fractal and fractional

Review

Fractal Theory in Thin Films: Literature Review and Bibliometric Evidence on Applications and Trends

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Abstract: A bibliometric analysis of publications on fractal theory and thin films is presented in this article. Bibliographic information is extracted from the Web of Science digital database and the bibliographic mapping undertaken using VOSviewer software. Based on the analysis, there is a growing trend in research on the applications of fractal theory in thin film technology. The factors driving this trend are discussed in the article. The co-citation, co-authorship and bibliographic coupling among authors, institutions and regions are presented. The applications of fractal theory in thin film technology are clarified based on the bibliometric study and the directions for future research provided.

Keywords: thin films; thin film deposition; bibliometric analysis; VOSviewer; fractals; fractal theory

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1. Introduction

Thin film technology finds application in various areas in modern society, including electronics (micro-and nano-electronics), optics, biomedicine and medicine, sensors, surface protection, energy and fuels, spintronics, magnetism and others [1]. Some of the examples of thin film materials include copper, aluminium, gold, aluminium zinc oxide, hydroxyapatite, titanium, titanium carbide, complex polymers, etc. [2–4]. There are several thin film deposition methods that have been classified broadly as chemical vapour deposition, physical vapour deposition and chemical methods [1]. Due to evolution of the thin film deposition technology, it is nearly possible to deposit thin films of all materials, including metals, non-metals, alloys/compounds, ceramics, polymers and composites. These materials can be converted into thin films from different forms based on the method of deposition, including solid (for physical vapour depositions), gases (for chemical vapour depositions) and liquids (for chemical methods). Readers are referred to a review by Abegunde et al. [5] to understand the classifications and scientific operation of various thin film deposition methods.

In thin film technology, the scientific focus is to manufacture quality structures with the appropriate behaviour and performance. As such, characterization techniques and tools are very important. One such important tool, over the years, has been the fractal theory [6]. The fractal theory is based on mathematical formulations that assume self-affine and self-similar properties of a behaviour and has been described in detail by various academics [7–10]. There are various techniques used in fractal analysis of surfaces (including thin films), some of which include power spectral density function (PSD), Higuchi Technique, multifractal approach, area-based methods and so forth [11–14]. These techniques have been shown to compliment the statistical methods of surface roughness (and structure growth studies) of thin films during deposition. As such, a lot of studies have been published on fractal characterisation of thin films. The purpose of this study is to undertake a bibliometric analysis of the published literature on this topic based on the Web of Science database to show the holistic achievement and progress of the research. In addition, the study, based on the existing literature, aims to provide clarity on the applications of fractal theory/methods in thin film technology. The article will be very useful for researchers in the field to understand the impact of this topic to the industry, development and prospects for further research and innovation.

2. Materials and Methods

In this study, Visualisation of Similarities (VOS) Viewer Software, version 1.6.18, Centre for Science and Technology Studies, Leiden University, The Netherland, is used to map bibliographic information of publications. The software, commercially known as VOSviewer is an open-source computer program that was developed by Eck and Waltman (2010) [15]. The VOSviewer software is very powerful for graphical representation of bibliometric maps and it is able to synthesise large amounts of bibliometric data into easy-to-interpret maps. With this software, the influence of co-authorship, co-occurrence, bibliographic coupling and co-citation on authors, organizations and regions can be studied for various publications [16]. According to Henry Small (1973), co-citation is the frequency with which two documents are cited together by a third document and it is an indication that the articles are related [17]. Bibliographic coupling occurs when two publications cite the same third research publication and it can apply to authors, documents and institutions [18].

To obtain the bibliographic details, data were extracted from the Web of Science (WoS) Core Collection database. The WoS is the most trusted digital database for scientific research and findings since it is known to maintain high standards and ethics in research practices. It is one of the oldest databases for scientific information, data and publications. The WoS database was accessed on 13 April 2022 through the *University of Johannesburg* (UJ), South Africa digital library services. The search criteria were based on the following topics: fractal in thin films, fractal theory in thin film analysis, fractal characterisation of thin films, fractal analysis of thin films and fractal theory in thin film deposition. The search query was formulated as follows in the WoS database, ts = ((fractal in thin films) OR (fractal theory in thin film analysis) OR (fractal characterisation of thin films) OR (fractal analysis of thin films) OR (fractal theory in thin film deposition)). The objective was to obtain publications related to applications of fractal theory in thin film deposition and materials and as such the search was limited to the above specific queries. Using broader sets of queries yielded more results but with so many irrelevant articles, which needed further (and tedious) filtering. On searching (based on these topics), 1334 documents were obtained out of which 1280 were journal articles, 135 conferences and others (notes, letters, book chapters, etc.). The search period was filtered between 1982 and 2022. Then, the search was further filtered to only original research articles (excluding review papers) and only 1270 documents satisfied the criterion. Finally, the full records of the journal documents including name of authors, titles, abstract, date of publication, affiliations, journal names and citation reports were downloaded. The bibliographic information was stored as *.txt* and uploaded to VOSviewer software for bibliometric analysis. For detailed procedure on VOSviewer software analysis in scientific research, readers are referred to works by Nyika and co-authors [19–22].

3. Results and Discussion

3.1. Characteristics of Retrieved Publications

When the search query was input into the Web of Science (WoS) database, a total of 1270 original journal articles (excluding review and conference publications) was obtained, which accounts for about 88.1% of all the documents. As shown in Figure 1, most of the articles were written in the English language (which accounted for 97.4% of the total articles). Chinese language articles accounted for 2.0% of the retrieved publications, whereas French-written articles accounted for just 0.2%. Articles published in other languages (German, Portuguese, Russian and Spanish) accounted for 0.3% of the total publications. Of the retrieved articles, 18% (n = 230) were open access while 0.005% (n = 6) were early access publications.

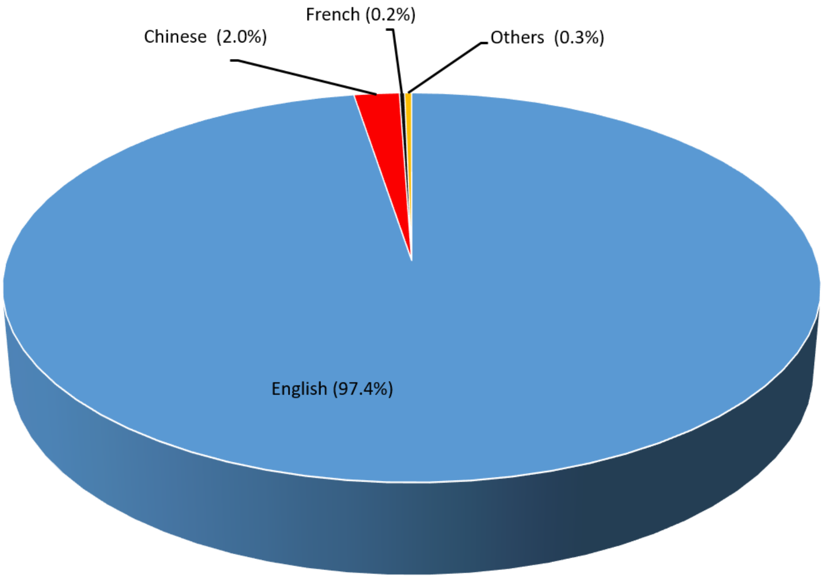

Figure 1. Distribution of retrieved articles on fractal theory in thin film materials by language. It can be seen that most of the articles in the topic are written in English.

3.2. Publication Growth Trend

The trends in publications in terms of annual outputs since 1982 to 2022 were analysed from the WoS and are represented in Figure 2. It can be seen generally that research publications in fractal theory in thin films has been in an upward trend. The research on this topic up to 1990 was very limited, with very high research outputs recorded between 2006 and 2021. It can also be seen that the average highest number of publications recorded is in recent years, 2018–2021, indicating the emerging research and industrial importance of fractal theory in thin film technologies and materials. In the early 1990s, most of the articles on thin film materials were focusing on functionality in terms of surface and other properties for various applications, in which fractal theory applications were limited. However, as demonstrated by the articles obtained from 2000 onwards, there has been a need for atomic and structural tuning of properties in thin film materials for advanced-level applications, such as solar cells, microelectronics, etc. As such, fractal tools have been extensively employed to characterize these materials for optimal tuning and performance.

The trend can also be attributed to the promising performance attributes provided by fractal-like devices. For instance, solar cells exhibiting fractal-like features have been said to perform better. Such solar cells exhibit higher absorption to solar than the normal solar cells and the fractal thin film structure enhances its performance in a wide range of wavelengths [23]. For example, Sierpinski (fractal) back-structure thin solar cells have been demonstrated to absorb more light than other types of solar cells [24]. Fractal-structured thin films used in gas sensing offer superior properties and performance; some examples of fractal thin film structures used in gas sensing are Tin oxide (SnO_2) thin films, SnO_2/CuO thin films, TiO_2, α-Fe_2O_3 fractals, ZnO fractals, tungsten oxide, bismuth vanadate, etc. [25]. Properties of thin films, such as sheet resistance, have been related to fractal dimension and, therefore, the concept is being used in the design of ohmic, barrier contacts, thin film transistors, thin film capacitors, etc. [26,27]. The trend can also be attributed to the enhanced technology of topography information acquisition, i.e., there is powerful equipment for surface characterization, such as atomic force microscope (AFM), field emission scanning electron microscope (FESEM), scanning tunnelling microscope (STM) and transmission electron microscope (TEM).

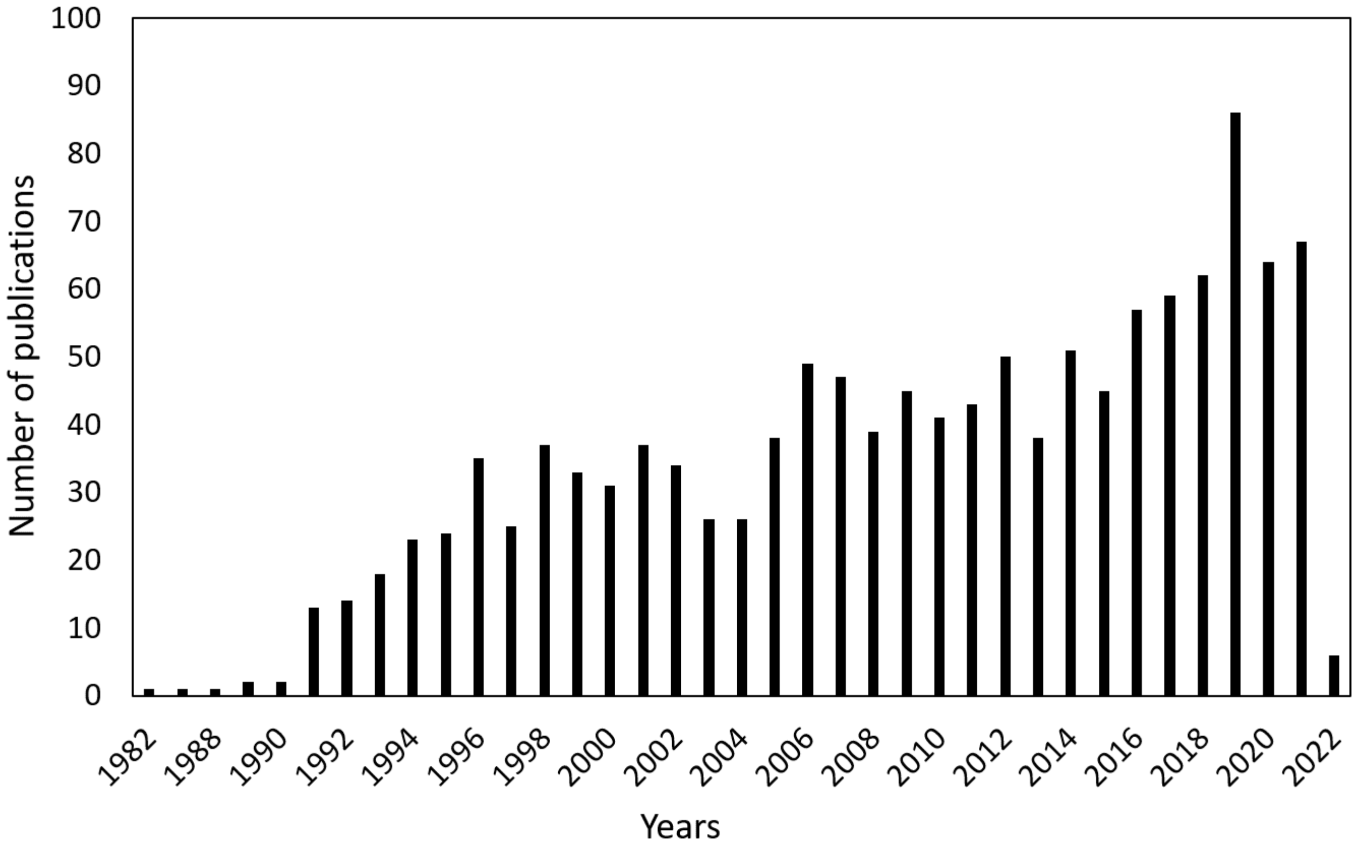

Figure 2. The publication trend on fractal theory in thin film materials for the period 1982–2022 according to Web of Science database.

Table 1 provides bibliographic details of the top 10 highly cited articles on fractal theory and thin film technology and materials over the years (1992–2022). As shown, the most cited (with 782 citations) article, by Majumdar and Bhushan (1991), in the Journal of Tribology-Transactions of the ASME, demonstrated the use of scale-independent fractal technique for analysis of optical interferometry and scanning tunnelling microscopy data of thin film surfaces [28]. The study demonstrated that area-based fractal techniques are powerful tools for surface roughness characterization since they are not affected by measurement parameters of the data-logging equipment [29]. The second most highly cited article, published in 2014 by Fan et al. [30], is a typical demonstration of the use of fractal theory as a method for fabricating patterned electronic circuits. It has been reported in various studies that patterned (or literally fractal) thin film structures offer attractive performance of electronic and solar devices [31,32]. Therefore, fractal techniques can be used to design patterned (fractals) thin film devices for enhanced performance. A similar concept is demonstrated by the third most highly cited article, published by Arabatzis et al. [33]; fractal dimension was used to characterize the evolution of silver–titanium dioxide thin films during deposition. These top 10 articles demonstrate four important aspects of fractal theory in thin film technology, namely, (1) specific applications of fractals in thin films, (2) capabilities of fractal techniques, (3) examples of thin film materials characterized via fractal theory and (4) some of the surface topography techniques.

Table 1. The bibliographic details of the ten leading articles (highest citations) on fractal theory in thin film technology.

Rank	Title of Article	Author/Year	Journal	Research Area	Country/Institution	Citations
1	Fractal Model of Elastic-Plastic Contact Between Rough Surfaces	Majumdar, A & Bhushan, B/1991	Journal of Tribology-Transactions of the ASME	Engineering	USA/Arizona State University	782
2	Fractal design concepts for stretchable electronics	Fan, JA et al./2014	Nature Communications	Science & Technology	USA/Howard Hughes Medical Institute	592
3	Silver-modified titanium dioxide thin films for efficient photodegradation of methyl orange	Arabatzis, IM et al./2003	Applied Catalysis B-Environmental	Chemistry, Engineering	Greece/NCSR Demokritos, Inst Phys Chem	433
4	Impedance of constant phase element (CPE)-blocked diffusion in film electrodes	Bisquert, J et al./1998	Journal of Electroanalytical Chemistry	Chemistry, Electrochemistry	USA/UnivJaume	327
5	Dynamic Scaling of The Island-Size Distribution and Percolation in A Model of Sub-monolayer Molecular-Beam Epitaxy	Amar, JG et al./1994	Physical Review B	Materials Science, Physics	USA/Emory University	310
6	Robust fluorine-free superhydrophobic PDMS-ormosil@fabrics for highly effective self-cleaning and efficient oil-water separation	Cao, CY et al./2016	Journal of Materials Chemistry A	Chemistry, Energy & Fuels, Materials Science	Peoples R China/Soochow University	320
7	Near-field optical spectroscopy of individual surface-plasmon modes in colloid clusters	Markel, VA/1999	Physical Review B	Materials Science, Physics	University of Georgia	291
8	Fractal dimension and size scaling of domains in thin films of multiferroic $BiFeO_3$	Catalan, G/2008	Physical Review Letters	Physics	England/University of Cambridge	227
9	Effect of roughness as determined by atomic force microscopy on the wetting properties of PTFE thin films	Miller, JD/1996	Polymer Engineering and Science	Engineering, Polymer Science	USA/University of Utah	222
10	The Formation of Dew	Beysens, D/1995	Atmospheric Research	Meteorology & Atmospheric Sciences	France/CEA, CTR ETUD SACLAY	220

3.3. Analysis of Journals and Categories

3.3.1. Journal Analysis

The journal analysis revealed a total of 441 journals published in the search query. Table 2 shows the top 20 journals publishing in the fields of "fractals and thin films". As can be seen, a wide range of journals, based on the subject, are active in publishing original research on the search query. These journals are drawn across various disciplines, including surface, optic and microelectronic engineering, chemistry and physics. Of the 20 journals, 13 journals have at least 15 publications with *Applied Surface Science* and *Physical Review B,* with 53 articles each (accounting for 4.2% of the total publications). The *Journal of Applied Physics* and *Thin Solid Films* follow closely, with 42 articles each (3.3% of total publications). The other highly publishing journals include *Journal of Physical Chemistry C* (*25 articles*, *2.0%*), *Applied Physics letters* (*22 articles*, *1.7%*), *Acta Physica Sinica* (*19 articles*, *1.5%*), *Physical Review E* (*19 articles*, *1.5%*), *Journal of Materials Science Materials in Electronics* (*17 articles*, *1.3%*), and *Applied Physics A Materials Science Processing*, *Materials Research Express* and *Surface Science* (*16 articles each*, *1.3%*). These top journals mostly cover topics related to surfaces, interfaces, nanostructures and applications. *Applied Surface Science Journal*, for instance, deals with atomic- and molecular-level properties of materials and it is easy to infer that fractal theory is a powerful tool for characterising nanoscale and atomic-level construction of thin film structures, as evidenced by the other top journals, such as thin solid films, applied physics letters and so forth. These characterisations extend to magnetics, superconductors, electronics, semiconductors and photonics. A critical examination of Table 2 on the publication titles gives a snippet of the applications for fractal theory in thin film materials.

Table 2. Top 20 leading journals in research on fractal theory in thin film technologies and materials according to Web of Science database.

Rank	Publication Titles	Record Count	Percentage (%) of Published Records
1	Applied Surface Science	53	4.2
2	Physical Review B	53	4.2
3	Journal of Applied Physics	42	3.3
4	Thin Solid Films	42	3.3
5	Journal of Physical Chemistry C	25	2.0
6	Applied Physics Letters	22	1.7
7	Acta Physica Sinica	19	1.5
8	Physical Review E	19	1.5
9	Journal of Materials Science Materials in Electronics	17	1.3
10	Applied Physics A Materials Science Processing	16	1.3
11	Materials Research Express	16	1.3
12	Surface Science	16	1.3
13	Physical Review Letters	15	1.2
14	Macromolecules	14	1.1
15	Surface Coatings Technology	14	1.1
16	Journal of Physical Chemistry B	12	0.94
17	Langmuir	12	0.94
18	Physica A: Statistical Mechanics and its Applications	12	0.94
19	Journal of Physics Condensed	11	0.87
20	Journal of Magnetism and Magnetic Materials	10	0.79

The top 10 most active publishers in this topic are shown in Table 3. As shown, Elsevier Ltd, (Amsterdam, Netherlands) is the leading publisher in fractal theory of thin film materials and technology with 439 articles, which accounts for 33.2%, followed by Springer Nature, Berlin, Germany (118, 8.9%), American Institute of Physics, Maryland, USA (100, 7.6%), American Chemical Society, Washington, USA (97, 7.3%), Institute of Physics Ltd., Bristol, United Kingdom and Wiley, Hoboken, New Jersey, USA (71, 5.4%) and American Physical Society, Maryland, USA (64, 4.8%), in that order. Other publishers in the top ten include Taylor & Francis, Milton Park, Oxfordshire, UK, Royal Society of Chemistry, London, UK, and Multidisciplinary Digital Publishing (MDPI), Basel, Switzerland. The high number of counts in Elsevier Ltd. is attributable to the high number of journals dealing with physics, chemistry and surface engineering of thin film properties, such as *Applied Surface Science*. Similar to insights provided in Table 2, these observations provide information regarding the applications of fractal theory in thin film materials.

Table 3. Top 10 most active publishers on fractal theory in thin films.

Rank	Publishers	Record Count	Percentage
1	Elsevier	439	33.2
2	Springer Nature	118	8.9
3	Amer Inst Physics	100	7.6
4	Amer Chemical Soc	97	7.3
5	IOP Publishing Ltd.	71	5.4
6	Wiley	71	5.4
7	Amer Physical Soc	64	4.8
8	Taylor & Francis	33	2.5
9	Royal Soc Chemistry	28	2.1
10	Multidisciplinary Digital Publishing	23	1.7

The bibliographic coupling among the most influential journals undertaken using the VOSviewer software is shown in Figure 3. During mapping in VOSviewer software, the minimum number of articles in a journal was 5 and, of the 441 sources, 55 met the threshold. For each of the 55 sources, the total strength of the bibliographic coupling links with other sources was calculated and the sources with the greatest total link strength were selected. As shown, the circle represents a journal and the curved line shows the interconnection of the journal to the others. The curve thickness indicates the strength of the interrelationship among journals. The bibliographic coupling yielded four clusters of journals denoted by different colours, namely red (28 articles), green (16 articles), blue (9 articles) and yellow (2 articles) clusters. These clusters are based on the search query and indicate the groupings of journals, as per research areas. Evidently, the *Applied Surface Science*, *Physical Review B* and *Journal of Applied Physics* have the largest circles, implying they have the highest number of publications and strong interrelationships with other journals. These three journals belong to the red and green clusters (Figure 3) and are associated with atomic properties in thin films, surface engineering and evolution of surface structures. A close look at these top journals indicates that fractal theory is widely used to study and characterise the evolution of surface structures during thin film depositions [34–37]. These journals are strongly connected with others, which indicates their impact on this topic.

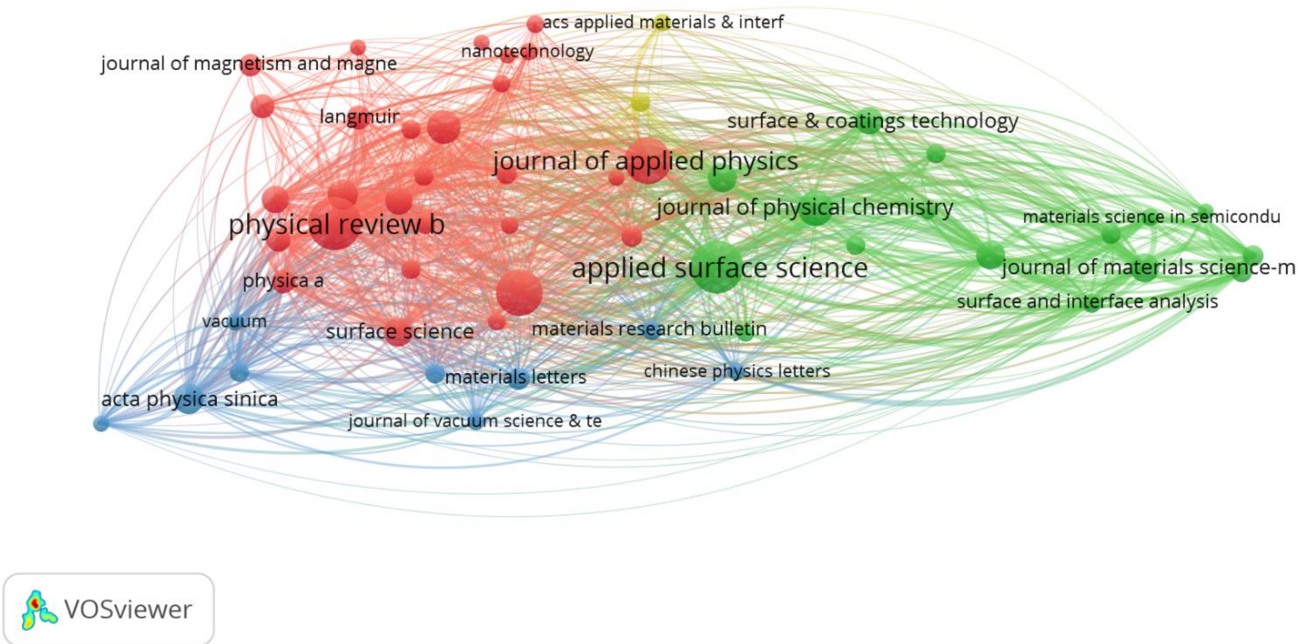

Figure 3. Bibliographic coupling of the identified journals publishing on fractal theory of thin films.

A co-citation analysis based on minimum number of citations of a source of 20 was undertaken and, of the 5520 sources, only 297 satisfied the threshold. A network map showing the co-citation patterns of the journals is shown in Figure 4. Five clusters are visible in the map in the fields of Physics, appearing as a green cluster (e.g., Physical Review B, Journal of Applied Physics, etc.), Engineering, appearing as a red cluster (e.g., Applied Surface Science, Wear, International Journal of hydrogen Energy, etc.), Chemistry, appearing as a blue cluster (e.g., Macromolecules, Langmuir, Soft mater, etc.), Materials Science, appearing as yellow cluster (e.g., Advanced Materials, Advanced Functional materials, etc.) and Applied Physics and Chemistry, appearing as purple cluster (e.g., Journal of Power Sources, Journal of Electrochemical Society, etc.). There is a very strong co-citation of journals in Physics and Engineering. However, there is a weaker co-citation of journals in the other fields—Chemistry, Materials Science and Applied Physics. This can be attributed to the application of fractal theory as a principle for explaining the physics/mechanisms of surface roughness, spatial patterning and structure development during thin film deposition [38]. In fact, there are lots of recent studies utilizing fractal techniques to characterize the micromorphology of thin film structures [39,40].

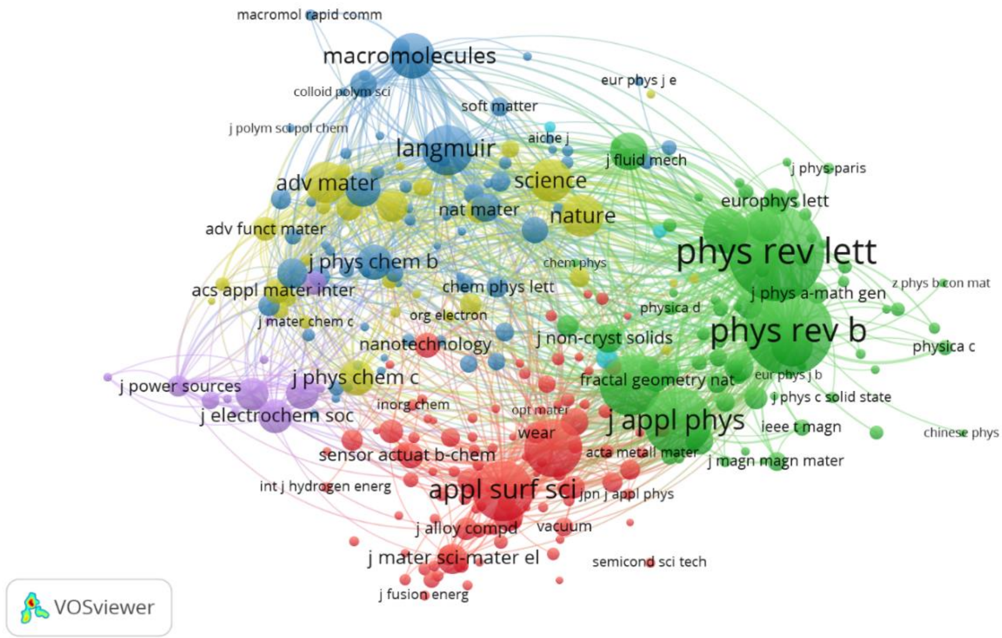

Figure 4. Co-citation of articles across the leading journals in fractal theory of thin films.

A citation map network across the journals is represented in Figure 5. Similar to the co-citation network, the map shows five clusters for the leading journals, as differentiated by the colours. The highly cited articles belong to journals in the fields of Engineering and Physics (clustered in blue and red, respectively) and a strong association among these journals exists. These fields are key to the development of fractal theories for characterisation and patterning of thin films in Materials Science, Chemistry and Applied Physics.

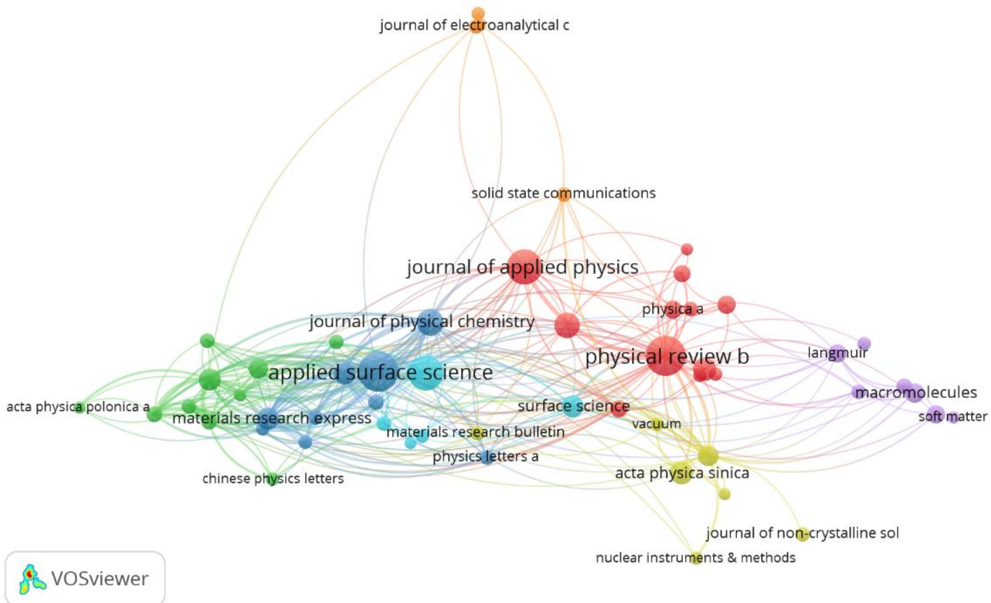

Figure 5. A map network showing citations of the leading journals in fractal theory of thin films.

3.3.2. Analysis of Categories

In this case, two categories were considered, namely, the WoS categories and research areas. The WoS categories were based on the classification by the database, whereas research areas were based on the general classification of the publication topics. The analysis of categories is helpful in determining the focus areas of the search topic, i.e., fractal theory. Considering both categories, Tables 4 and 5, Applied Physics and Physics have the highest count of published articles, followed by Materials Science, Chemistry and Engineering. The very high number of publications related to the Physics category is an indication that fractal techniques are utilized for the characterization of nanoscale surface dynamics of spatial patterns in thin films. Understanding the surface dynamics (Physics) of thin films is helpful in enhancing their properties and performance. The high number of articles in the Chemistry category is evidence that fractal theory is used in studying the atomic patterning of the deposited thin films. Through the use of fractal measurements, such as fractal dimension, various authors have been able to characterize the crystallography and morphology of chemical structures and defects in thin film materials. The Materials Science category is evidence of the role played by fractal theory in designing and predicting the properties of thin film materials. The occurrence of the Engineering category in this list is further evidence for the application of fractal theory in evaluation for performance of thin film materials. The Engineering category herein refers to the broader term, encompassing several research areas, some of which include nanoscience, electronics, polymer science, optics, electrochemistry, mechanical and mechanics, metallurgy, ceramics and biophysics. In this regard, it can be inferred from the Engineering category that fractal theory is utilized in studying coatings for surface protection and for nanoscale roughness characterization [41]. The engineering category indicates that the fractal techniques have been used for a wide range of applications, including electronic, polymer, optics, electrochemical, energy, environmental and other materials. Other research areas are related to instrumentation and microscopy; these are closely related to the data acquisition techniques suitable for fractal characterization of thin film surfaces. Specifically, surface scanning techniques, such as atomic force microscopy, scanning tunnelling microscopy, scanning electron microscopy, etc., are used to acquire visual data of surface morphology of features, which are used in the computation of fractal parameters, such as fractal dimension, Hurst component and others.

Table 4. Top twenty-five Web of Science categories on fractal theory of thin films.

Rank	Web of Science Categories	Record Count	Percentage Count
1	Physics Applied	425	33.5
2	Materials Science Multidisciplinary	424	33.4
3	Physics Condensed Matter	315	24.8
4	Chemistry Physical	227	17.9
5	Materials Science Coatings Films	133	10.5
6	Physics Multidisciplinary	132	10.4
7	Nanoscience Nanotechnology	102	8.0
8	Chemistry Multidisciplinary	74	5.8
9	Engineering Electrical Electronic	68	5.4
10	Polymer Science	68	5.4
11	Optics	42	3.3
12	Physics Mathematical	37	2.9
13	Electrochemistry	32	2.5
14	Engineering Mechanical	32	2.5
15	Multidisciplinary Sciences	32	2.5
16	Engineering Chemical	31	2.4
17	Physics Atomic Molecular Chemical	31	2.4
18	Physics Fluids Plasmas	25	2.0
19	Metallurgy Metallurgical Engineering	24	1.9
20	Chemistry Analytical	21	1.7
21	Instruments Instrumentation	21	1.7
22	Mechanics	21	1.7
23	Microscopy	20	1.6
24	Materials Science Ceramics	17	1.34
25	Mathematics Interdisciplinary Applications	16	1.26

Table 5. Top twenty-five Web of Science research areas on fractal theory of thin films.

Rank	Research Areas	Record Count	Percentage Record Count
1	Physics	726	57.2
2	Materials Science	530	41.7
3	Chemistry	307	24.2
4	Engineering	145	11.4
5	Science Technology Other Topics	134	10.6
6	Polymer Science	68	5.4
7	Optics	42	3.3
8	Electrochemistry	32	2.5
9	Mathematics	24	1.9
10	Metallurgy Metallurgical Engineering	24	1.9
11	Instruments Instrumentation	21	1.7
12	Mechanics	21	1.7
13	Microscopy	20	1.6
14	Energy Fuels	14	1.1
15	Anatomy Morphology	10	0.79
16	Environmental Sciences Ecology	10	0.79
17	Thermodynamics	10	0.79
18	Computer Science	9	0.71
19	Crystallography	9	0.71
20	Life Sciences Biomedicine Other Topics	9	0.71
21	Nuclear Science Technology	9	0.71
22	Water Resources	6	0.47
23	Biochemistry Molecular Biology	5	0.39
24	Biophysics	4	0.32
25	Meteorology Atmospheric Sciences	4	0.32

3.4. Keyword Analysis

Keyword analysis in this case was used to identify the various themes on fractal theory in thin films. It can be seen in Figure 6 that there are eight (8) themes or clusters in the search query. These themes are clustered in different colours, as shown in Figure 6. These themes can be further synthesized into three broad categories, namely, (i) data collection techniques, (ii) fractal analyses techniques and (iii) applications of fractal theory in thin film materials. The data collection techniques involve the microscopy methods used in imaging to obtain surface topography information and atomic force microscopy is the most utilized method [39,42], although scanning electron microscopy has also been utilized [43]. Over the period of bibliometric analysis in this study, it has been observed that various data acquisition techniques for fractal analysis have been utilized (Table 6). These techniques have been applied in pure metals, alloys, composites, polymers and ceramic thin film materials (see Table 6).

The various methods of fractal analyses applied in various studies were also identified in this keyword analysis. The fractal dimension was used as the most effective quantitative descriptor of self-affine/similar surfaces of thin film surfaces [44]. Hurst exponent, which relates to autocorrelations of the time series in surface roughness of thin film structures, has also been used as a quantitative measure of fractal properties [45,46]. As seen in Figure 6, fractal dimension and Hurst exponent are strongly related to surface roughness and microstructural features of thin films. The relationships indicate that fractal characterization is applied in evaluating the growth of surface features during atom diffusion, crystallization and growth of thin film surface features [36,47,48]. There are various calculation techniques used in determining fractal dimensions and other parameters for fractal measurement; some of these include power spectral density function, perimeter-area-based methods, autocorrelation functions, Higuchi, Box-counting, triangulation and other methods [38,49–51].

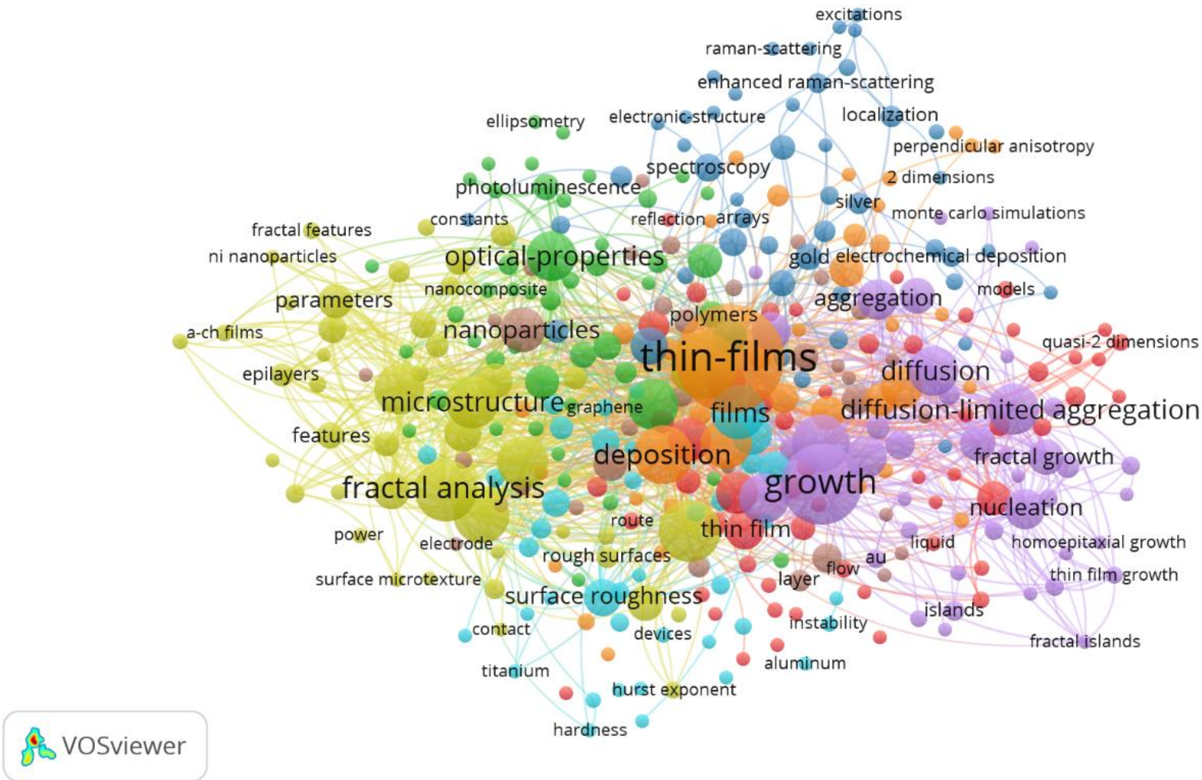

Figure 6. Bibliometric analysis of keywords on fractal theory in thin film applications. In total, eight clusters in different colours are shown in the map.

The third category derived from the keyword analysis is on the applications of the fractal theory in thin film materials and depositions. As evidenced, fractal formulations are used to characterize the surface roughness of thin film materials. These formulations have been regarded as superior to statistical tools, since they are scale invariant and, hence, more accurate for surface characterizations. In practice, surface roughness is a measure of evolution of structural features during thin film depositions/growth. As such, fractal techniques are applied to understand the evolution of structures at nanoscale level during thin film formation. It, therefore, implies that fractal theory could be related to the recrystallization and nucleation of grains in thin film deposition. By extension, most of the properties of thin film surfaces can be explained via fractal characterizations. Some of these properties include surface wettability [52], electrical [26], electrochemistry [53,54], nano-indentation [55], fouling [56], optical [57] and other properties. Fractal studies have been reported for various thin film materials based on the application of such films, according to the keyword analysis in Figure 6.

3.5. Analysis of Regions and Institutions

3.5.1. Region

The subject of fractal theory and thin films has been studied across different regions. Figure 7 shows the top 25 most-publishing countries on the search query and it can be seen that the People's Republic of China is the leading publisher (accounting for 18.73%) in this subject. The second-most-publishing country is the USA, followed by Iran, India, Germany and France, in that order. There is no doubt that the list is dominated by the most developed countries, except Iran and South Africa. All these countries are characterized by either advanced and developing manufacturing industries in semiconductors or related fields. The leading companies in the fields of semiconductors, electronics and related fields are mostly hosted in China, the USA, Japan, Germany and South Korea. There is intensive research in developing economies, such as South Africa, due to the country's policy on adoption of Industry 4.0 by the society. Industry 4.0 is supported by various technologies, such as additive manufacturing, virtual and augmented reality, Internet of Things (IOTs), etc. [1]. These technologies utilize a lot of sensors, which are usually fabricated from thin film materials; fractal techniques are used to pattern the films for effective performance in sensors and semiconductors [36].

Table 6. Various thin film materials and their deposition methods characterized by fractal techniques (1982–2022).

Year	Authors	Thin Film Material	Method of Deposition	Imaging Technique
1982	RF Voss, et al. [58]	Gold (Au)	Electron-beam evapouration	Transmission electron microscopy (TEM)
1989	JR Ding, BX Liu [59]	Silver-cobalt (Ag-Co)	Evapouration	Transmission electron microscopy (TEM)
1991	BX Liu, J Wang, ZZ Fang [60]	Cobalt (Co)	Electron-gun evapouration	Transmission electron microscopy (TEM)
2000	G.A. Niklasson, et al. [61]	Tin dioxide (SnO2)	Spray pyrolysis	Atomic force microscopy, light scattering
2009	T Toyama, Y Sobajima, H Okamoto [62]	microcrystalline Si (μc-Si)	plasma-enhanced chemical vapour deposition (PECVD)	Atomic force microscopy (AFM)
2009	C Trapalis [63]	TiO_2	Sol-gel	Atomic force microscopy (AFM)
2016	GH Solookinejad, ASH Rozatian, MH Habibi [64]	ZnO	Sol-gel	Atomic force microscopy (AFM)
2016	J Arjomandi, D Raoufi, F Ghamari [65]	Pyrrole (Py) conductive polymer	Cyclic voltammetry	Atomic force microscopy (AFM)
2019	Kavyashree et al. [66]	Copper-doped strontium hydroxide ($Cu{:}Sr(OH)_2$)	Successive ion layer adsorption and reaction (SILAR)	Scanning electron microscopy (SEM)
2019	R Prajapat, YC Sharma [67]	$Cu_2ZnSnSe_4$	Sputtering and electron beam deposition	Atomic force microscopy (AFM)
2019	L Eftekhari, D Raoufi [68]	ZrO_2	Electron beam evapouration	Atomic force microscopy (AFM)
2019	B Astinchap [69]	Titanium	Magnetron sputtering	Atomic force microscopy (AFM)
2019	FM Mwema, ET Akinlabi, OP Oladijo [55]	Aluminium	RF magnetron sputtering	Field emission scanning electron microscopy (FESEM) and Atomic force microscopy (AFM)
2020	Ş Ţălu et al. [70]	Silver/diamond-like carbon nanocomposite	co-deposition by sputtering and RF-PECVD	Atomic force microscopy (AFM)
2020	F Ghribi et al. [71]	$CuInS_2$	RF magnetron sputtering	Atomic force microscopy (AFM)
2020	AR Jahangiri et al. [72]	AlZnO	Magnetron sputtering	Scanning electron microscopy (SEM)
2021	S Soumya et al. [73]	Molybdenum Oxide (MoO_3)	Pulsed laser deposition	Atomic force microscopy (AFM)
2021	Z Ebrahiminejad, S Asgary, P Esmaili [74]	Cu-doped Indium sulphide	Chemical bath deposition	Atomic force microscopy (AFM)
2021	Y Romaguera-Barcelay et al. [75]	$GdMnO_3$	Spin coating	Atomic force microscopy (AFM)
2021	Y.Romaguera-Barcelay et al. [76]	BiZn0.5Ti0.5O3	RF magnetron sputtering	Atomic force microscopy (AFM)
2022	E Teimouri et al. [77]	TiB_2	Laser ablation technique	Atomic force microscopy (AFM)
2022	A Das et al. [54]	2D $Cd_{1-x}Pb_xS$	Pulsed laser deposition (PLD)	Atomic force microscopy (AFM)
2022	F Ghribi et al. [78]	Co10%–Alx Co-doped Zinc Oxide	Pulsed laser deposition (PLD)	Atomic force microscopy (AFM)

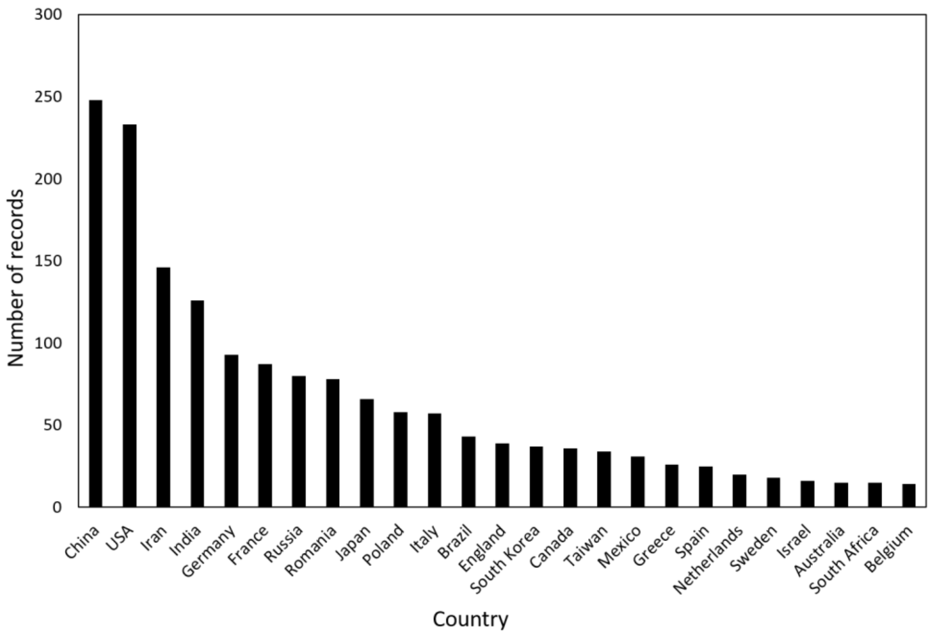

Figure 7. Top 25 publishing countries on the subject of fractal theory in thin film techniques and materials.

The research in various countries is also driven by the existing collaborations among those countries. In bibliometric analysis, collaborations can be measured through bibliographic coupling among countries. Bibliographic coupling of countries occurs when publications from two countries reference a publication from a third country. A bibliographic analysis of the top countries in the field of fractal theory and thin films based on a threshold of 5 and minimum number of citations per document of 500 was undertaken and is presented in Figure 8. There are two clusters, represented in red and green colours. The red cluster is composed of countries with the highest number of research outputs, whereas the blue cluster consists of countries with the strongest bibliographic links. As shown, Iran has the highest total link strength of 40,252, followed by Romania (37,624), Poland (23,586), India (20,930), the USA (20,764) and China 17,542). This means that these countries have a central influence on the research in fractal theory and thin film technology. Despite China and the USA being the most highly publishing countries, they have lower coupling strength compared to smaller countries, such as Iran, Romania, Poland and India. This means that research outputs in these countries (green cluster) are easily accessible by researchers in other countries. In addition, researchers from these (green cluster) countries are likely to collaborate strongly with researchers in other countries; for instance, researchers from Iran and Romania have extensively collaborated with researchers from Africa [34,79–81] and Europe [82–84]. There is a need to enhance research collaboration between the USA, China, Germany, Japan, etc. (red cluster) with the rest of the world, since these countries boost the cutting-edge technologies in thin films. The collaboration is necessary for the holistic generation of knowledge and the need to access and share research facilities in thin film technologies and fractal computation amongst different countries. These collaborations are important for marginalized countries, especially those of Africa, Latin America and Asia, to enhance their research and development in the subject. The subjects of fractal theory and thin film are very important to propel the growth of cutting-edge industries, such as semiconductors and electronics. Additionally, the governments in such countries should invest in thin film deposition facilities to enhance research and device development for their economies. The emergence of South Africa among the top 25 countries (Figure 7) is due to the government's investment in research facilities, such as the state-of-the-art atomic layer deposition, ALD (at the *University of Johannesburg*), sputtering facilities (at various institutions), laser deposition techniques at *Council for Scientific and Industrial Research* (CSIR), etc.

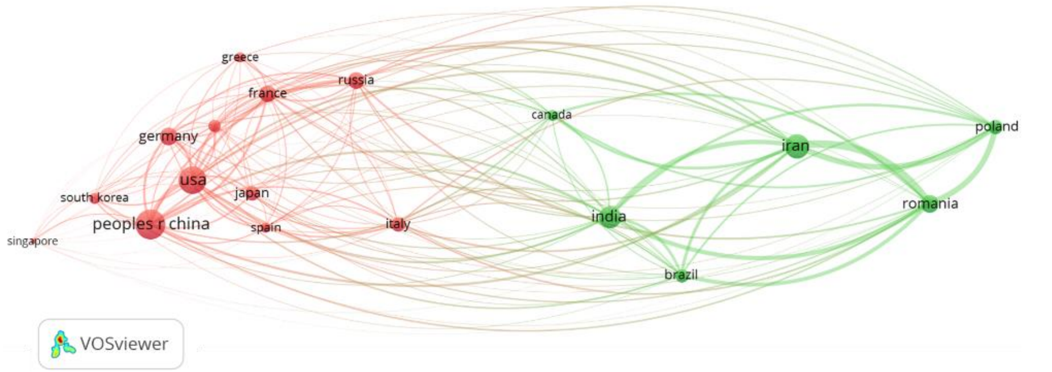

Figure 8. A network map showing bibliographic coupling of countries on the research subject of fractal theory in thin films. A threshold of 5 and minimum number of 500 citations was used in the analysis.

3.5.2. Institutions

Table 7 shows the top 10 research institutions and universities actively involved in research on the search query, "fractal theory in thin films". The top 10 ranking consists of institutions whose contribution to the subject is almost 2% in terms of research outputs in the form of peer-reviewed journal articles. As shown, Islamic Azad University tops the list with 74 (5.6%) outputs, followed by Chinese Academy of Sciences (70, 5.3%), Technical University of Cluj Napoca (64, 4.8%), CNSR (52, 3.9%) and Russian Academy of Sciences (41, 3.1%), in that order, make the top five institutions. The other institutions in this list include League of European Research Universities, Tsingua University, US Department of Energy, IIT system in India and UDICE French Research Universities. These institutions and universities are mostly based in China, Europe and the US, although other Asian institutions are ranked. As shown in Figure 8, these countries are industrialized and have embraced Industry 4.0 technologies in their economies and, therefore, their institutions are obliged to provide solutions in the relevant fields, such as thin film manufacturing. In addition, countries, such as Iran and United Arab Emirates (UAE), in which Islamic Azad University is based, are rapidly growing their economies through manufacturing and, hence, the university has taken the advantage of the government's policy to become the leader in research on thin films and analyses.

Table 7. Top 10 research institutions on fractal theory in thin film deposition and technologies.

Rank	Research Institution/University	Number of Outputs	% of Total Outputs
1	Islamic Azad University	74	5.6
2	Chinese Academy of Sciences	70	5.3
3	Technical University of Cluj Napoca	64	4.8
4	Centre National De La Recherche Scientifique CNSR	52	3.9
5	Russian Academy of Sciences	41	3.1
6	League of European Research Universities, LERU	31	2.3
7	Tsinghua University	31	2.3
8	United States Department of Energy, DOE	31	2.3
9	Indian Institute of Technology System IIT System	27	2.0
10	UDICE French Research Universities	24	1.8

Bibliographic coupling of institutions occurs when publications from one institution are cited by publications from two different institutions. Figure 9 shows a complex VOSviewer bibliographic network of coupling amongst the institutions. There is diversity and interconnections of research work being undertaken from various institutions. As shown, there are four clusters in this network and it can be seen that there are four institutions that have coupling link strengths above 10,000, namely, Technical University of Cluj-Napoca (Romania), Islamic Azad University (Iran), University of Warmia and Mazury (Poland) and Malayer University (Iran). The bibliographic coupling of institutions is contradictory to the results presented in Table 7; i.e., the most influential institutions in terms of the number of publication outputs and citations do not imply the most influential in terms of bibliographic coupling. The observation may be attributed to high collaborations among these four institutions with the rest of the world (for instance, see the recent research of [85] with institutions from Romania, Russia, Iran and Czech Republic). For instance, although the Chinese Academy of Sciences is highly ranked in terms of publications and citations, it has lower bibliographic coupling than the University of Johannesburg (South Africa). A snippet review of some of the publications by the South African institutions on fractal theory and thin films shows very high diversity in collaborating institutions—Czech Republic, India, Romania, Russia, etc. [81].

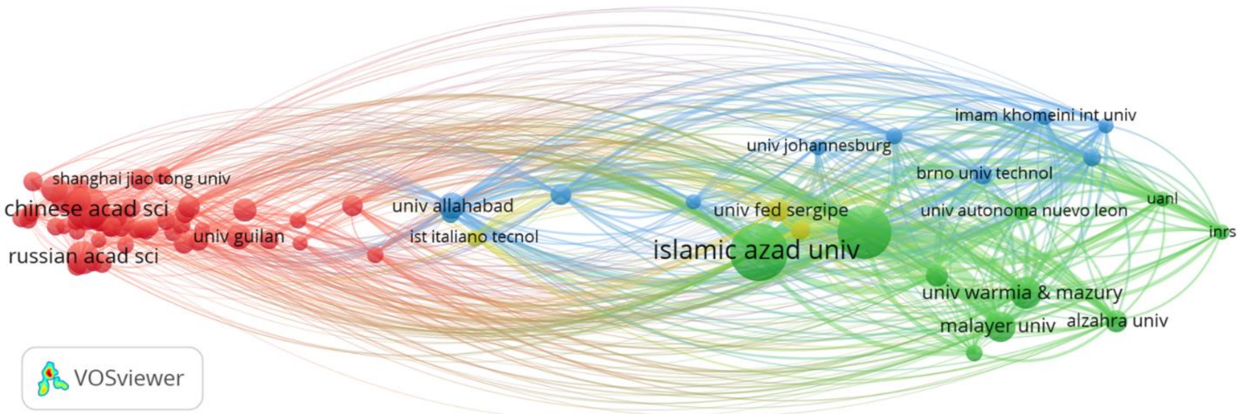

Figure 9. A map of bibliographic coupling of institutions publishing in fractal theory and thin films. A threshold of 5 documents and 50 citations per institution.

3.6. Author Analysis

The top 10 contributing authors in the topic of fractal theory and thin films are shown in Table 8. The authors are ranked in terms of the quantity of publications. The author with the leading number of publications is Professor Ştefan Ţălu, who has almost twice the number of publications as the second-ranked author. Most of Ţălu's publications involve multifractal, mathematical methods of surface analyses, fractal geometry and fractal analysis. He has a Web of Science (WoS) *h-index* of 33. The other nine authors in this list include Solaymani (35 articles), Yadav (26 articles), Chen (23 articles), Kulesza (22 articles), Bramowicz (21 articles), Matos (18 articles), Rezaee (18 articles), Shek (18 articles) and Arman (17 articles). Professor Ştefan Ţălu has the highest number of citations in the field of fractal theory and thin films with his highly cited article, titled "AFM imaging and fractal analysis of surface roughness of AIN epilayers on sapphire substrates". The article has 77 citations as per Web of Science database and it deals with fractal characterization of 3D surface morphology of AFM imaging of AlN epilayers deposited on sapphire substrates through magnetron sputtering [83]. Other highly cited articles by the author include "Micromorphology characterization of copper thin films by AFM and fractal analysis [86]"(68 citations), "Microstructure and Tribological Properties of FeNPs@a-C:H Films by Micromorphology Analysis and Fractal Geometry [87]" (67 citations) and "Ion implantation of copper oxide thin films; statistical and experimental results [88]"(66 citations).

Table 8. Top 10 most influential authors in fractal theory in thin films.

Rank	Authors	Record Count	% of Total	WoSh-Index	Institution	Country	Total Citations
1	Ţălu S	64	4.8	33	Technical University of Cluj-Napoca	Romania	1466
2	Solaymani S	35	2.6	29	Islamic Azad University	Iran	851
3	Yadav RP	26	2.0	14	DeenDayal Upadhyay Govt PG Coll	India	362
4	Chen ZW	23	1.73	12	University of Science and Technology of China	China	292
5	Kulesza S	22	1.66	19	University of Warmia & Mazury	Poland	588
6	Bramowicz M	21	1.59	20	University of Warmia & Mazury	Poland	586
7	Matos RS	18	1.36	10	Universidade Federal de Sergipe	Brazil	113
8	Rezaee S	18	1.36		Islamic Azad University		176
9	Shek CH	18	1.36	40	Hong Kong Polytechnic University	Hong Kong	223
10	Arman A	17	1.30	16	Academic Center for Education, Culture & Research (ACECR), Sharif University	Iran	298

A co-citation occurs when two documents are cited by the same third document. The co-citation of authors occurs when two documents from different authors receive a citation from a third document from a different author. The analysis relies on the assumption that papers cited by the same document are highly related and their objectives are similar. Figure 10 shows the map network visualization of the co-citation of authors in fractal theory and thin film deposition and the analysis was based on a minimum threshold of 20 citations. As shown, each author is represented by a circle and the relationship between authors (co-citations) is represented by the links. The higher the total link strength, the larger the circle and larger the name of the author. As shown, there are six clusters in the co-citation visualization map. The first cluster (Cluster 1 in red) is anchored by researchers, such as Mandelbrot, Yadav and Raoufi; the cluster is composed of heterogenous topics, involving classical formulation of fractals and their applications in thin films characterization. The second cluster (Cluster 2 in green) is anchored by authors, such as Stockman, Stauffer, Feder, Shalaev and Yagil, and these authors undertake research involving mathematic formulations of fractal theory. The third cluster (Cluster 3 in blue) is anchored by Witten, Chen and Vicsek and the researchers have been involved in basic applications of fractal theory in thin film deposition. Cluster 4 (yellow) consists of Talu, Stach, Matos, Dalouji and Mwema; the authors in this cluster undertake research involving innovative applications of fractal theory in thin film technology, such as prediction of film growth and properties, patterning and manufacturing of high-performing devices (e.g., solar cells, electronic circuits, etc.). The applications of AFM techniques for fractal characterisation have also been underscored by the authors in Cluster 4. Meakin, Hwang, Amar and other authors anchor Cluster 5 (purple) and the authors are involved in research on fractal characterisation of various thin films. Finally, Cluster 6 (green) consists of authors, such as Ghosh and Swain, who focus on multifractality, chaos and thin film depositions, such as sol–gel.

Figure 11 illustrates bibliographic coupling of authors publishing in the field of fractal theory in thin films. There are four clusters distinguished by various colours. The green cluster is anchored by Stefan Talu, who focuses on mathematical techniques for fractal analyses of thin film materials and other surfaces. The red cluster is anchored by Yadav, Chen, Raoufi and Gosh, who have generally worked on various fractal techniques in the characterisation of thin film materials. The blue cluster is anchored by authors, such as Solaymani, Bramowicz and Dalouji, whereas the blue cluster is anchored by two authors, Karani and Mallik.

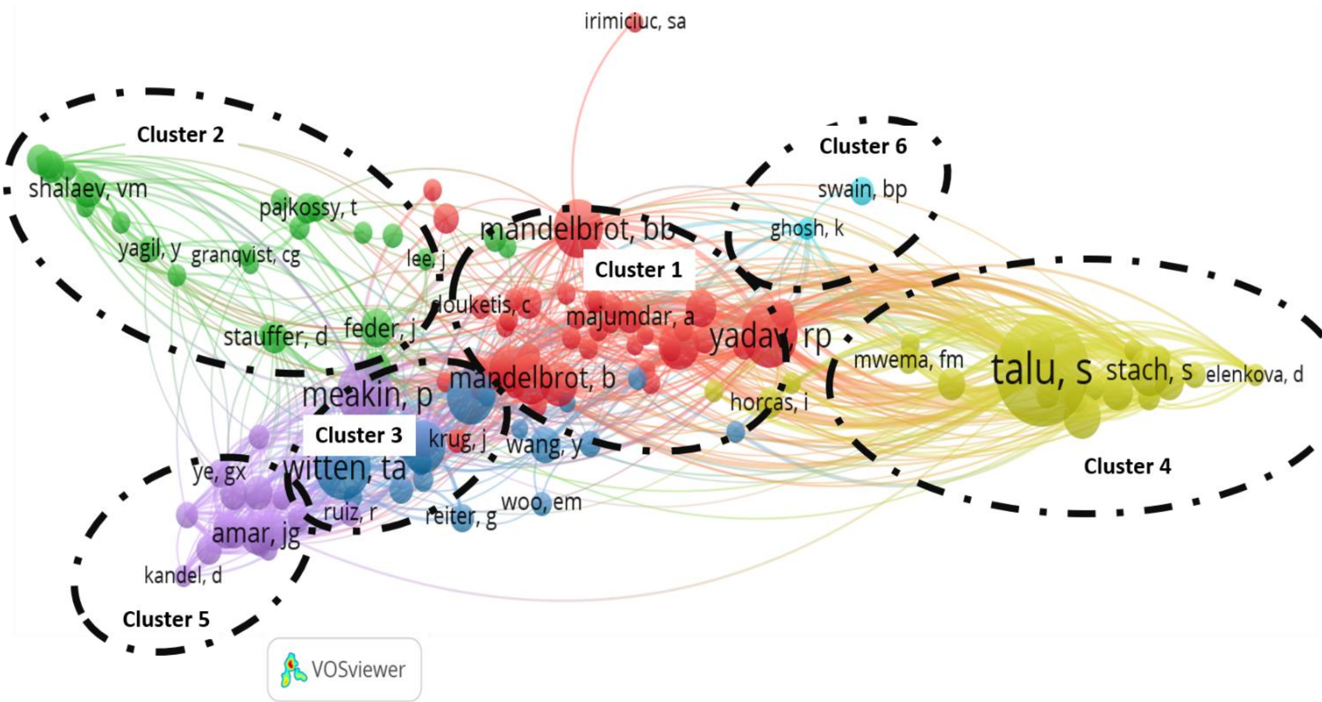

Figure 10. Mapping of co-citation of authors in fractal theory and thin film depositions. A minimum number of citations for each author is 20.

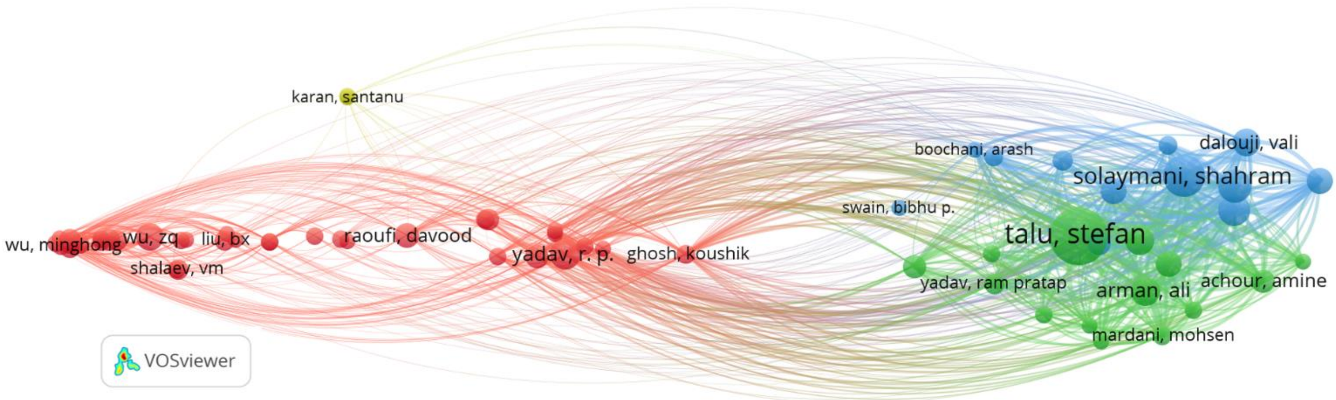

Figure 11. Bibliographic coupling of authors publishing in fractal theory of thin film materials. Minimum number of documents and citations for each author is 5 and 20, respectively.

Figure 12 shows a co-authorship network map of authors publishing in fractal theory in thin film deposition and materials. As per the analyses, 63 authors satisfied the search criterion and their co-authorship map is shown in Figure 13. The co-authorship map shows the various authors publishing various articles together and the interconnection strength is determined by the number of co-authored articles. It can be seen that most of the authors are not interconnected and, therefore, the co-authorship in this subject seems to be low. However, around 30 authors have extensively co-authored publications together in the subject.

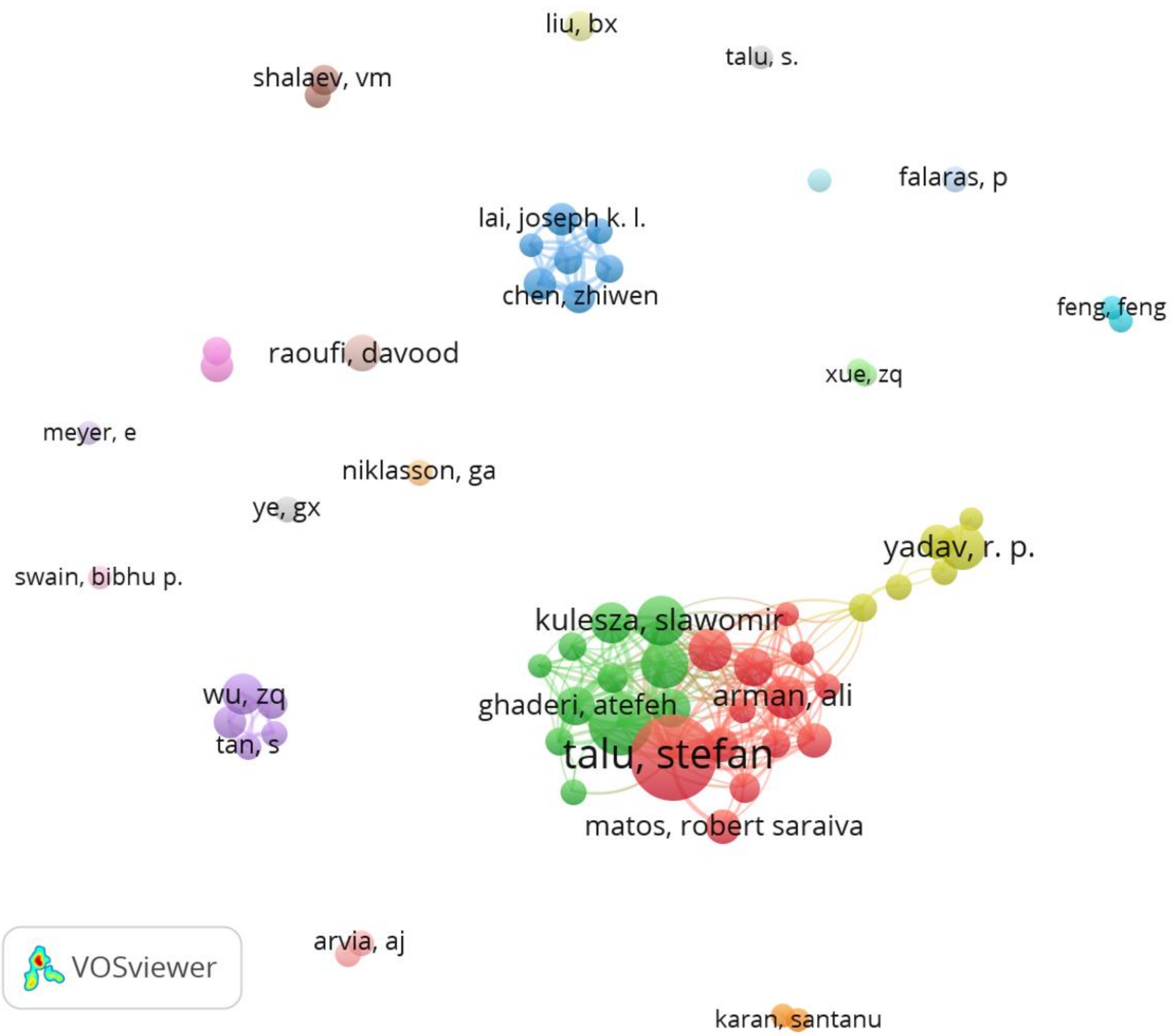

Figure 12. Co-authorship of authors researching fractal theory in thin film applications: minimum publication threshold of 5 documents and 20 citations per author.

An expanded view of Figure 12, showing the co-authorship network of the 30 authors, is shown in Figure 13. There are four clusters, which are anchored around the highly publishing authors, namely, Talu, Solaymani, Yadav and Rezaee. It is not surprising that the highly publishing authors (top 10) shown in Table 8 feature as the anchors in the co-authorship map. There is a direct relationship between co-authorships and research impact and, therefore, for acceleration of developments in the thin film industry and fractal techniques, authors across different regions and institutions are encouraged to collaborate and co-author research outputs together. It can also be observed that publications with a high number of co-authors, recently, attract a larger audience and more citations. Research findings presented in such articles tend to be highly trusted and, therefore, attract higher readability and applications. Professor Ştefan Ţălu is the most trusted researcher on this topic due to the various collaborations and co-authored works he has generated; he has published widely on fractal theory and applications to nearly all methods of deposition, including physical vapour depositions, chemical vapour depositions, chemical methods and so many others. He has also applied various techniques in fractal analyses, including power spectral density, Minskowski functions, multifractal, area based and so forth [43].

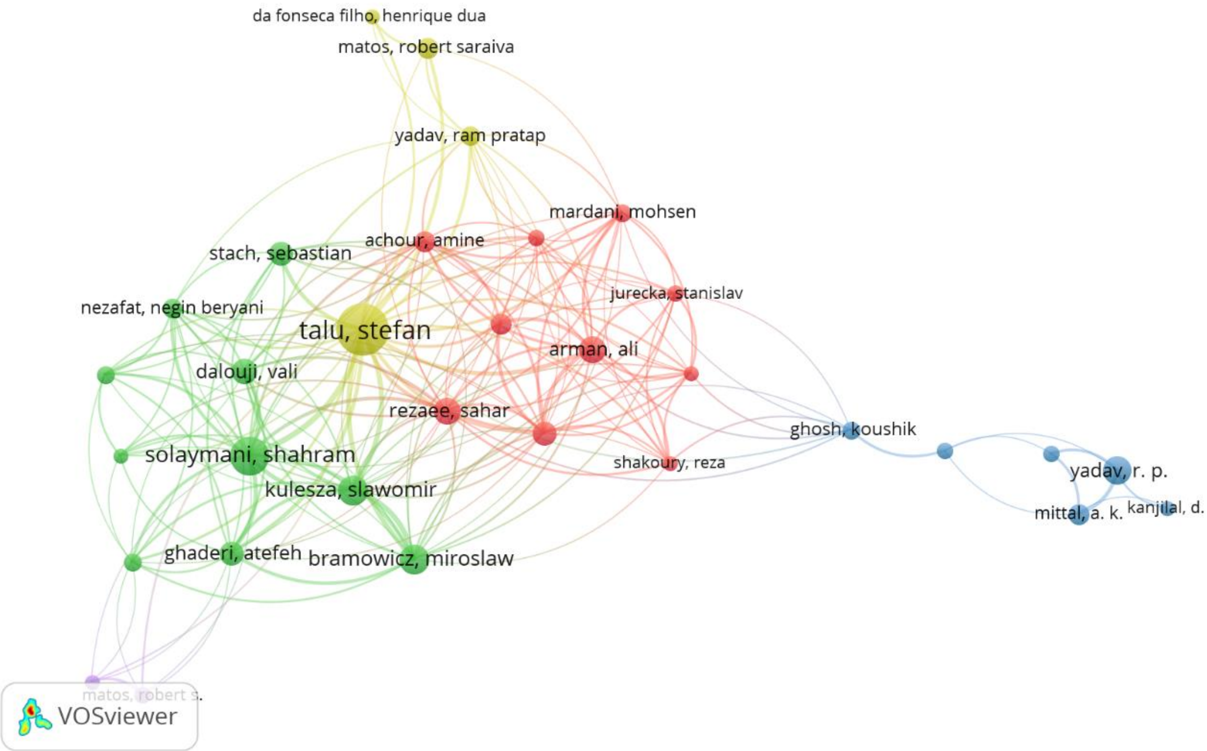

Figure 13. Expanded view of Figure 12 showing co-authorship of authors publishing in fractal theory in thin film applications.

3.7. Applications and Future Directions

From the preceding bibliometric analysis, there is no doubt that fractal techniques are extensively gaining interest in the study of thin films and depositions. The WoS database reveals a very large content of fractals and thin films. Besides the journal articles, there are several review papers, which clearly outline the power of fractal theory in thin films and applications. The most recent review article on this topic, titled "*Application of Fractal Geometry in Gas Sensor: A Review*" and published by Tian and co-authors in 2021 in *IEEE Sensors Journal*, underscores the importance of the search query in this bibliometric analysis [89]. The article reveals that gas sensors exhibiting fractal geometry have superior performance as compared to others. Since thin films are used as sensing structures in these applications, the creation of thin films exhibiting fractal-like morphologies is very important. As such, fractal techniques and theory can be applied to build superior performing gas sensing devices. Analogically, solar cells exhibiting fractal-like characteristics have been shown to perform better than the traditional types and, therefore, fractal theory can be used to create such solar devices [90]. Fractal-like thin film materials, such as silver oxide [91], tetra-cyanoquinodimethane (TCNQ) [92], gold, palladium [93], etc., have been fabricated for such applications.

Fractal techniques have been traditionally preferred over statistical methods in computing surface roughness of thin film structures. The fractal techniques describe both lateral and vertical roughness properties of a surface and, therefore, can study the growth of thin films during deposition. In addition, fractal methods are not influenced by the measuring parameters of the imaging equipment and, therefore, more reliable [94]. In this regard, fractal dimension is mostly used to quantify the extent of roughness of a structure [36,79,95–97]. Through the fractal theory, therefore, detailed roughness information, through various mathematical models and image manipulation, is provided for thin film materials and surfaces.

The lateral characterisation of thin films through fractal techniques has made it easier to understand the growth behaviour of thin film structures during deposition. Several studies relating the deposition characteristics to the fractal parameters during thin film growth have been published [30,38,98,99]. The general inference from these publications is that through the use of computer-generated structures (using fractal theory), it is possible to predict the morphology and behaviour of thin films from a specific deposition technique. A detailed demonstration of the application of fractal theory in thin film property prediction was published by Mwema and co-authors (2021) in a book titled, "Sputtered Thin Films: Theory and Fractal Descriptions" [36] and in an article titled, "demystifying fractal analysis of thin films" [51]. The prediction models presented in these references were solely based on image analyses and future work can focus on numerical tools using computation software, such as *MATLAB* programs, to build open-source models. In addition, fractal techniques and tools can be extended to simulate the creation of property-tuned morphologies for specific deposition thin film techniques and applications.

4. Conclusions

In this article, bibliometric analysis of fractal theory/techniques and thin films was presented. Based on the bibliographic information of original (data-based) journal articles in the Web of Science digital database, data regarding bibliographic coupling, co-citation, co-authorship and co-occurrence of authors, documents, institutions and regions was generated and analysed in VOSviewer software. The results in this article provide insights into the evolution of application of fractal theory in the thin film industry since 1982. It is clear that China and the USA are the most influential countries due to the obvious reason of huge investment in thin films and nanotechnology by these countries. There is heterogeneity in terms of the most influential authors in this subject; bibliographic coupling and co-citation analyses indicate non-uniform clusters in terms of subjects and co-authorship in this subject. However, as expected, regions, such as Africa and Asia (except China and India), lag behind in this subject, although there are few authors featuring among the top 100 in terms of research publications and co-authorship.

From the bibliometric study, the application of fractal theory in thin films can be summarized in four areas, namely, (1) a tool for creation of superior devices, (2) characterization of roughness and structure evolution, (3) prediction of structure evolution during thin film depositions and (4) an optimization tool for thin film (structure) creation.

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