INTERNATIONAL JOURNAL OF
AUTOMOTIVE SCIENCE AND TECHNOLOGY

2024, VOL. 8, NO:1, 65-77 www.ijastech.org e-ISSN: 2587-0963

A bibliometric overview of research on auxetic structures: Trends and patterns

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Abstract

Auxetic structures have very interesting features compared to traditional structures and can also be used in the automotive industry thanks to their lightness and strength have attracted the attention of researchers in recent decades. The current study summarizes the contributions made by researchers from all over the world between 2002 and 2022 in the field of auxetic structures. Using the Scopus database, a bibliometric analysis was used to examine the scientific studies in the area. The analysis covered different characteristics of publications, including publication type, main study fields, journals, citations, authorship patterns, affiliations, and keywords. The bibliometric indicators showed that there were 2599 publications published by 5161 authors in 85 countries from 2002 to 2022. The results also showed that the publications produced came primarily from China, the United States, and the United Kingdom, and the publications produced from these countries ac-counted for 42.99% of all publications. In particular, the most productive author, country, institution and journal are Grima JN, China, Ministry of Education China and Composite Structures, respectively. This study has great value since it demonstrates how to research topics change from year to year and can predict future development trends.

Keywords: Auxetic structures; Bibexcel; Bibliometric analysis; Scopus; VOSviewer

Research Article

History
Received 11.10.2023
Revised 09.11.2023
Accepted 17.01.2024

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To cite this paper: Cetin, E., Seyitoglu, S.S. A bibliometric overview of research on auxetic structures: Trends and patterns. International Journal of Automotive Science and Technology. 2024; 8 (1): 65-77. http://dx.doi.org/10.29228/ijastech..1374313

1. Introduction

Since the materials used in the automotive industry are durable and light, lattice structures attract the attention of researchers due to their properties such as strength and lightness. In this context, auxetic materials, which behave contrary to traditional materials, are a very hot topic in recent years.

A material's Poisson's ratio is defined as the relationship between transverse and longitudinal strains in structures under axial loads, and according to the classical theory of elasticity, the Poisson's ratio ranges from 0 to 0.5 for isotropic materials for homogeneous, isotropic and thermodynamically correct solids. Ordinary materials expand laterally when compressed and contract laterally when stretch, and so exhibit positive Poisson's ratio behavior. Poisson's ratio varies depending on the material; for instance, it is approximately 0.27 for steel, 0.33 for aluminum, 0.45 for lead 0.5 for rubbers, 0.1 to 0.4 for typical polymer foams and almost zero for cork. On the other hand, some materials exhibit inverse behavior in contrast to ordinary materials, and Poisson's ratio of that kinds of materials is negative. The transverse dimensions of such materials increase under axial tensile load and decrease under compression load. Typical deformation behavior of traditional and auxetic structures are given in Fig. 1.

The materials having negative Poisson's ratio were originally named ‘‘auxetics’’ by Evans in 1991 [1], and the auxetic term was derived from the Greek word "auxetos" which means "that tends to increase". Compared to materials having positive Poisson's ratio, auxetic materials have superior properties such as energy absorption [2–7], fracture toughness [8–10], shear resistance [11–13], in-plane indentation resistance [14–16], sound insulation [17–19], negative compliance [20–22], synclastic behavior [23,24]. In addition to its uncommon behavior, auxetic materials attract the attention of many researchers [25–34] due to their wide application in many fields.

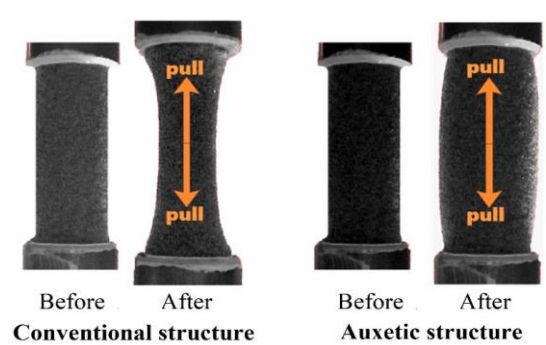

Fig. 1. Deformation behavior of conventional (non-auxetic) and auxetic structures under tensile loading [1].

As a result of detailed research, to the best of our knowledge, there is no study on the evolution, change and development of studies on auxetic structures. Motivated by this, in this study, a globally comprehensive bibliometric analysis on auxetic structures was carried out using the Scopus database for the years 2002–2022. The main objective of this study is to help researchers anticipate possible future research areas, identify the most cited authors and articles, and gain a better understanding of the evolution of research in the auxetic structure field.

2. Geometrical configuration of auxetic structures

Since the earliest instance of auxetic material documented in the literature by Love [35] in 1944, many auxetic materials have been proposed and produced with developing production technology. These materials can be mainly categorized into the following groups based on the variance in the geometrical configuration of auxetic materials and structures. The classification of the geometrical configuration of auxetic materials is presented in Fig. 2.

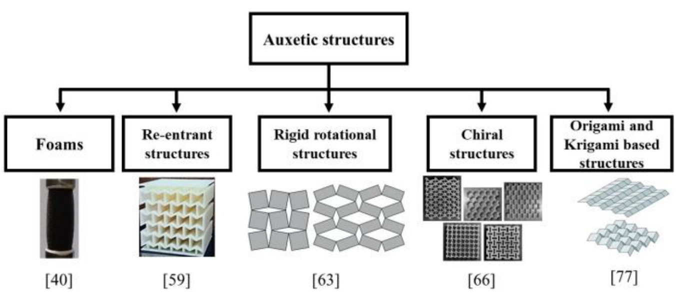

Fig. 2. Classification of the geometrical configuration of auxetic materials

2.1 Foams

The traditional method for producing auxetic open-cell foams involves three steps: volumetric compression of the pristine foam using a mold, annealing and the manufacturing chamber's release of the foam [36–38]. Volumetric compression causes the cell struts to buckle and the auxetic foams to have a re-entrant topology, while annealing stabilizes the geometry of the pores and produces the negative Poisson's ratio effect.

The first pioneering work on foam materials with negative Poisson's ratio was published by Lakes [36] in 1987. Lakes transformed an auxetic foam with a Poisson's ratio of -0.7 from an open-cell polymeric foam, and created the production technique that includes compression, heating, cooling and relaxation to make an auxetic foam sample having small dimensions. In 1997, Chan and Evans [37] developed a new fabrication technique to make both small and large auxetic foam samples. Additionally, the stability of the auxetic foams has been enhanced by employing the multi-stage method that divides the transformation process into different stages. Thanks to this method, different Poisson's ratio values and anisotropy degrees for auxetic foams could be obtained. The process was further enhanced by Scarpa et al. [38–40] to produce auxetic specimens with high resilience, high energy dissipation per unit volume and better stiffness under compressive cyclic fatigue loading. Bianchi et al. [41] carried out an experimental study examining the relationship between mechanical properties and production parameters of polyurethane auxetic foams. The results showed that the most important production factor for the auxetic foams was discovered to be compression, both radial and axial. Besides, Bianchi et al. [42] described a new manufacturing process for auxetic foams, which can be made in complex and arbitrary shapes and manufactured in large bulk quantities. As opposed to conventional negative Poisson's ratio foams, samples of sheets made using the new production approach exhibit more uniform Poisson's ratio behavior under tensile loading and up to an order of magnitude more energy is dissipated per unit volume during cyclic tensile-tensile loading. The literature contains review articles describing the state of the art for auxetic foam manufacture, characterization, and applications [25,33].

2.2 Re-entrant structures

Another typical auxetic structure is the re-entrant structure, which is composed of periodic hexagonal units with two negative angles joined together. The re-entrant edges are simultaneously bent and pulled under a uniaxial tensile load, and as a result of this deformation, the cell faces expand simultaneously, increasing the volume of the cell in both axial and transversal directions. The illustration of auxetic behavior on reentrant structures is given in Fig. 3.

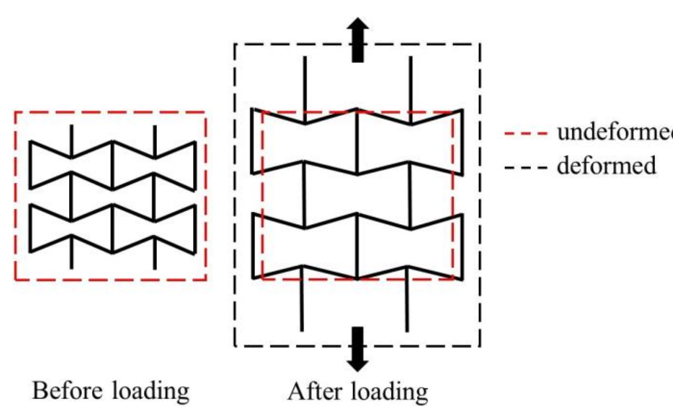

Fig. 3. The illustration of auxetic behavior on re-entrant structures.

By changing the polygonal cell and negative angles, a variety of re-entrant structures have been reported in the literature, including the 3-star shaped [43,44], 4-star shaped [43,45], 6-star shaped [43], and double-arrowhead shaped [46–51] auxetic structures. Gibson et al. [52] first proposed the re-entrant structure in the honeycomb in 1982, and developed a basic 2D model to show the behavior of conventional and auxetic structures. To estimate the elastic constants of the cells of the structures by flexure, stretching, and hinging, Master and Evans [53] provided a theoretical model for 2D re-entrant structures. Lakes and Elms [16] concluded that the re-entrant structures outperform typical foams of the same density in terms of yield strengths and energy absorption. In another study, the dynamic crush and indentation responses of 2D re-entrant structures were theoretically investigated by Hu et al. [54,55]

Other re-entrant structures can likewise provide auxetic effects. The Lozenge and Square grids, introduced in the missing-rib structure, are two further significant auxetic foam geometries [56–58]. In addition, Grima et al. [43] proposed a new type of auxiliary structure that they called "connected stars" where the stars have rotational symmetry of order three, four or six. They used the EMUDA method (a technique of analysis based on force-field molecular modeling simulations) for creating star-shaped systems, which have a potential for auxetic behavior. Najafi et al. [59] investigated experimentally the energy absorption performance of the arrowhead, chiral and re-entrant geometries under quasi-static and low velocity impact loads. The results showed that the arrowhead and chiral structures showed better performance than the re-entrant structure under quasi-static loading, on the other hand, under low-velocity impact loading, the performance of the re-entrant structure significantly increased and was comparable to the performance of the arrowhead and chiral structures. Guo et al. [46] presented a numerical and experimental study on the double arrow-head configuration-based 3D auxetic plate-lattice structures, and examined the mechanical characteristics of the proposed double arrow-head structures. In another similar work [49], the mechanical properties of the composite 3D double arrow-head auxetic structure, which is made from carbon fiber reinforced polymer using an assembly method, were studied using theoretical, numerical and experimental methods.

2.3 Rigid (or semi-rigid) rotational structures

Rigid or semi-rigid rotational structures, another type of auxetic structure, are connected by simple hinges at their corners. When these type of structures are stretched, it rotates around the hinges, causing an auxetic response, which causes expansion in both axial and transverse directions. The rotational structures are referred to by several names depending on the geometrical variations, and they can be classified as rotating triangles [44,60], rectangles [61], squares [62], rhombi [63] and parallelograms [63]. In addition to this classification, these structures can also be divided into different subclasses such as Type I and Type II [63]. The studies on rotational structures have shown that these structures can show positive or negative Poisson ratios depending on their geometric configuration [44,60]. Besides, these structures can also present both in-plane isotropic and anisotropic properties [63]. Furthermore, based on the rotating rigid unit mechanism, Gatt et al. [64] suggested a novel class of hierarchical auxetic structures. According to the works, auxeticity can be reduced or increased by altering pore size, and the mechanical properties of the rotating rigid structures can be enhanced thanks to the advantages of the hierarchical system.

2.4 Chiral structures

The chiral structure, which is first proposed by Kelvin [65], is defined as the structure formed by connected by tangential elastic ligaments (ribs) to a central cylinder (node) and not superimposed on its mirror image. In contrast, the anti-chiral structures show reflexive symmetry. There are five typical types: trichiral, tetrachiral, hexachiral, antitrichiral, and antitetrachiral structures (Fig. 4).

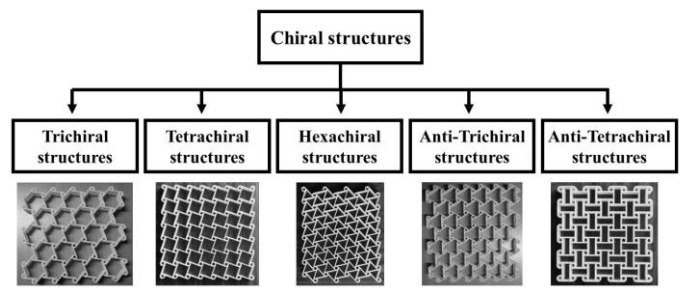

Fig. 4. Classification of chiral structures.

Under tensile or compressive load, chiral structures exhibit negative Poisson's ratios due to the simultaneous cylindrical and ligament rotation and ligament bending [66,67]. The auxetic effect and mechanical characteristics of the chiral structures are governed by the ligament number and the ligament length-to-cylinder radius ratio [66]. Alderson et al. [66] and Mousanezhad et al. [68] also showed that the Young's modulus increased as the number of ligament number increased. Ha et al. [69] revealed that unlike auxetic structures such as re-entrant structures, the Possion ratios of chiral structures are not depend on the angles of the structures. The findings of an investigation on auxetic chiral models by Gatt et al. [70] using analytical and finite element methods showed that the geometry and mechanical characteristics of the constituent materials had a significant influence on the mechanical characteristics of the flexing anti-tetra chiral system. Grima et al. [71] proposed a novel class of structure known as "meta-chiral". This type of structure consists of the fundamental characteristics of the chiral and anti-chiral structures. Different angles and aspect ratios between the ligaments and nodes affect Poisson's ratio of the meta-chiral structures. By creating hybrid metamaterials, Jiang and Li [72] were able to combine chiral and re-entrant structures. These structures, which had the re-entrant core cells in the center of a basic chiral cell, were then examined utilizing finite element simulations and mechanical tests on 3D printed models.

The development of manufacturing technology has recently led to an increase in research interest in 3D chiral metamaterials. Wu et al [73] presented a new type of 3D chiral meta-materials by utilizing the chiral structures' node rotation and ligament bending deformation characteristics. Similarly, Ebrahimi et al. [74] proposed a novel 3D metachiral structures having a variety of Poisson ratios.

2.5 Origami-based and Kirigami-based metamaterials

Origami and Kirigami are the traditional Japanese art forms of folding and cutting paper that offer powerful ways to create auxetic metamaterials [75,76]. Fold lines of Origami act as hinges, and the deformation characteristics of origami-based auxetic structures are determined by position and length of the fold lines. The Kirigami-based metamaterials are created by making several cuts in thin-sheet materials [77]. The Kirigami structure's auxetic principle is similar to the rotating rigid structures, in which the connecting hinges are rotated by the cutting units. Additionally, a class of zigzag auxetic metamaterials was created by combining the Kirigami and Origami techniques [78].

3. Bibliometric literature analysis

Bibliometric is a well-known research methodology in the field of information science, particularly for assessing the quality of research output. The bibliometric analytical technique, which has been widely used across a range of fields, uses mathematical and statistical methods to quantitatively examine academic literature [79]. A group of techniques known as bibliometric use the document system and bibliometric properties as the subject of the research topic. Time analysis, geographic analysis, and content analysis are bibliometric analysis techniques [80]. Temporal bibliometric analysis often concentrates on the evolution of study fields across different phases based on the quantity of publications, authors, and citations. The geographic analysis demonstrates the international distribution of research areas based on document outputs by countries and organizations. Content analysis, which differs from temporal and geographic analysis, seeks to pinpoint current hotspots based on the frequency of author keywords and subject distribution. The structure, traits, and patterns of the underlying science and technology can be studied using bibliometric methods [81].

As a result of the literature research, there are two well-established (i.e., Web of Science and Scopus), constantly expanding and generally accepted databases. In this study, studies between 2002-2022 were discussed and only the Scopus database was used. The terms "Auxetic Structures", "Auxetic-Structures" and "AuxeticStructures" were chosen as research keywords for research. The documents were examined for document type, language, authorship, article citation analysis, country, keyword distribution and reference analysis. By utilizing bibliographic data, the free software VOSviewer was utilized to produce bibliometric maps of many scientific disciplines [82]. The software was used for importing information from the database, calculating the association of terms, extracting the citation relationship between publications, and visualizing the data. With this method, it is possible to automatically and systematically analyze virtually any number of articles and the connections among them. We present a report on the bibliometric assessment we carried out in October 2023, in this study. The research procedure used in this study is shown in Fig. 5.

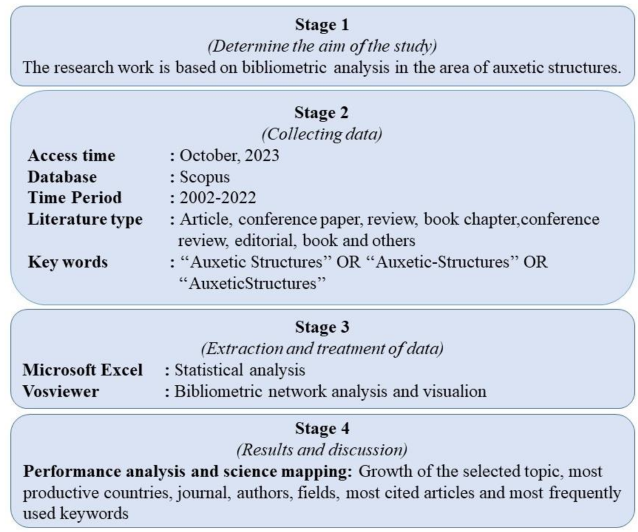

Fig. 5. Research procedure used in this work.

The number of documents may indicate the research topics change year by year and also these indicators may reflect trends the future development. Fig. 6 depicts the annual number of documents from 2002 to 2022. The horizontal axis represents the year and the vertical axis shows the number of documents. The word "Auxetic structures" was used in a total of 2599 scientific papers between the years 2002-2022. 31 of these studies (1.19%) were carried out between 2002 and 2010, 230 (8.84%) from 2011 to 2015, 1080 (41.55%) from 2016 to 2020, and 1258 (48.40%) from 2021 to 2022. In terms of documents published between 2002-2010, the number of documents is relatively low. In the following years, the number of documents showed a gradual upward trend and reached its peak in 2022. These results reveal that the topic "auxetic structures" is a hot topic with increasing popularity in recent years.

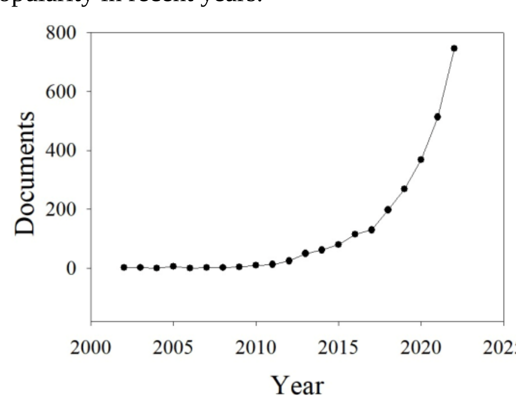

Fig. 6. The annual number of published numbers.

In comparison to journals in the same field, the citescore was the most direct indication for assessing the influence of academic journals. Moreover, these top journals' titles and subject categories confirmed the central position of material studies in mechanical research. However, considering the Citescore, it is seen that the top three journals are Composites Part B Engineering, Additive Manufacturing and Materials and Design, respectively.

Table 1 shows the top 10 journals in terms of publication count that provide information on "Auxetic Structures", along with citescore, SJR and SNIP. Table 1 indicates that all of these publications are in the discipline of mechanical engineering and mostly concentrate on mechanics and materials. Composite Structures, Physica Status Solidi B Basic Research, and Smart Materials & Structures are leading three journals with 138, 111 and 88 articles, respectively.

Table 1. Top 10 journals in the relevant field from 2002 to 2022.

Source	Docs.	%	Citescore 2022	SJR 2022	SNIP 2022
Composite Structures	138	5.30	10.9	1.45	1.97
Physica Status Solidi B Basic Research	111	4.27	3.3	0.40	0.59
Smart Materials and Stru ctures	88	3.38	7.5	0.91	1.20
International Journal of Mechanical Sciences	87	3.34	11.3	1.53	2.02
Materials	78	3.00	5.2	0.56	1.07
Materials and Design	74	2.84	13.5	1.74	2.20
Thin Walled Structures	65	2.50	9	1.43	1.97
Composites Part B Engineering	40	1.53	23.2	2.30	2.67
Additive Manufacturing	30	1.15	17	2.63	2.48
Advanced Engineering Materials	29	1.11	6.5	0.86	1.07

SJR (SCImago Journal Rank); SNIP (Source Normalised Impact per Paper)

Fig. 7 provides a thorough description of the various types of documents. As shown in Fig. 7, articles (77.60%) and conference papers (11.58%) made up the most types of documents among the 2599 records in the area. It was followed by 189 reviews and 60 book chapters. That is, the majority of those who were interested in this topic selected articles and conference proceedings. In addition, researchers mostly preferred English language to share the results of their studies.

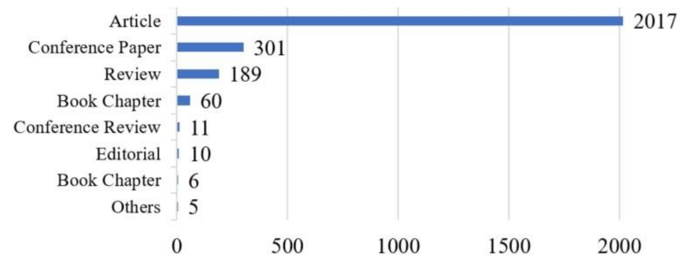

Fig. 7. The type distribution of the publications.

The number of publications from a country reflects that country's attention and overall strengths in relevant research areas. Fig. 8 depicts the geographic distribution of case studies based on the locations of auxetic structure studies. In addition, Table 2 shows the ranking of the top 10 most productive countries. In terms of the number of publications, the 10 most productive countries realized approximately 67.84% of the total publications. It should be mentioned here that a publication was taken into account for both countries in the statistical analysis if it had more than one author from each country. The majority of Auxetic Structures publications come from China, the United States, and the United Kingdom, with China accounting for 25.39% of all publications between 2002 and 2022. Additionally, the results show that China, USA and UK account for 42.98% of all publications on auxetic structures, which is higher than all countries combined. All of the countries on this list play a significant role in developing manufacturing technology, and as a result, their academic communities have contributed more to this field.

Countries can communicate with each other to improve themselves and find innovative solutions to problems through academic cooperation. In addition, developing countries can learn different experiences from developed countries through international cooperation. Therefore, it is quite important for different countries to cooperate academically. The interna-tional collaboration is represented visually in Fig. 9 to enable understanding of stronger or weaker linkages depending on the connections among different countries. In Fig. 9, each line on the node represents a relationship between two countries, and each node is a country. The connections between coun-tries determine the community structure, or clustering, where certain vertices (countries) are linked through collaborations more or less densely than others. Every country has a tenden-cy to collaborate more with other countries on auxetic struc-tures research, according to the collaboration map. The Unit-ed States and China were seen to maintain active partner-ships with the other nations, followed by the United Kingdom and Australia. As mentioned above, these countries have advanced production techniques such as additive manufac-turing technology, and thus various research groups in these countries are in close contact with each other. On the other hand, the data shows that more than 140 different countries contributed to the published publications. 85 of the countries publishing on this subject have cooperated with each other. However, it is clear that only a limited number of countries account for the majority of publications. In this regard, inter-national research funding organizations should collaborate to offer additional options for international collaboration. A classification of the topics of articles that coexist with the topic of auxetic structures is shown in Fig. 10. Not surprisingly, engineering stood out in a majority group and it was closely followed by Materials Science and Physics and Astronomy.

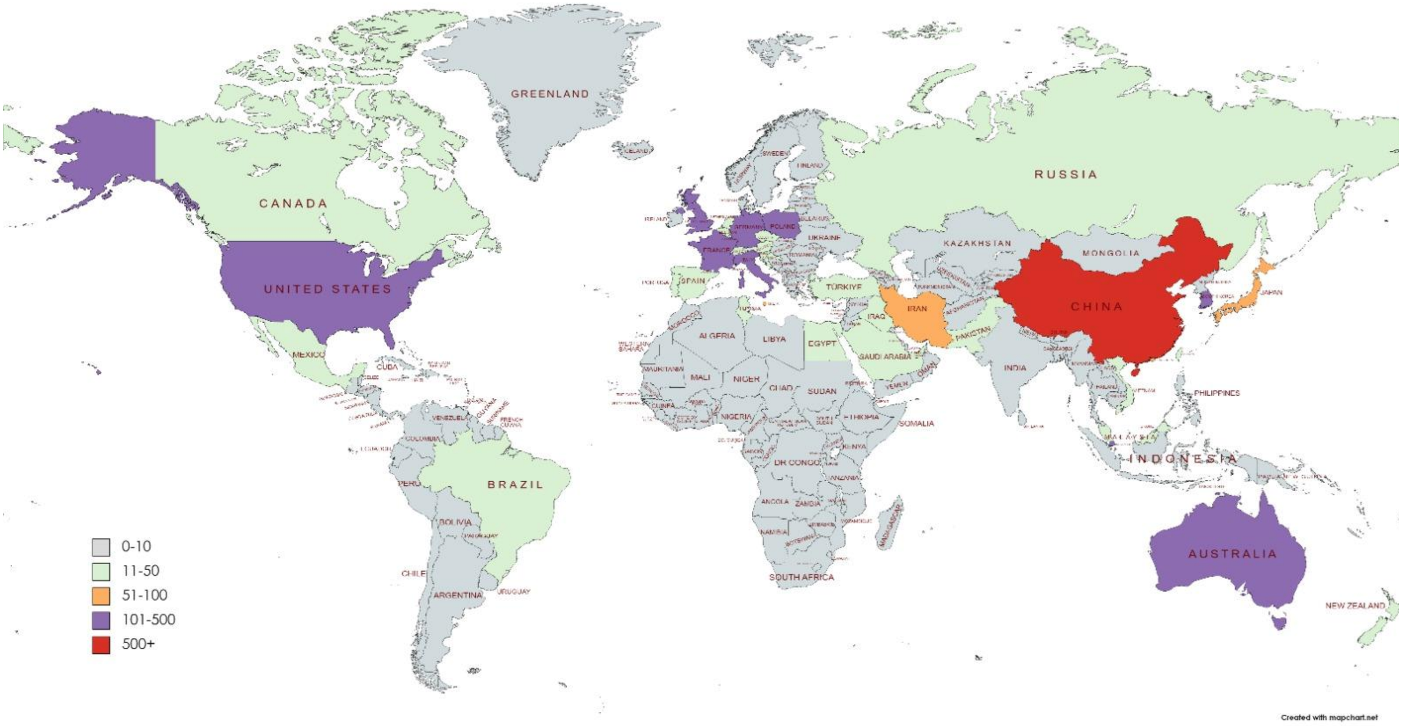

Fig. 8. Geographical distribution of publications based on locations of auxetic structures studies.

Table 2. Top 10 productive countries between 2002 and 2022.

Rank	Country/Territory	Documents	%
1	China	915	25.39
2	United States	367	10.18
3	United Kingdom	267	7.41
4	Australia	171	4.74
5	Italy	131	3.63
6	Germany	131	3.63
7	India	126	3.49
8	Singapore	119	3.30
9	Poland	114	3.16
10	South Korea	105	2.91

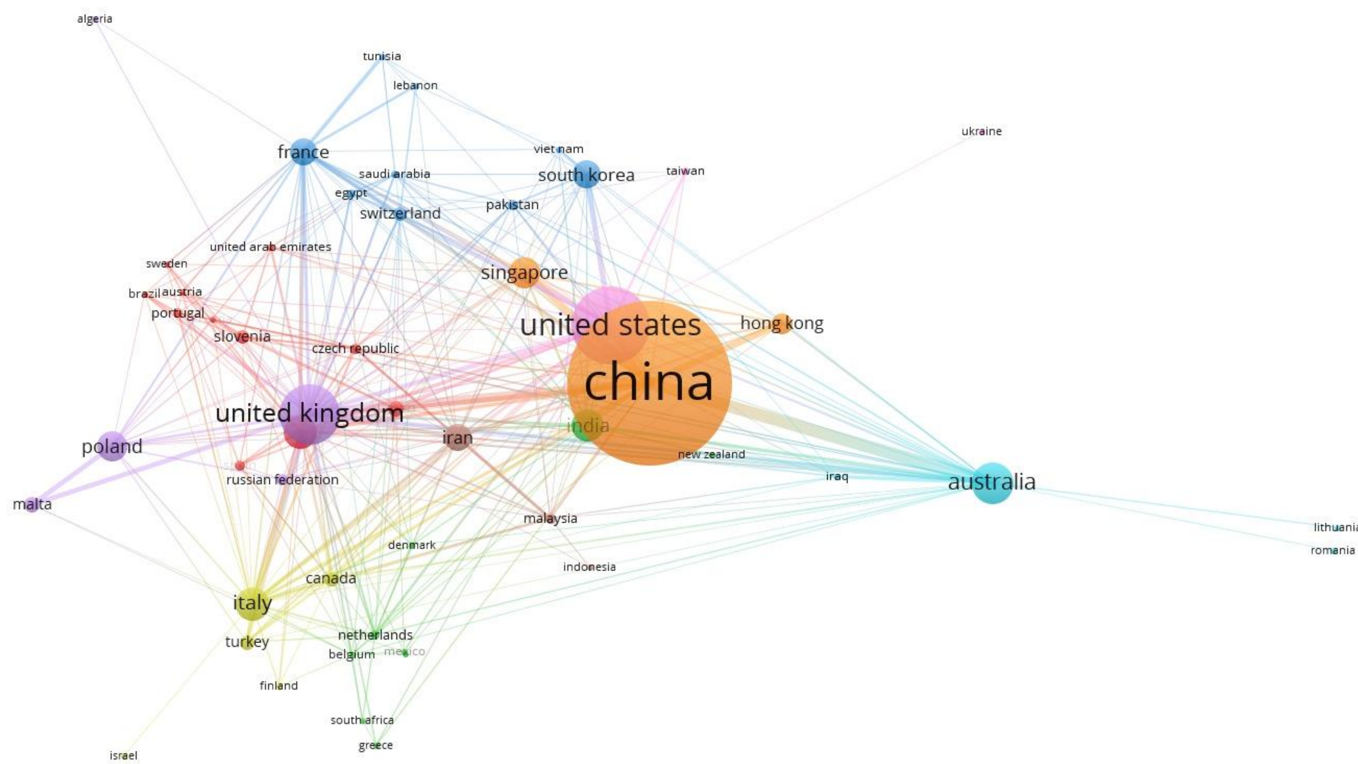

Fig. 9. International collaboration between countries for auxetic structures.

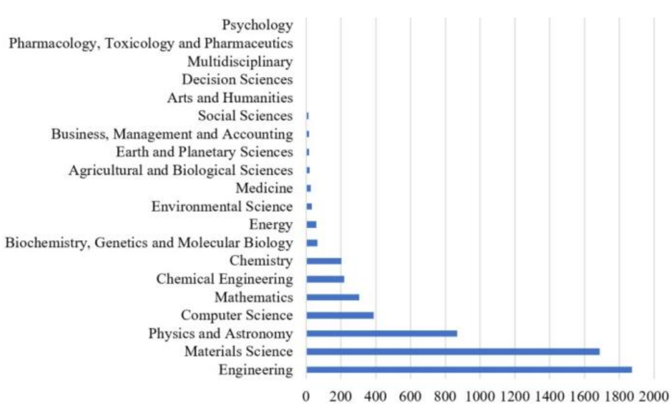

Fig. 10. Classifications of publications according to subject.

Table 3. The top 10 most productive institution between 2002 and 2022

Rank	Institutions	Country	Docs.
1	Ministry of Education China	China	109
2	Harbin Institute of Technology	China	95
3	Beijing Institute of Technology	China	59
4	Hong Kong Polytechnic University	Hong Kong	54
5	University of Bristol	United Kingdom	53
6	University of Malta	Malta	51
7	RMIT University	Australia	50
8	Huazhong University of Science and Technology	China	47
9	CNRS Centre National de la Recherche Scientifique	France	46
10	Politechnika Poznanska	Poland	43

The top 10 most productive institutes in the field of auxetic structures research from 2002 to 2022 are shown in Table 3. It is seen from the table that there are 4 Chinese institutions among the 10 most productive institutions. It is followed by Hong Kong, United Kingdom, Malta, Australia, France and Poland. Ministry of Education China is the most productive institution with the largest amount of total publications, followed by Harbin Institute of Technology, and Beijing Institute of Technology. Ministry Education China is produced 76.14% of its publications in the last three years.

Table 4 summarizes the main characteristics of the most often cited studies by examining at the annual citations of publications. The publication made by Thompson et al. [83] is the most cited of all publications, followed by the article by Chen et al. [84] and Zhang et al. [85] The article with the most citations per year (251.2) is titled “Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints”. This paper is published in CIRP Annals - Manufacturing Technology in 2016 and received 1260 total citations. The publication with the second highest citations is titled “3D printing of ceramics: A review”. This publication is published in Journal of the European Ceramic Society in 2019 and received 1117 total citations. The paper with the third highest citations is titled “A Comprehensive Survey on Particle Swarm Optimization Algorithm and Its Applications”. This paper is published in Mathematical Problems in Engineering in 2015 and received 818 total citations. The results of these articles reflect that the topic of auxetic structures is current and important.

Table 4. Top 10 most cited publications

Rank	Documents	Source	First Author	Year	Annual Citation	Ref.
1	Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints	CIRP Annals - Manufacturing Technology	Thompson, Mary Kathryn	2016	210	[83]
2	3D printing of ceramics: A review	Journal of the European Ceramic Society	Chen, Zhangwei	2019	372.3	[84]
3	A Comprehensive Survey on Particle Swarm Optimization Algorithm and Its Applications	Mathematical Problems in Engineering	Zhang, Yudong	2015	116.8	[85]
4	Auxetic metamaterials and structures: A review	Smart Materials and Structures	Xin, R.	2018	154.2	[86]
5	Additive manufacturing of metallic components by selective electron beam melting - A review	International Materials Reviews	Körner, C.	2016	102.8	[87]
6	Influence of defects on mechanical properties of Ti-6Al-4V components produced by selective laser melting and electron beam melting	Materials and Design	Haijun, G.	2015	87.2	[88]
7	3D soft metamaterials with negative poisson's ratio	Advanced Materials	Sahab, B.	2013	64.8	[89]
8	Negative poisson's ratio in single-layer black phosphorus	Nature Communications	Jin-Wu, J.	2014	72.62	[90]
9	Tailored 3D mechanical metamaterials made by dip-in direct-laser-writing optical lithography	Advanced Materials	Tiemo, B.	2012	56.3	[91]
10	Mechanical metamaterials associated with stiffness, rigidity and compressibility: A brief review	Progress in Materials Science	Xianglong, Y.	2018	138.5	[92]

Fig. 11 illustrates the cooperation network of the authors. The size of the circles, which represent each author individually, is proportionate to the number of collaborations. The number and thickness of the lines between the authors reflect the level of collaboration in the field. The field of auxetic structures has been studied by 5161 authors in total. Among these authors, Grima J.N., who originates from Malta, is the most productive author with 50 publications, followed by Scarpa F. (48 publications) from United Kingdom and Hu H. (42 publication) from Hong Kong. Additionally, Fig. 12 shows the network of the most frequently used keywords. The use of keywords in research papers is particularly interesting for tracking and searching scientific and engineering field developments. Author keywords in the area of auxetic structures are used in keyword analysis. The results show that negative Poisson's ratio is the most used category (306 times), followed by auxetic (279 times) and additive manufacturing (236 times).

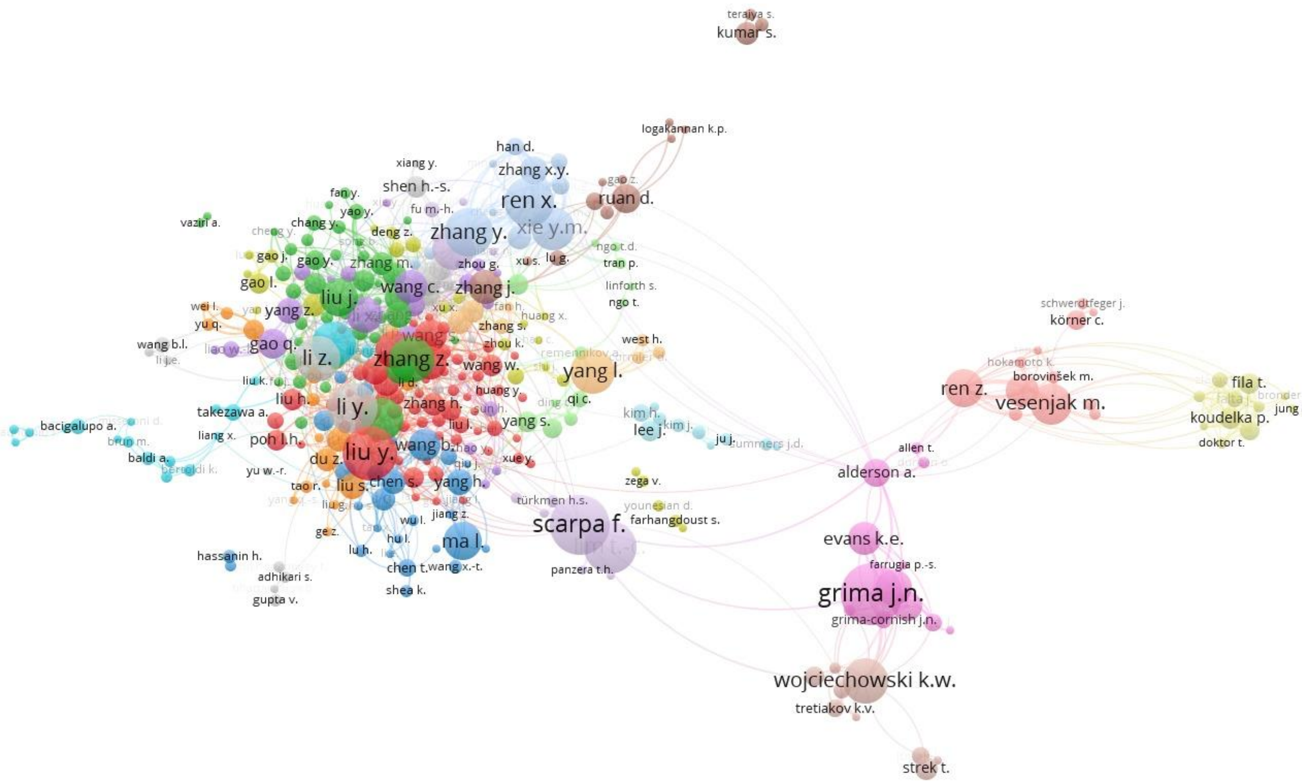

Fig. 11. The cooperation network of the authors

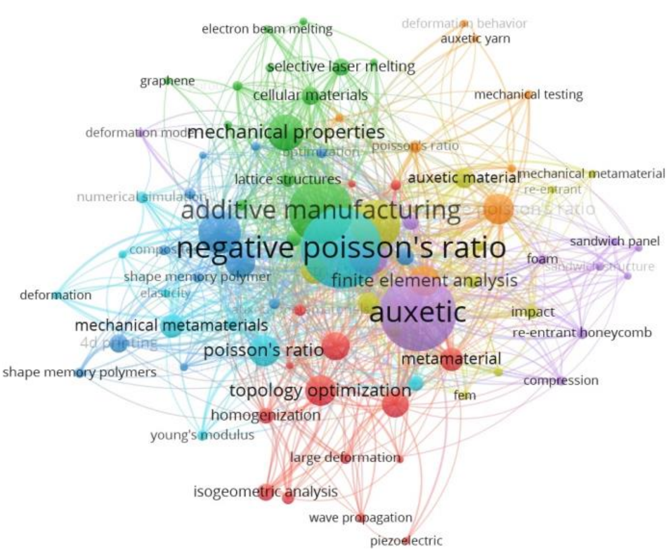

Fig. 12. The network of the most frequently used keywords in auxetic structures related research

3.1 Bibliometric approach in the Automotive field

The terms "Auxetic Structures", "Auxetic-Structures","AuxeticStructures" and “automotive” were chosen as research keywords for research. The word "Auxetic structures" and “Automotive” were used in a total of 226 scientific documents between the years 2002-2022. 10 of these studies (4.42%) were carried out between 2002 and 2015, 81 (35.84%) from 2016 to 2020 and 135 (59.73%) from 2021 to 2022. In terms of documents published between 2002-2015, the number of documents is relatively low. In the following years, the number of documents showed a gradual upward trend and reached its peak in 2022. Fig. 13 depicts the annual number of documents from 2002 to 2022. The horizontal axis represents the year and the vertical axis shows the number of documents.

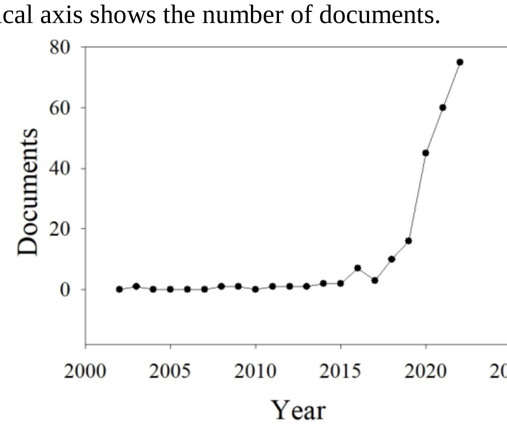

Fig. 13. Trends in “Auxetic Structures” and “Automotive” publications (2002-2022)

Composite Structures, Thin Walled Structures, and International Journal of Mechanical Sciences are leading three journals with 15, 14 and 12 articles, respectively. Composite Structures that has an citescore of 10.9 and an SJR of 1.455 is the most preferred journal and accounts for 6.63 % of the total "auxetic structures and automotive publications from 2002 to 2022. Fig. 14 depicts a thorough description of the various types of documents. There are 5 document types in the database. Articles are the dominant document comprising 154 of the total. The remaining publications are conference proceeding papers (29), reviews (33), book chapter (9) and book (1). In addition, the dominant language for publications in related area is English (214) which is followed by Chinese (11 %). Researchers mostly preferred English language to share the results of their studies. China which has 99 publications is the most productive country and accounts for 43.80 % of the total "auxetic structures" and "automotive" publications from 2002 to 2022. The second most productive country is United States (31 publications) which is followed by United Kingdom (29 publications), India (21 publications) and Australia (18 publications) respectively. Fig. 15 shows the cooperative relationships among the productive countries for related areas by using social network analysis. The China and United Kingdom were seen to maintain active partnerships with the other nations, followed by the United States. In addition, Fig. 16 shows the network of the most frequently used keywords. The results show that additive manufacturing is the most used category (31 times), followed by energy absorption (29 times) and negative Poisson's ratio (29 times).

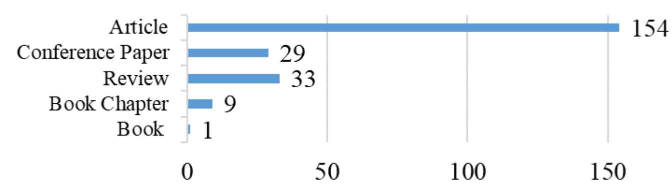

Fig. 14. Number of published document types between 2002 and 2022

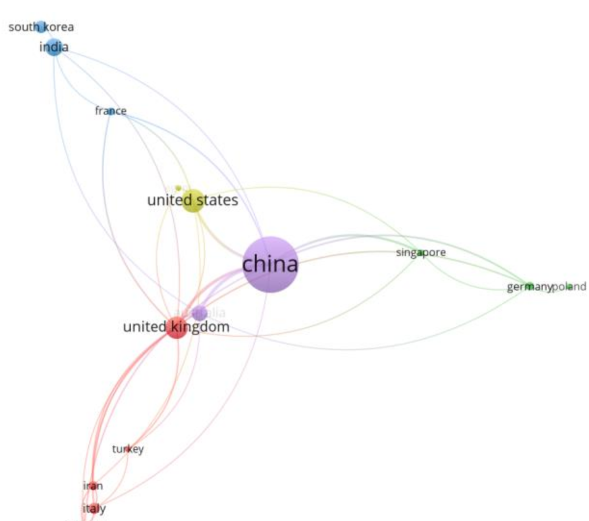

Fig. 15. The cooperation network of the productive countries for related area

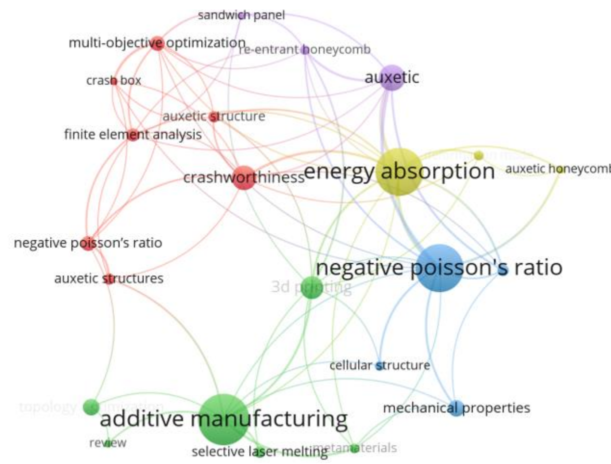

Fig. 16. The network of the most frequently used keywords in related area

4. Conclusion

The present study is a bibliometric analysis study to compile the contributions made by researchers from around the world in the field of auxetic structures between 2002 and 2022. In this study, using the Scopus database, different characteristics of publications are discussed, including publication type, main fields of study, journals, citations, authorship patterns, links, and keywords. The main findings from the bibliometric analysis can be summarized as follows:

- Between 2002 and 2022, 5161 authors in 85 countries produced 2599 papers on auxetic structures in journals and conference proceedings.
- The majority of publications were produced by China, the USA, the UK and Australia. The top 10 productive institutes and countries account for 20.64% and 67.52% of the total publications of auxetic structures, respectively.
- The most productive journal is Composite Structures with 138 publications.
- The most productive author is Grima JN, who has 50 publications.
- The most cited publication published in CIRP Annals - Manufacturing Technology and it accounts for 2.3 % of the total citations.
- 5457 keywords were used in 2599 publications, according to a study of keyword usage frequency, and the keyword "negative Poisson's ratio" made up 5.6 % of all keywords.
- Most of the studies on auxetic structures in the field of automotive engineering were carried out between 2021-2022 with 59.73%.

In the light of above information, in the near future, auxetic structures—known for their special ability to expand when stretched— are expected to gain significant importance in various fields. These structures have the potential to completely transform the development of advanced textiles in the field of materials science, producing incredibly flexible and durable textiles that can be used for medical textiles, sportswear, and protective gear. Moreover, auxetic structures have the potential to improve the engineering of robust and flexible parts for a variety of sectors, such as construction, automotive, and aerospace. Furthermore, auxetic materials may find use in the biomedical engineering field in the creation of novel medical devices with enhanced mechanical and biocompatibility, including scaffolds and implants. Auxetic structures are showing increasing interest, which highlights their potential to influence the development of new materials.

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Erhan Cetin: Conceptualization, Writing-original draft, Writing - review & editing
Sertac Samed Seyitoglu: Conceptualization, Data curation, Writing-original draft, Methodology, Software, Writing - review & editing

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