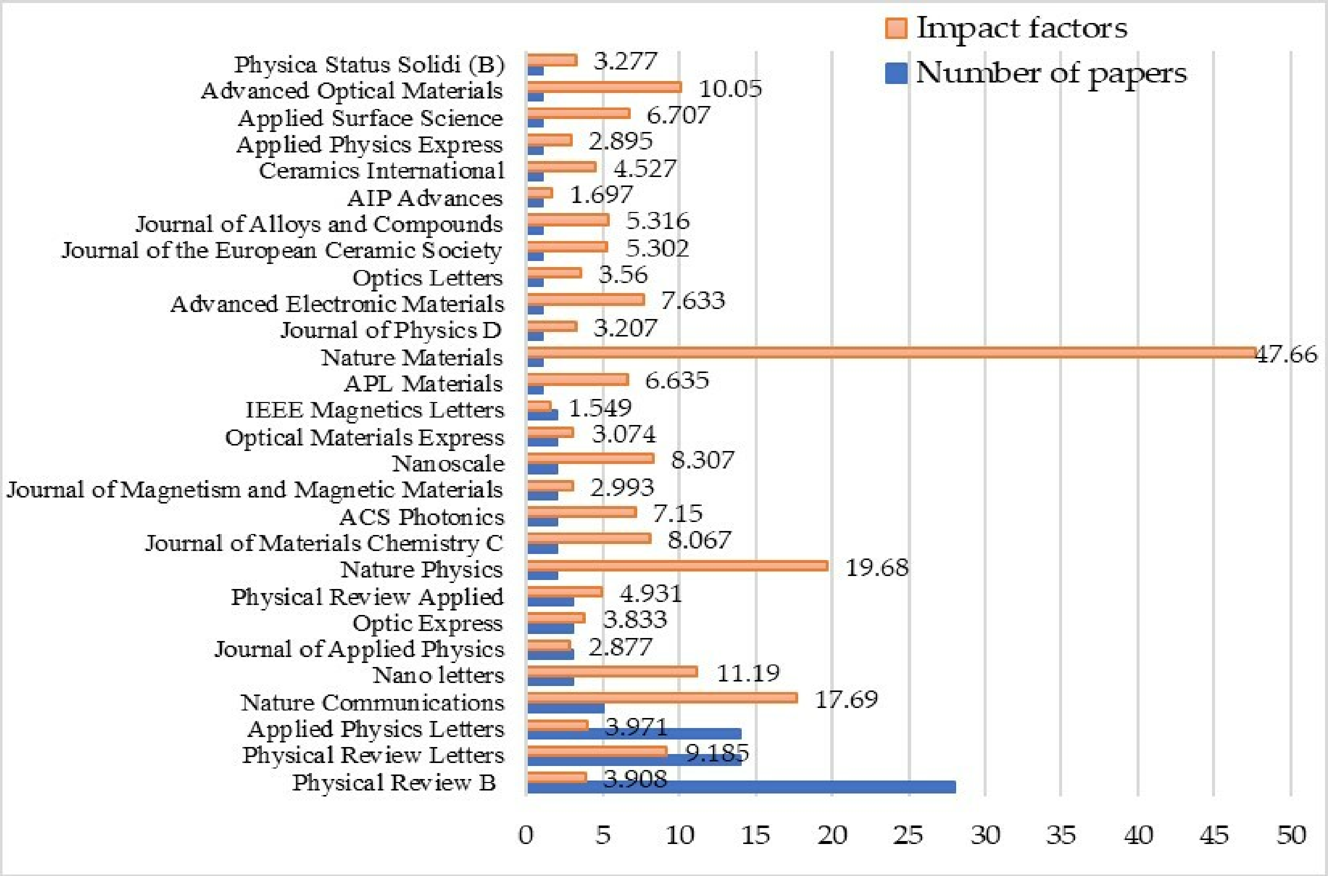

Figure 8. Evaluation of top citation papers over various journals and journal impact factors.

Figure 9 examines the journals according to the publisher and active areas in YIG research. In Figure 9, 11 distinct publishers were identified for the 100 most-cited papers. The American Physical Society (APS) published high-quality publications of 45% of the most cited papers. The related journals that were published in APS were *Physical Review B*, *Physical Review Letters*, and *Physical Review Applied*. The most frequently cited publication was *Physical Review B* (28%), followed by *Physical Review Letters* (14%) and *Physical Review Applied* (3%). In addition, the first- [13] and second-ranked [36] top papers were published in *Physical Review Letters*, which were published by the APS. The impact factors of the associated papers were 9.185, which is rather high. The third- [18] and fourth-ranked [68] papers appeared in *Physical Review B*, which was published by the same publisher, APS, and had an impact factor of 3.908. The remaining publishers involved in the YIG publications were Applied Physics Letters (AIP) (19%), Elsevier (6%), Optica (6%), American Chemical Society (ACS) (5%), Nature Research (5%), Royal Society of Chemistry (RCS) (4%), Nature Publishing Group (3%), Wiley-VCH (3%), Institute of Electrical and Electronics Engineers (IEEE) (2%) and Institute of Physics (IOP) Publishing (2%).

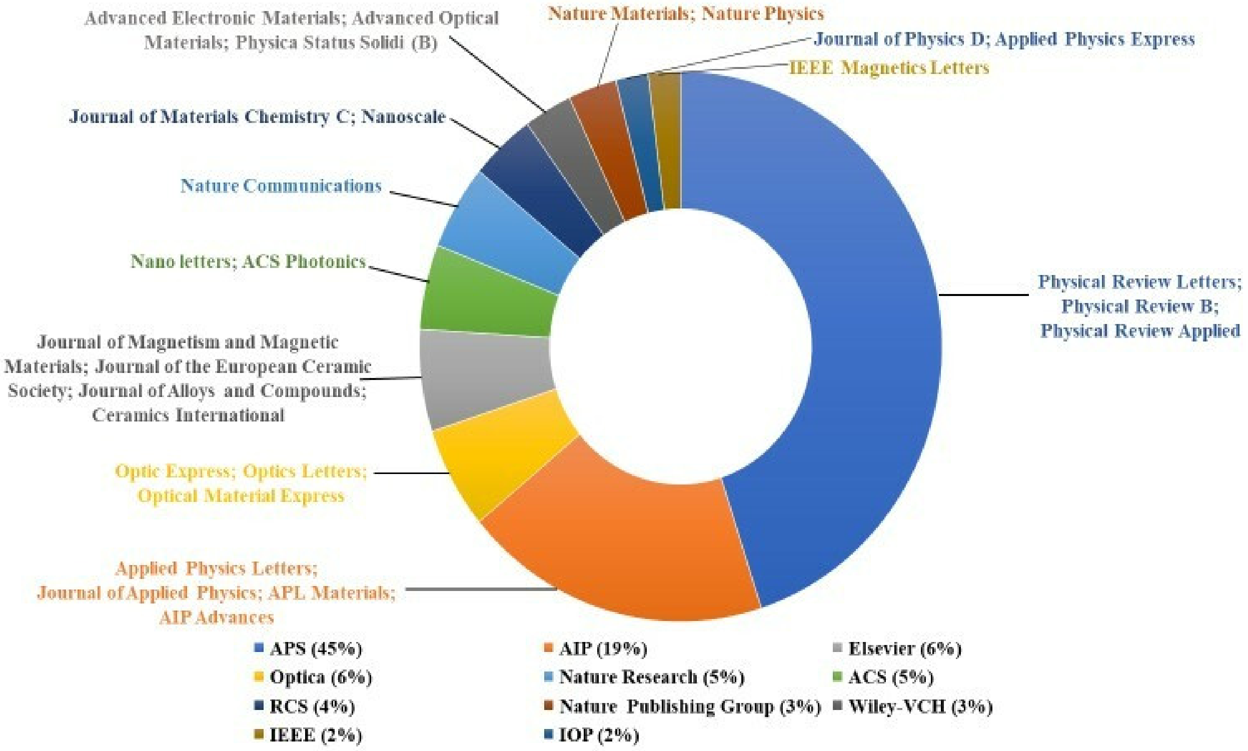

Figure 9. Publishers of the top articles.

It is acknowledged that Nature Publishing Group publishes one of the most widely-read, prestigious, and high-quality academic publications in the world. As seen in Figure 9, Nature Publishing Group has the highest impact factor compared with the other publishers. Intriguingly, three YIG publications have been published by the Nature Publishing Group in *Nature Materials* [76] and *Nature Physics* [10,23]. The impact factors of *Nature Materials* and *Nature Physics* were 47.66 and 19.68, respectively, as depicted in Figure 8. A high impact factor of 17.69 was also displayed by *Nature Communications*, which had five YIG publications [24,72,82,103,117] that were published in *Nature Research*. Figure 9 illustrates the advances and achievements of YIG research that have been globally embraced and published in prestigious journals and publishers.

5. Issues and Recommendations

The challenges in this YIG research sector have been addressed in this paper, such as lattice mismatch and a drastic variation in the thermal expansion coefficient, as well as difficulties in the annealing temperature factor, Y-Fe-O phase complexity, and addition of substituents.

5.1. Lattice Mismatch between Substrate and YIG

Even though high-quality YIG thin films can be epitaxially grown on lattice-matched gallium gadolinium garnet ($Ga_3Gd_5O_{12}$, GGG) substrates using physical vapor deposition techniques, it is necessary to deposit phase pure YIG films on Si substrates to integrate this material into silicon photonic and spintronic systems. However, developing phase-pure YIG on silicon has been difficult due to the lattice mismatch between the silicon substrate and YIG. First, the unit cell of YIG has a significantly greater lattice constant. The unit cell of YIG has a significantly greater lattice constant (12.376 Å) than that of the lattice constant of silicon (5.65 Å) [145]. Furthermore, a process growth YIG on quartz substrate may be challenging due to weak adhesion and lattice mismatch [146].

However, through misfit dislocation and thermal expansion coefficient mismatch, strain relief enhances magnetic properties [126]. For example, YIG growth on a YAG substrate has a larger lattice mismatch than YIG growth on a GGG substrate. YIG growth on the YAG substrate had a shorter FMR linewidth than YIG films deposited on GGG under the same circumstances, suggesting that lattice mismatch improves the magnetic characteristics of the YIG films [126]. The stresses generated during film growth are inherent and frequently compressive [137].

5.2. Annealing Temperature Factor

Annealing temperature affects the growth phase of pure YIG thin films. In the subsequent annealing procedure, a low deposition temperature results in partially amorphous YIG thin films, whereas a high deposition temperature results in non-garnet phase development. A low annealing temperature also results in a partly amorphous phase, but an excessively high annealing temperature reduces saturation magnetization, probably as a result of the production of Fe^{2+} ions. According to [145], the optimal post-deposition annealing temperature for the development of YIG on silicon using the PLD technique is 800 °C–850 °C. Arsad and Ibrahim [32] reported that YIG films formed on a quartz substrate using the sol-gel process exhibit a polycrystalline YIG structure during annealing in oxygen at temperatures of 700 °C, 800 °C, and 900 °C.

5.3. The Complexity of the Y-Fe-O Phase

During the deposition process, secondary phases such as yttrium oxide (Y_2O_3), ferromagnetic (Fe_2O_3), and multiferroic perovskite ($YFeO_3$) may develop [145]. Using a deposition and post-deposition annealing (PDA) technique, multiple groups have demonstrated the presence of these secondary phases during the formation of polycrystalline YIG on silicon and quartz substrates. In addition, the formation of Fe, Y, and O_2 vacancies can occur when YIG films are formed by PLD at low oxygen pressure [137]. Relationships between the material structure and growth conditions have not yet been thoroughly investigated. Consequently, future research should focus on the associations between material structure and growth circumstances.

5.4. Addition of Substituents

Bismuth (Bi) and cerium (Ce), which are commonly employed to increase the Faraday effect, tend to crystallize into secondary oxide phases, rather than substituting for Y in a single-phase garnet structure [136]. The work of Ibrahim and Arsad [33] demonstrates that the morphology of Ce-substituted YIG with a composition range of 0–0.25 has a remarkably homogenous structure, indicating that Ce has completely replaced YIG and produced a single-phase structure. In contrast, the structure of the film with a Ce composition of 0.3 is inhomogeneous due to the presence of cerium dioxide (CeO_2) impurity. However, Ce improves YIG's magneto-optical performance (Ce-YIG). Ce-doping increases the near-infrared Faraday rotation and magneto-optical figure that are of merit in yttrium. Ce-YIG is beneficial for nonreciprocal photonic devices [125]. In the future, substituent addition in film should be prepared with a more effective and efficient process, so that there are more promising films for application.

6. Conclusions and Future Directions

YIG as a scientific research field is extremely important for an industrial application, with 5429 publications since 1957. This study provides a comprehensive bibliometric analysis of the YIG field's most highly cited works from 2012 to 2022. It is the first time a bibliometric analysis tool has been utilized in the field of YIG. The literature search was conducted using the Scopus database and criteria specific to thin film and magnetic properties. The following are the major conclusions drawn from the bibliometric analysis:

- "Thin film" and "magnetic properties" are the main category for which YIG is studied. YIG research has led to a rapid increase in research output from 2012 to 2022 (10 years).

The number of papers for the last ten years has risen most since last year (1961 to 2011). Reviewing the top 100 cited papers reveals that 2015 had the most publications compared to other years.

- The bibliometric analysis revealed that 19 countries contributed to the YIG field, with the USA contributing the largest papers contributions in YIG research. The USA was the first nation to publish YIG studies (in 1957) related to the formation of the crystalline structure of YIG [60]. The USA exhibited a consistent publication of high-quality papers from 2012 to 2020. The top-ranked study came from the USA, and its author was Wang et al. [13]. It is evident that this technology has reached a high level of global maturity, but further study is still required in the YIG field.
- The subject subfields of magnetization characterization attained the highest frequency proportion of citations (91%). Preparation/fabrication of YIG is in the second position, followed by magnon, with a frequency weight of 56% and 54%, respectively.
- Pulsed laser deposition (PLD) was the most popular methodology preparation utilized by highly cited papers. YIG films were also fabricated via sputtering and liquid phase epitaxy (LPE) techniques. It was revealed that PLD can make films of good quality for magneto-optical devices. GGG, YAG, silicon, and quartz are substrates for YIG. Most cited papers used GGG substrate for growing YIG films. Researchers have measured numerous characterizations of films, including magnetic, morphological, magneto-optical, structural, electrical, and optical properties.
- The keyword findings show that "iron" attracted the most interest compared to the other keywords. Nevertheless, additional keywords including "yttrium iron garnet", "garnets", "film", and "temperature" had the most importance and attention in YIG research.
- *Physical Review B*, having published 28% of the articles, was the journal with the greatest influence on YIG research. Having published 14% of the articles each, *Physical Review Letters* and *Applied Physics Letters* were the second-most-cited journals. It is noteworthy that Nature Publishing Group also published YIG publications. Nature Publishing Group publishes one of the world's most widely-read, prominent, high-impact, and high-quality academic journals.
- Through a survey of the literature, the following opportunities and challenges have been summarized: lattice mismatch between substrate and YIG, annealing temperature factor, Y-Fe-O phase complexity, and addition of substituents. Recommendations based on identified technological challenges would aid in the achievement of YIG research worldwide and provide a scientific foundation for technology development.

There are still several limitations to this study. The bibliometric studies used to identify emerging subjects are limited. The scope of the analysis is limited in that it only identified studies published between 2012 and 2022. In line with the restricted number of publication years, there is a significant citation rate for years before 2012. It was discovered by Ma et al. [147] in 2002 and received the highest number of citations at ~1123, whereas the paper by Serga et al. [1] in 2010 received 841 citations. Ma et al. [147] explored YIG- and lithium niobate-based optical waveguides, including materials, processing, and devices. Serga et al. [1] studied YIG magnonics to discuss the transferability of ferrite concepts and ideas to contemporary nano-scale systems. If high-citation publications are included, it can reflect the great interest in real-world research and YIG outcomes. Therefore, future studies should consider high-citation publications, even if they were published a long time ago. In addition, as a drawback of this study, this analysis excluded several high-quality articles that lacked relevant keywords or were written in a language other than English. Because this study did not analyze the contents of the articles, the results may be insufficient; thus, additional research is required. Another important limitation of this study is that the YIG evolution was researched and evaluated using the Scopus database. Additional data sources, such as Google Scholar, Web of Science, etc., may be valuable for spotting new findings. Our research is based on publications in the Scopus database that limit to the articles for documentation. The topics mentioned in this situation might be quite helpful for the sectors to include other documents such as conference papers, book series, or books. Finally, some indicators should be made from patent statistics to provide insight into technical trends. As a result, not all articles and patents in the subject field were included. In the future, we will refine our search using alternate analysis tools or examine multi-source, heterogeneous data from several viewpoints.

Author Contributions: A.Z.A.: Conceptualization, data curation, formal analysis, methodology, writing—original draft preparation, A.W.M.Z.: writing—review and editing, supervision, N.B.I.: writing—review and editing, supervision, M.A.H.: resources, supervision. All authors have read and agreed to the published version of the manuscript.

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