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A Systematic Literature Review of Characterization of Porous Materials and Their Materials Properties With the Support of Mapping Bibliometrics Using VOSviewer Software and Pico Framework

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Abstract
Because their performance is highly dependent on their material qualities, porous materials are widely used in engineering, environmental, biomedical, and energy applications. Despite a growing body of research, no prior review has methodically combined bibliometric analysis with a thorough assessment of characterization methods based on the material attributes under investigation. Thus, the purpose of this study is to identify research trends, analyze how characterization techniques have evolved, and assess their contributions to the material properties of porous materials. A mixed strategy that integrated a modified PICO-based systematic review with bibliometric analysis using VOSviewer was used. 41 studies published between 2014 and 2024 were chosen for qualitative analysis after a thorough screening process. Eight research clusters were found using bibliometric mapping, with the most popular subjects being characterisation, porosity, pore size, and scanning electron microscopy (SEM). According to the systematic review, porosity (25), mechanical (20), thermal (8), and optical (5) qualities were explored more frequently than structural parameters (38 research). Because they offer thorough information on morphology, microstructure, and phase composition—all of which have a direct impact on material performance—SEM, pore size analysis, and phase characterization continue to be the principal methods. In order to promote future developments in porous material characterisation, this review summarizes existing characterization methodologies, points out research gaps, and highlights the benefits of combining bibliometric mapping with systematic review techniques.

INTRODUCTION

Solid materials with interconnected or isolated pores (Boucher, 1976; Sefara, 2007) that greatly affect their chemical and physical properties are known as porous materials (Rice, 1997). The International Union of Pure and

Applied Chemistry (IUPAC) divides porous materials into three categories based on pore diameter: microporous (less than 2 nm), mesoporous (between 2 and 50 nm), and macroporous (more than 50 nm) (Bardestani et al., 2019; Barton et al., 1999; Davis, 2002; Leng et al., 2021; Low et al., 2018). Porous materials have garnered significant interest in engineering (Pinheiro et al., 2013; Tang et al., 2004; Topgaard, 2015), environmental, biological (Alhassan et al., 2024; Bennett et al., 2021; Bustillo et al., 2014; Qi et al., 2019; Reinhardt et al., 2006; Thananukul et al., 2021; Topgaard, 2015), and energy applications (Fateh et al., 2021; Parsons et al., 2010; Sultana et al., 2018) due to their adjustable pore topologies (Pabst et al., 2018), large surface area (Maciejewska et al., 2018), and multipurpose qualities (Shamaei et al., 2013).

Membranes, catalysts, adsorbents, filters, sensors, thermal insulation, biomedical scaffolds, and electrochemical electrodes are just a few of the many applications for porous materials (Salem, 2023). These materials' pore design, microstructure, chemical makeup, and other material characteristics all have a significant impact on how well they work. Therefore, comprehending the connection between pore structure and material performance requires precise characterization (Lee et al., 2012; M et al., 2019; Modena et al., 2019).

To assess porous materials, a number of characterization methods have been developed. Pore size distribution (K. S. . Sing, 1991), specific surface area (K. Sing, 2001), porosity (Landers et al., 2013), and density are frequently measured using helium pycnometry (K. S. W. Sing, 2004), gas adsorption (Espinal, 2012), and mercury intrusion porosimetry (Schlumberger & Thommes, 2021; Zaleski et al., 2009). Information on morphology (Messineo et al., 2016), phase composition, microstructure, thermal stability (Dutil et al., 2014) , and mechanical behavior (Aksenov & Mikolaenko, 2020; Belin & Epron, 2005; Dargar et al., 2017; Jin et al., 2020; Phillips et al., 2022; Rao et al., 2019) can be obtained through complementary methods such as scanning electron microscopy (SEM) (Belli et al., 2017; Lidia et al., 2018; Trikkaliotis et al., 2021), X-ray diffraction (XRD) (Belli et al., 2017; Lidia et al., 2018; Trikkaliotis et al., 2021), spectroscopy, micro-computed tomography (micro-CT) (Kumar & Venkatesh, 2019), ultrasound (Belli et al., 2017; Gräsel et al., 2017; Mcclements, 2007), and thermogravimetric analysis (TGA) (Belli et al., 2017; Modena et al., 2019; Trikkaliotis et al., 2021). The objective material attribute and pore structure determine which characterisation method (Sanjay et al., 2019) is best because each methodology reveals various aspects of porous materials (Vajtai, 2020).

Porous materials have been covered in a number of review publications from the viewpoints of individual characterisation techniques (Kangas et al., 2014), pore structure studies (Nugraha & Kulsum, 2017; Rahma, 2017), synthesis methods (Bekas et al., 2016; Gandomi et al., 2018), and applications (Liu et al., 2021). Nevertheless, the use of characterisation techniques to ascertain various material properties of porous materials has not been thoroughly examined in many publications (Modena et al., 2019). Reviews that are currently available typically focus on the characterization techniques themselves without thoroughly connecting them to the particular material qualities under investigation, such as structural, mechanical, thermal, optical, and porosity-related properties. As a result, scholars continue to lack a comprehensive understanding of contemporary characterization techniques and the emerging research trends in this area.

The current study fills this gap by combining a systematic review based on the modified PICO framework with bibliometric mapping using VOSviewer (van Eck & Waltman, 2010). The PICO framework offers a transparent and repeatable method for finding, screening, and assessing pertinent papers (Shah et al., 2020), while VOSviewer allows the visualization of study progress, keyword correlations, and developing research topics. Combining these two methods enables both qualitative evaluation of characterization methods and quantitative mapping of research trends, offering a more complete view than each strategy alone.

In order to assess current research trends using bibliometric analysis, identify current knowledge gaps and future research possibilities, and rigorously identify the characterization techniques utilized for porous materials, this study will examine the material qualities under investigation. This study specifically responds to the following queries: (1) In order to ascertain the material properties of porous materials, which characterization techniques are most commonly used? (2) Which characteristics of materials have been thoroughly studied and which are still unexplored?

The results of this study offer researchers a thorough reference for choosing appropriate characterization methods based on the characteristics of the target material, discovering unexplored research avenues, and assisting in the future development of multifunctional porous materials. Additionally, this work shows how to enhance evidence synthesis in materials science by combining bibliometric analysis with systematic review approach.

METHOD

This study examines earlier studies on the properties of porous materials included in the SCOPUS database's Science section (https://www.scopus.com/) (Oladinrin et al., 2023). Analysis of porous material characterization consists of 2 parts. The first part uses VosViewer and the second part uses the PICO framework. Vosviewer is used to identify and analyze the characteristics of porous materials, while the PICO framework is used to select empirical studies that can answer specific research questions for clinical practice decision making using modified problem, intervention, comparison and outcome criteria (Batubara et al., 2022). The visualization displayed from the Vosviewer analysis is used as a basis for the PICO analysis.

Part 1 - **VOSviewer** ***analysis procedures***

VOSviewer analysis is a data analysis that can be used to visualize and analyze networks and clusters of complex data (Fig 1). Using VOSviewer makes it easy to explore the relationships between various elements in the SCOPUS database, such as research keywords, international dissemination and cross-country collaboration. A keyword map to explore the relationships between concepts or keywords in the literature has been created. Therefore, research related to the characterization of porous materials studied as a whole in this study was identified. Apart from that, it is also essential to see the trajectory and relationship between researchers and their participating countries. So, a map of the countries participating in the relevant study was produced through a network of co-authors.

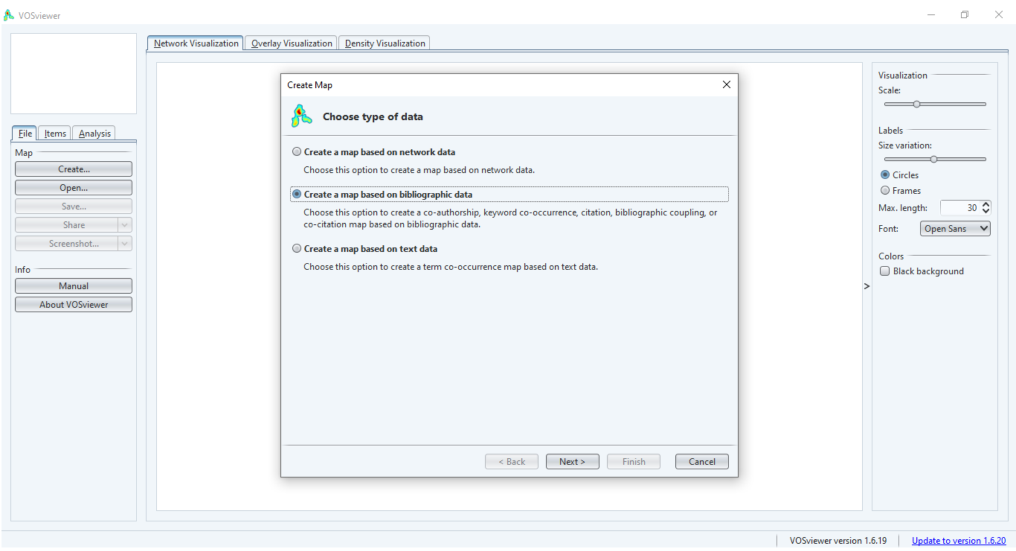


Figure 1. Managing VOSviewer to produce maps

Part 2 - Comprehensive evaluation of a few articles

On May 9, 2024, the SCOPUS database was accessed, with the institution's permission to search for articles that met the criteria for this study. Search results were refined to articles published in English in the field of science. The exported data was then filtered based on the research title, followed by abstraction based on research questions and criteria during the filtering process.

This research section comprehensively concentrates on a total of 41 research articles for in-depth review. The main aim of this systematic study is to comprehensively determine the characterization of porous materials. The aim is to collect comprehensive data to determine what methods are used to characterize porous materials and what material properties are characterized in porous materials.

- Their primary focus is on the methods used to characterize porous materials.
- They report material properties determined from the characterization of porous materials.
- Has been published in an English language journal or reported in the 2014-2024 period.

The use of this review phase will facilitate the analysis process, which may include identifying unexplored research areas and integrating ideas from various research topics. Additionally, these phases are critical in reducing research bias; they guarantee, for example, that the review process is independent of the results reported in the research abstract. Given that the review process requires a thorough or explicit assessment of methodology and results, researchers can utilize this review structure to summarize various evaluation constructs. This has proven to be very useful in discussing research, concluding, and making recommendations.

RESULT AND DISCUSSION

SCOPUS Database

The SCOPUS database is used to search for research on the characterization of porous materials. Related research studies were found from an extensive collection of porous materials and characterization research articles available in the SCOPUS database. Figure 2 shows 41 English-language research articles at the final publication stage resulting from SCOPUS database searches between 2014 and 2024.

Date: 09 May 2024
Results: 41
(from SCOPUSDatabases)
You searched for:
TOPIC: "characterization" AND "porosity" AND "material"
Timespan=2014 to 2024
Search language=English

Figure 2. SCOPUS search result related to the matter of porous material characterization

VOSviewer analysis

Map of publication development based on keywords

VOSviewer analysis using keywords can see how specific keywords often appear together and how research titles relate to one another in a complex network. Based on keywords, developments in the Scopus-indexed material porosity characterization topic area from 2014-2024 formed into 8 clusters with a total of 129 items. Ten objects make up Cluster 1 in red, twenty in Cluster 2 in green, and eighteen in Cluster 3 in dark blue. There are sixteen items in Cluster 4 (yellow), sixteen in Cluster 5 (purple), fourteen in Cluster 6 (light blue), thirteen in Cluster 7 (orange), and nine in Cluster 8 (brown).

The publication development map based on keywords was analyzed using network visualization (figure 3), overlay visualization (figure 5) and density visualization (figure 6). Network visualization shows the relationships or networks of publication data. Suppose the cursor is highlighted on one of the words (figure 4), for example, on the word characterization. In that case, a relationship or association with other publication words in one network will appear, such as mechanical properties, mechanical characterization, ceramics, alumina, b.porosity, pore size, porosity and so on if the words compressive strength are highlighted, b.porosity, c. mechanical properties, alumina, ceramics, mechanical properties, mechanical characterization, hardness and others, where there are 128 links and a total link strength of 416. If the cursor is placed on the word porous material, there are 47 links and a total link strength of 70 with connected words. If the cursor is placed on the word mechanical properties, there are 75 links and a total link strength of 133 with connected words. If the cursor is placed on the word porosity, there are 84 links and a total link strength of 150, with the words connected. So, from the four keywords taken, the word characterization has the most relationships or associations with other publication words in one network compared to the other three words. This indicates that the most significant nodes show the most connections with other published words. Likewise, the minor node, such as the word porous material, has the slightest connection with other published words.

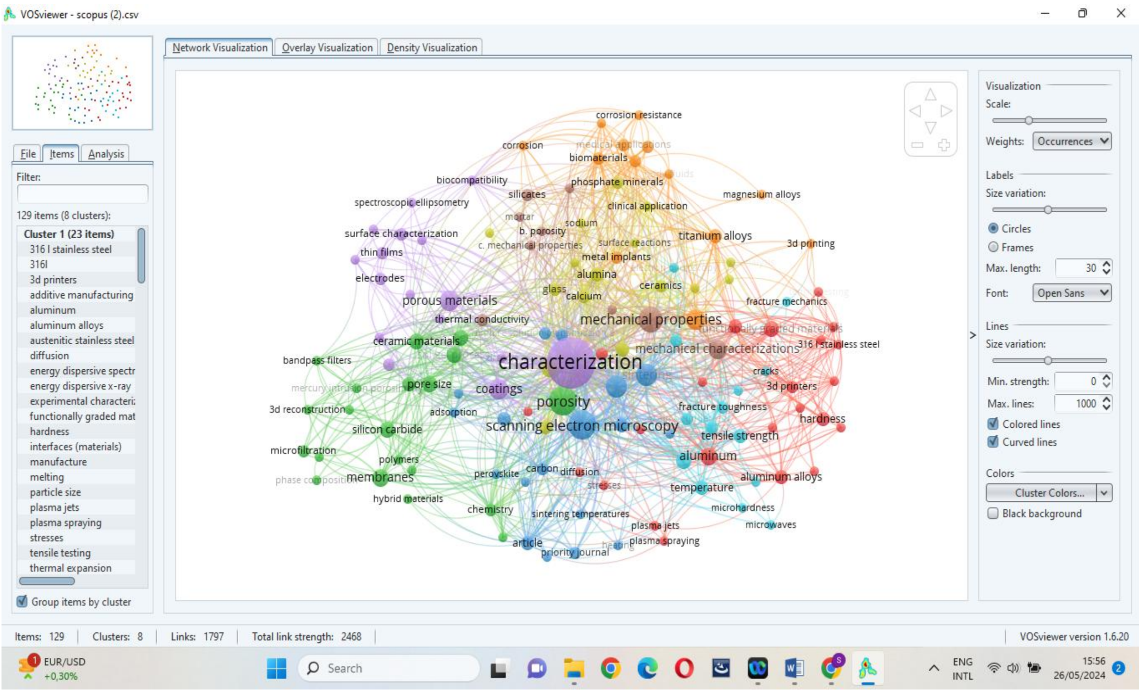
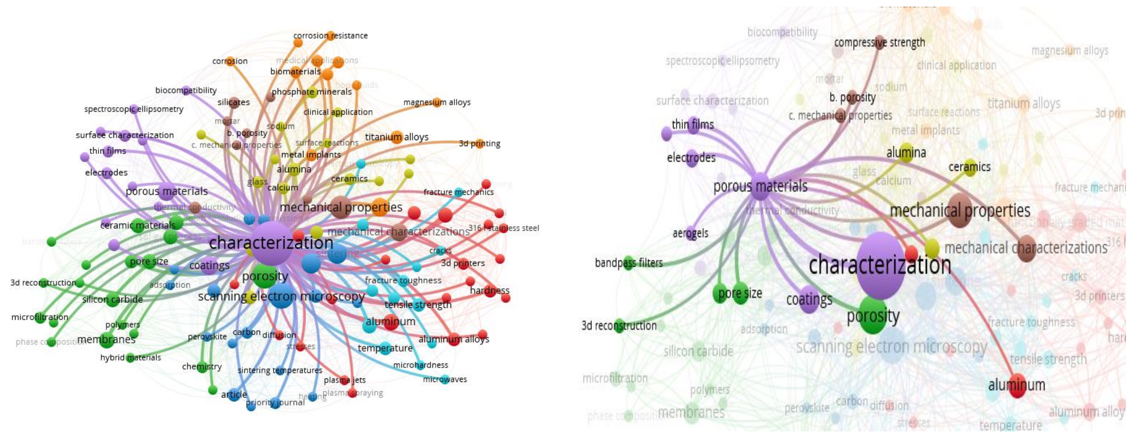


Figure 3. The network visualization map constructed with the keywords



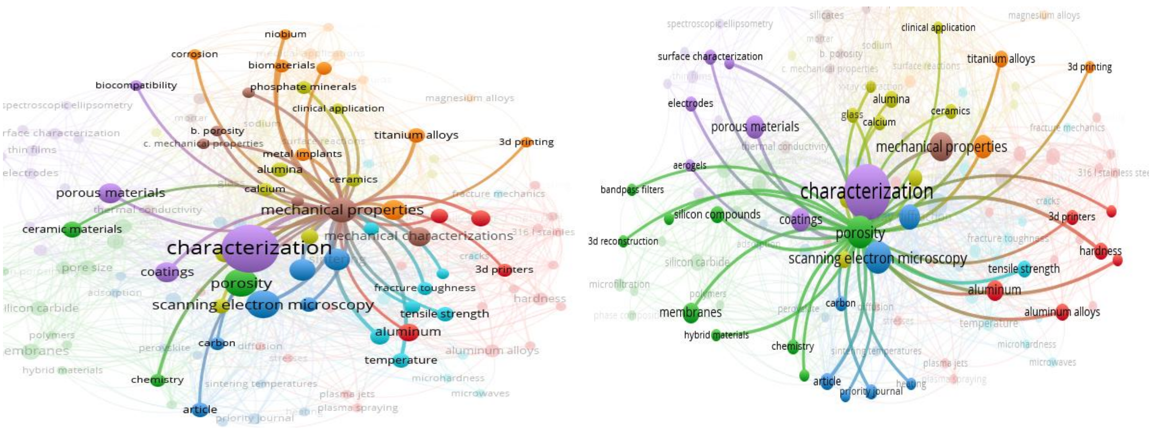


Figure 4. The analysis of the relationships among the keywords using the network visualization map

The overlay visualization shows the impact score of the publication. Yellow represents items with a high impact score from publications, while blue represents items with a low impact score from publications. There are five keywords in yellow, namely we43, presence, part, XRD and phase composition. Density visualization shows the density of the most publications or studies on a particular topic. This study is represented by the colors blue (low), green (medium) and yellow (high). The words with the most frequency are mechanical property, alloy, powder, sample, membrane, structure and pore.

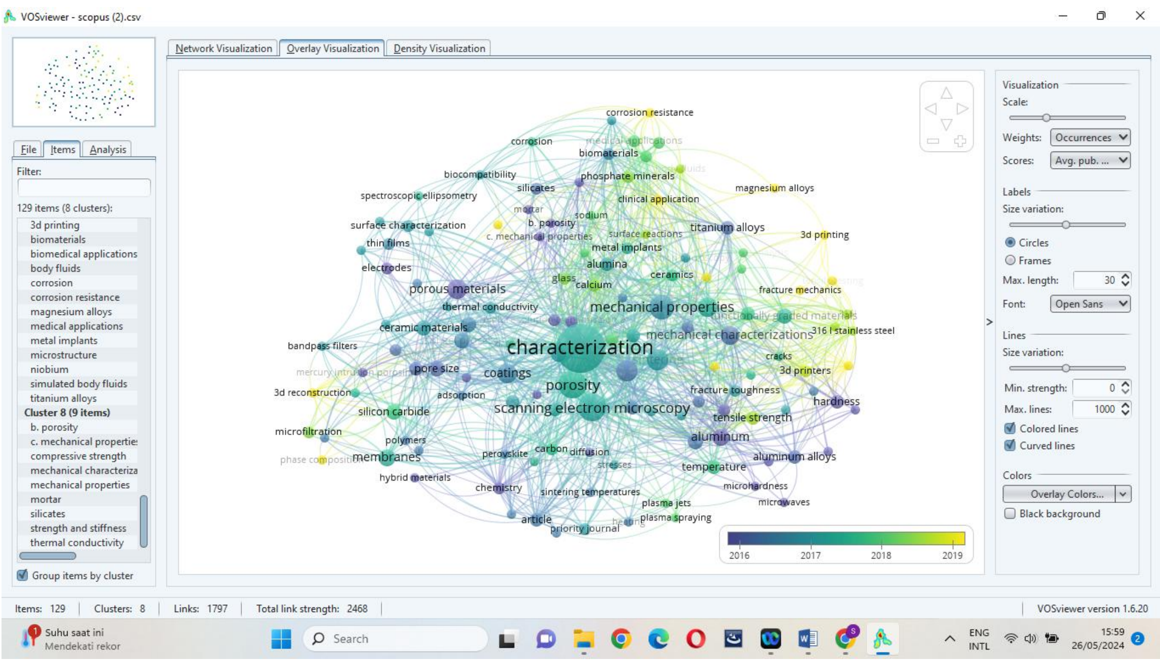


Figure 5. The overlay visualization map created through the keywords

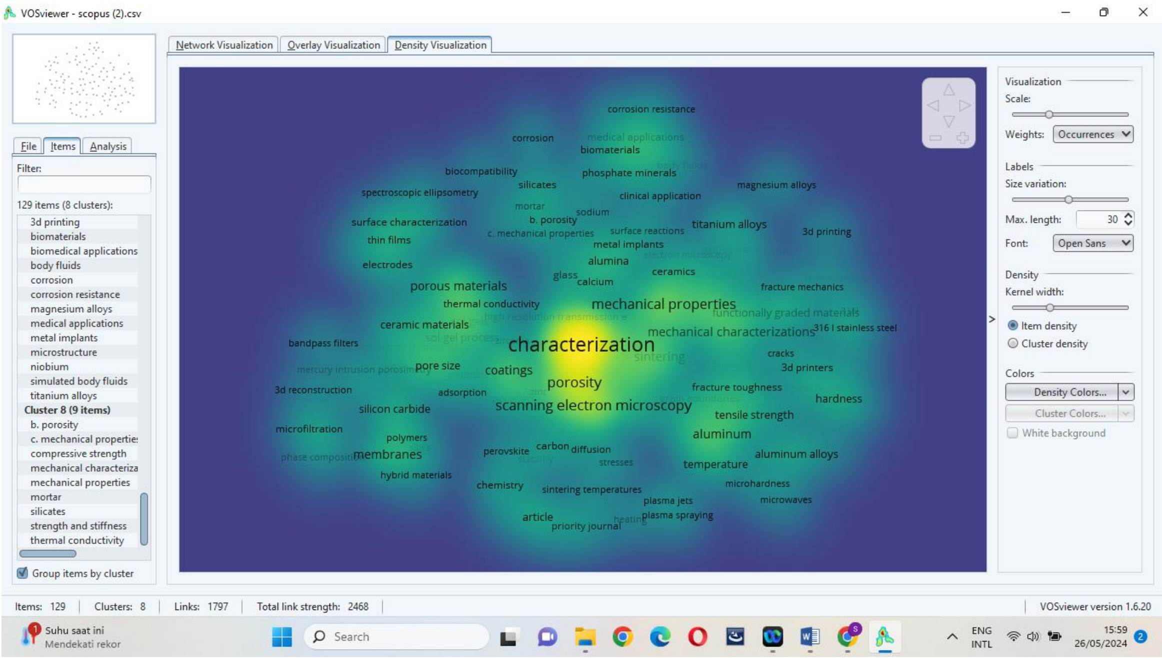


Figure 6. The density visualization map constructed with the keywords

Co-authorship development map – Analyzing countries

The visualization in Figure 7 provides a comprehensive analysis of countries involved in producing articles on material porosity using VOSviewer, highlighting the collaborative nature of this research. The size of the nodes in the visualization reveals the significance of each country, while the links between the nodes represent the strong relationships and shared goals between the countries. The degree of cooperation between the nations is shown by the thickness of the linkages and the separation between the nodes. The analysis clearly identifies Germany and Spain as the network centers, with Turkey and the United States also playing significant roles in global research. The study uncovered 16 countries, which were grouped into 5 clusters: Denmark, Italy, Portugal, and Spain (Cluster 1); Cyprus, Greece, Switzerland, and the United States (Cluster 2); Germany, Japan, and Australia (Cluster 3); Austria, France, and Turkey (Cluster 4); and Czech Republic and the United Kingdom (Cluster 5). Austria and Greece emerged as key players with the most connections to other countries. Austria is linked to Turkey, France, Greece, the United States, the United Kingdom, and Cyprus, while Greece has connections with the United States, the United Kingdom, Cyprus, Portugal, and Spain.

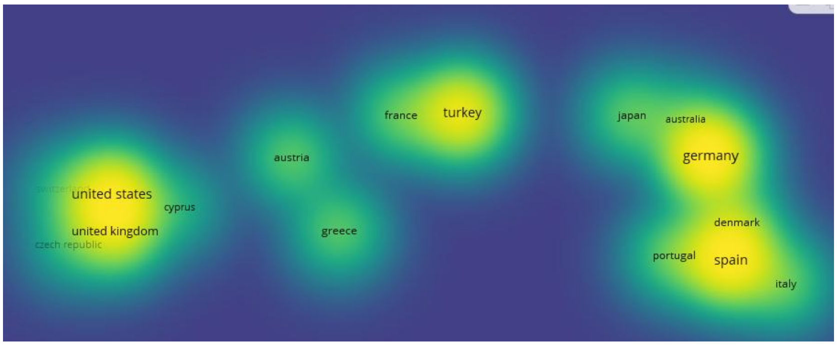


Figure 7. The prior research's network visualization, overlay visualization, and density visualization of the nations participating.

Systematic review through reporting study of PICO

Overview of relevant studies

Based on the results of identification through careful screening procedures and systematic reviews, 41 research articles were obtained. These results were obtained through a review process based on the PICO framework. The PICO framework has a role in evaluating the quality of research and ensuring reporting standards are met, so the context of these 41 articles is necessary. The details of this systematic review are summarized in Table 1.

Based on a comprehensive review of 41 articles that meet all the criteria established in the characterization of porous materials. In general, 38 studies report the characterization of porous materials to determine their structural properties, and 25 studies report the characterization of porous materials to determine their porosity. Apart from that, 20 studies report the characterization of porous materials to determine their mechanical properties, eight studies report the characterization of porous materials to determine their thermal properties, and five studies report the characterization of materials related to their optical properties. In this study, it was reported that only six studies determined one material property under study, while in the other 35 studies, more than one material property was determined. Morphology, microstructure, particle size distribution, surface properties, phase characteristics (such as phase identification, crystal structure, phase composition, phase constituents, phase fraction, and phase distribution), elemental analysis, internal structure, structural quality, laminated structure, and structural features are among the structural attributes examined in the reviewed studies. Because they together reveal details on the material's geometry, internal organization, chemical composition, phase evolution, and structural integrity, these characteristics are crucial for comprehending the structure–property relationship of materials. Thorough structural characterization makes it possible to assess how processing conditions affect microstructural development, which in turn determines the materials' mechanical, thermal, electrical, acoustic, and long-term performance. The porosity studied in this research includes pore size distribution, porosity content, boundary of porosity, pore structure, fractional porosity, porous position, porosity variations, size of pore, density of pores, open porosity, apparent porosity, textural-porous properties, pore formation, porosity amount. The mechanical properties examined in this research include tensile strength, flexural testing, elastic modulus, flexural modulus, flexural strength, microhardness, hardness, bending strength, fracture toughness, tear strength, burst strength, and fracture stresses. The thermal properties studied are thermal behavior, thermal conductivity, and thermal stability. The optical properties examined in this research consist of refraction and transmittance index, optical inspection, opacity, brightness, yellowness index and degree of polarization.

There are five different geographic regions from which countries conduct research based on the articles discussed. The five regions are America, Europe, Asia, Australia and Africa. European countries are the countries that contribute the most to characterization research, both research in one agency and collaboration with other countries outside

European countries. One research article was conducted in Australia, and one research article was conducted in South Africa. In this research, Australia collaborated with Germany and Japan, while South Africa collaborated with Iran, Belgium and the Netherlands. Foundations financially support the majority of this research. Five studies should have mentioned funding sources, namely research conducted in Korea, Belarus and Mongolia, France, Spain, Turkey and Japan.

In the 41 studies reported, the majority determined more than one material property, so more than one method and instrument were used. Most of the 41 studies that were reported investigated multiple material properties using a variety of methods and instruments. Out of the 41 articles, 38 of them conducted structural characterization of the samples tested. Several techniques were utilized, including SEM, laser diffraction analyzer, optical microscopy, FESEM, EDS, Mid-IR-OCT, tomography, XRD, digital light microscopy, digital video microscope, Raman spectrometer, and TEM. These techniques enabled researchers to visualize and analyze the physical structure and surface properties of samples at the microscopic level.

Twenty-five research articles meticulously carried out porosity characterization with the assistance of image J software, which was used to analyze the results obtained from SEM and optical microscopy, Mid-IR OCT, mercury intrusion porosimetry, XCT, X-ray microtomography, Swanepoel method, a spectroscopic ellipsometer, surface area analyzer, method of bubbles in water, method of hydrostatic weighing, Arthur method, Archimedes method, N2 adsorption/desorption isotherms at 77 K, FESEM, gravimetric method, initial masses, and density. This comprehensive approach to porosity characterization is a testament to the thoroughness of the study.

Twenty research articles conducted mechanical characterization with utmost precision using various methods, such as universal testing machine, load frame, Vickers hardness testing machine, indentation tester, ASTM, bi-axial ring-on-ring bending test, and three-point-bending. This meticulous approach to mechanical characterization underscores the accuracy of the study.

Eight research articles provided detailed characterization of thermal properties using TGA, DTA, and calorimetry techniques. Lastly, five research articles reported the characterization of optical properties using the color touch reflectometer, optical microscopy, spectroscopic ellipsometer, and UV-VIS methods. Characterization of structural, porosity, mechanical, thermal, and optical attributes contribute to a deeper understanding of the materials studied. Of the 41 articles, 38 carry out structural characterization of the samples tested. SEM, laser diffraction analyzer, optical microscopy, FESEM, EDS, Mid-IR-OCT, tomography, XRD, digital light microscopy, digital video microscope, Raman spectroscopy, and TEM are among the characterization methods employed in the reviewed investigations. The most popular methods for analyzing the surface morphology, pore architecture, and microstructural characteristics of porous materials were SEM and FESEM, which offered comprehensive details on pore size, shape, and interconnectivity. To ascertain the elemental composition and confirm the uniform distribution of component elements, contaminants, or integrated additives inside the porous matrix, EDS was frequently used with SEM/FESEM. XRD was commonly employed to confirm structural changes during synthesis or post-treatment procedures, identify crystalline phases, and assess phase composition. High-resolution observations of interior nanostructures, crystal flaws, and particle surfaces that SEM was unable to resolve were made possible by TEM. Furthermore, Raman spectroscopy was used to detect structural flaws and chemical bonds, and laser diffraction analysis was used to ascertain the particle size distribution. When combined, these complementary characterization methods offer thorough structural information that facilitates a deeper comprehension of the connections between microstructure, composition, and the consequent attributes of porous materials. With these methods, scientists can observe and analyze the microscopic surface features and composition of samples. Twenty-five research articles carried out porosity characterization with the help of image j software from image results obtained from SEM and optical microscopy, Mid-IR OCT, mercury intrusion porosimetry, XCT, X-ray microtomography, Swanepoel method, a spectroscopic ellipsometer, surface area analyzer, method of bubbles in water, method of hydrostatic weighing, Arthur method, Archimedes method, N2 adsorption/desorption isotherms at 77 K, FESEM, gravimetric method, initial masses and density. Twenty research articles carry out mechanical characterization using several methods, namely universal testing machine, load frame, Vicker hardness testing machine, indentation tester, ASTM, bi-axial ring–on–ring bending test, three-point-bending. 8 research articles carried out detailed characterization of thermal properties using TGA, DTA, calorimetry techniques. The five research articles reported the characterization of optical properties using the color touch reflectometer, optical microscopy, spectroscopic ellipsometer and UV-VIS methods. Characterization of structural, porosity, mechanical, thermal and optical attributes contribute to a deeper understanding of the materials studied.

Table 1. Reporting specifics of the 41 studies that were evaluated.

No	Author	Sample	Characterization	Properties				
				MP	P	SP	TP	OP
1	Hartmann, C., Venkatesan, K., de Looze, G., Shen, S., Wilson, R	Magnesium alloys WE43 and AZ91D	SEM, Laser diffraction analyzer, optical microscopy, image j, FESEM-EDS, universal testing machine	√	√	√	×	×
2	Zorin, I., Brouczek, D., Geier, S., Schwentenwein, M., Heise, B.	Ceramic additive manufacturing: alumina dan zirkonia	Mid-infrared optical coherence tomography	×	√	√	×	×
3	Trevisan, M., Vicente, J., Ghidossi, R., Vincent, A., Moulin, P.	SIC membrane	X-ray tomography, SEM, mercury intrusion porosimetry	×	√	√	×	×
4	Rankouhi, B., Islam, Z., Pfefferkorn, F.E., Thoma, D.J.	316L stainless steel (316L) and Hastelloy X (HX) multi-material processing	SEM-EDS, XRD, load frame	√	×	√	×	×
5	Kılınç, A.Ç., Goktasş, A.A., Keskin, Ö.Y., Köktaş, S.	3d printing CuSn10 bronze alloy	laser scattering, SEM, thermogravimetric, TG/DTA, XRD, universal tensile testing machine	√	×	√	√	×
6	Sirkiä, S.V., Nakamura, M., Qudsia, S., Hupa, L., Vallittu, P.K.	bioceramics of hydroxyapatite and carbonate apatite, two bioactive glasses 45S5 andS53P4, and alumina	ATR-FTIR, SEM-EDX, XRD	×	×	√	×	×
7	Zarka, M., Dikici, B., Niinomi, M., Nakai, M., Yilmazer, H.	β-type Ti–29Nb–13Ta–4.6Zr (TNTZ)	SEM, AFM, XRD- EDS, Vickers tester,	√	√	√	×	×
8	Kucuk, Y., Oge, M., Gok, M.S., Karaoglanli, A.C.	Ferrochromium slag	SEM, TGA	×	×	√	√	×
9	Fry, A.T., Gorman, D.M., Brown, S.B.	Grade 91 tubing	XCT, SEM, Tomography	×	√	√	×	×
10	Yusefi, A., Parvin, N., Mohammadi, H.	W–Cu functionally graded material (FGM) with 11 layers, including a pure copper layer.	FESEM, SEM, ASTM, single edge bending speciments	√	×	√	×	×
11	Rewatkar, P.M., Taghvaee, T., Saeed, A.M., Sotiriou-	highly porous (>85%) SiC and Si3N4	SEM, TGA, XRD, mercury intrusion	√	√	√	√	×

	Leventis, C., Leventis, N.	monolithic aerogels	porosimetry, ASTM					
12	Justo, J., Távara, L., García-Guzmán, L., París, F.	3D printed long fibre reinforced Composites composite nylon-based coupons	ASTM, optical microscope	√	×	√	×	×
13	Kaspar, T.C., Reiser, J.T., Ryan, J.V., Wall, N.A.	corroded glass surfaces (silicate glass coupons altered)	spectroscopic ellipsometry,SEM-EDS	×	√	√	×	√
14	Vogel, D., Dempwolf, H., Baumann, A., Bader, R.	Coating poly-ether-ether-ketone (PEEK)	ASTM, centered load, calorimetry, digital light microscopy	√	√	√	√	×
15	He, Y., Zhang, Y., Zhang, J., Jiang, Y., Zhou, R.	Ti-13Nb-13Zr	SEM, XRD, testing machine	√	×	√	×	×
16	Václavík, M., Plachá, M., Kočí, P., Novák, V., Thompsett, D.	Three SiC filter samples with different amount of SCR catalyst	SEM, X-ray Microtomography, Mercury Porosimetry	×	√	×	×	×
17	Carrasco-Amador, J.P., Diaz-Parralejo, A., Macías-García, A., Díaz-Díez, M.Á., Olivares-Marín, M.	ZrO2/Y2O3/Al2O3-based microstructured multilayer sol–gel coatings	UV–Vis, SEM-EDS, optical microscopy, swanepoels methods	×	√	√	×	√
18	Rosu, D.-M., Ortel, E., Hodoroaba, V.-D., Kraehnert, R., Hertwig, A	pore-controlled TiO2layers : porous thin TiO2films	SEM, electron microscopy, Spectroscopic ellipsometry	×	√	×	×	√
19	Gontarczyk, K., Bury, W., Serwatowski, J., Durka, K., Luliński, S.	2,4,6-tris(4′-bromophenyl)-1,3,5-triazine	XRD, TGA, SEM	×	×	√	√	×
20	Aminipour, Z., Khorshid, M., Bayoumi, M., Wagner, P., Van der Bruggen, B	Black lipid membranes	SEM, surface area analyser	×	√	√	×	×
21	Zalaoglu, Y., Karaboga, F., Terzioglu, C., Yildirim, G.	pure and Au surface-layered Bi-2212 superconducting compounds	Vickers hardness, identation test load, X-RD	√	√	√	×	×
22	Fraga, M.C., Sanches, S., Pereira, V.J., Rodríguez-Castellón, E., Benavente, J.	A new silicon carbide ceramic membrane : Silicon carbide membranes	SEM	×	×	√	×	×
23	Salehi, M., Søgaard, M., Esposito, V., Schroeder, M., Hendriksen, P.V.	The perovskite-type oxide (La0.6Ca0.4)0.98(Co0.8Fe 0.2)O3-δ (LCCF)	SEM-EDS, thermogravimetry, XRD	×	×	√	√	×
24	Ravariu, C., Manea, E., Babarada, F.	Masks and metallic electrodes compounds	Optical microscopy, SEM	×	×	√	×	√
25	Mishra, R.R., Sharma, A.K.	Cylindrical pieces of AA7039 alloy	Optical microscopy, image analysis software, FESEM, XRD, Vicker's micro indentation hardness tester	√	√	√	×	×
26	Ivanets, A.I., Azarova, T.A., Agabekov, V.E., Prozorovich, V.G., Rat'ko, A.A.	multi-layer ceramic membranes on the basis of natural quartz raw ma-terial from Mongolia	XRD, SEM, method of bubble in water, method of hydrostatic weighing	×	√	√	×	×
27	Voicu, G., Ene, V.-L., Sava, D.-F., Surdu, V.-A.,	The vitroceramic materials	Arthur method, SEM-EDS, gravimetric	×	√	√	√	×

	Busuioc, C.							
28	Izzo, F., Arizzi, A., Cappelletti, P., Morra, V., Langella, A.	Twenty samples of mortar-based materials from Villa San Marco were collected (10 plasters, 8 mortars and 2 mosaic floors	Digital video microscope, optical microscopy, digital image analysis, XRD, SEM-EDS	×	×	√	×	×
29	Huang, Z., Wen, X., Tang, Z., Zhu, C., Qing, B.	Porous aluminum hydroxide materials	XRD, TEM, surface analyser	×	×	√	×	×
30	Sun, D.-L., Hao, X.-F., Yu, X.-C., Chen, X.-C., Liu, M.-H.	carbon fibre-reinforced laminated woodceramics	Archimedes method, SEM, Raman spectrometer, TEM, mechanical testing machine	√	√	√	×	×
31	Kostoglou, N., Tarat, A., Walters, I., Mitterer, C., Rebholz, C.	few-layer graphene powders	FESEM, XRD, N2 adsorption/desorption isotherms at 77 K	×	√	√	×	×
32	Aboulkhair, N.T., Maskery, I., Tuck, C., Ashcroft, I., Everitt, N.M.	Aluminium alloys	SEM, optical microscopy, nanoidenter	√	×	√	×	×
33	Yoon, H., Lee, H.H., Ahn, Y.N., Lee, J., Kim, H.	Al2O3–ZnO films	FESEM, TEM	×	√	√	×	×
34	Akmal, M., Khalid, F.A., Hussain, M.A.	316L stainless steel powder	SEM-EDS, ImageJ, Vickers hardness testing machine, optical microscopy	√	√	√	×	×
35	Santos, S.M., Carbajo, J.M., Quintana, E., Eugenio, M.E., Villar, J.C.	Bacterial cellulose	Color touch reflectometer, static dynamic contact angle, mercury intrusion porosimetry, SEM-XRD, FTIR	√	√	√	×	√
36	Zhang, J., Malzbender, J.	micro- and nano-porous alumina	bending tests, Vickers hardness, LM-SEM, mercury porosity	√	√	√	×	×
37	Palmero, P., Formia, A., Antonaci, P., Brini, S., Tulliani, J.-M.	eopolymeric samples	EN 12390-7 Standard, three-point-bending, FESEM, mercury porosimetry, laser-granulometry	√	√	√	×	×
38	Arrabal, R., Mohedano, M., Matykina, E., Mingo, B., Merino, M.C.	Plasma electrolytic oxidation (PEO) coatings	SEM-EDS, image j, XRD, vikers micro-hardness tester	√	×	√	×	×
39	Pandis, C., Trujillo, S., Matos, J., Mano, J.F., Gõmez Ribelles, J.L.	Poly(lactic acid) (PLA)	SEM, Gravimetric method, thermogravimetric analysis, dynamic mechanical analysis	√	√	√	√	×
40	Bansal, A., Sharma, A.K., Kumar, P., Das, S.	stainless steel-316	FESEM-EDS, XRD, Vickers microhardness tester, universal tensile machine	√	×	√	×	×
41	Fekri, N., Madden, J.D.W., Lee, N.Y.-J., Ko, F., Michal, C.A.	porous carbon nanofibre/polypyrrole films	SEM, initial masses and density	×	√	×	×	×

Notes:
MP: Mechanical Properties; P: Porosity; SP: Structure Properties; TP: Thermal Properties; OP: Optical Properties; √: yes; ×: No

Characterization of mechanical properties of porous materials

In the 41 studies reviewed, 20 studies characterized porous materials to determine their mechanical properties. Of the 20 studies, 6 of them determined hardness and microhardness which were determined using ASTM (Yuse et al., 2018), vicker hardness (Akmal et al., 2020; Arrabal et al., 2015; Bansal et al., 2014; Mishra & Sharma, 2016; Zalaoglu et al., 2017). Five studies reported determining the tensile test determined using a universal testing machine (Bansal et al., 2014; Hartmann et al., 2024; Kılınç et al., 2021), load frame (Rankouhi et al., n.d.), ASTM (Justo, 2018), five studies reported determining elastic modulus determined using ASTM (Justo, 2018; Rewatkar et al., 2018), testing machine (He et al., 2017; Sun et al., 2016), bi-axial ring – on-ring bending test (Zhang & Malzbender, 2015), vickers hardness (Zhang & Malzbender, 2015). Three studies were reported to determine flexural testing using frame load (Rankouhi et al., n.d.), centered load (Vogel et al., 2017), three-point bending (Palmero et al., 2015). Two studies determined fracture stresses using bi-axial ring-on-ring bending tests (Zhang & Malzbender, 2015), Vickers hardness (Zhang & Malzbender, 2015). Three other studies reported determining flexural modulus using centered load (Vogel et al., 2017), bending strength using a mechanical testing machine (Sun et al., 2016), fracture toughness using a mechanical testing machine (Sun et al., 2016), grammage (Santos et al., 2014), tear strength (Santos et al., 2014), burst strength (Santos et al., 2014). Hardness and microhardness are the mechanical properties that are most commonly determined in porous materials.

Porosity characterization in porous materials

Of the 41 studies reported on the characterization of porous materials, 25 studies determined the porosity of porous materials. There are 14 studies reported to determine porosity using image analysis software (Akmal et al., 2020; Hartmann et al., 2024; Mishra & Sharma, 2016; Zarka et al., 2020), mid-IR OCT (Zorin et al., 2022), mercury intrusion porosity (Santos et al., 2014; Trevisan et al., 2022; Václavík et al., 2017; Zhang & Malzbender, 2015), surface area analyzer (Aminipour et al., 2017), gravimetric method (Pandis et al., 2014), initial masses and density (Fekri et al., 2014), swanepoels methods (Carrasco-amador et al., 2017), spectroscopic ellipsometer (Rosu et al., 2016). Four studies reported determining pore size distribution using mercury intrusion porosimetry (Palmero et al., 2015; Trevisan et al., 2022; Václavík et al., 2017; Zhang & Malzbender, 2015). There are two studies reported to determine the size of pores using SEM (Rosu et al., 2016) and method of bubble in water (Ivanets et al., 2016). Two studies determined open porosity using the method of hydrostatic weighing (Ivanets et al., 2016) and the Arthur method (Voicu et al., 2016). Ten other studies determined the boundary of porosity using XCT (Fry et al., 2018), pore structure using mercury intrusion porosity (Rewatkar et al., 2018), macroporous using SEM (Václavík et al., 2017), porous position using X-ray microtomography (Václavík et al., 2017), density of pore using SEM (Rosu et al., 2016), apparent porosity using Archimedes method (Sun et al., 2016), microporosity using N_2 adsorption/desorption isotherms at 77 K (Kostoglou et al., 2016), pore formation using FESEM (Yoon et al., 2016), pore structure using FESEM (Yoon et al., 2016) and porosity amount using mercury intrusion porosimetry (Palmero et al., 2015). Mercury intrusion porosimetry is the only tool used to determine pore size distribution.

These techniques revealed important structural characteristics such as pore morphology, pore interconnectivity, particle shape, and surface roughness, which are closely associated with the functional performance of porous materials. For example, SEM and FESEM images were widely used to confirm the formation of interconnected porous networks and to evaluate pore uniformity after different fabrication processes, whereas TEM provided high-resolution observations of internal nanostructures and particle interfaces. Furthermore, SEM-EDS and SEM-EDX analyses enabled simultaneous examination of surface morphology and elemental composition, confirming the homogeneous distribution of constituent elements and verifying the successful incorporation of functional additives. In addition, two studies determined particle size distribution using a laser diffraction analyzer (Hartmann et al., 2024) and laser scattering

(Kılınç et al., 2021), demonstrating that particle size uniformity plays an important role in controlling pore formation and the overall structural characteristics of porous materials.

Structural characterization of porous materials

Of the 41 studies reported, only three studies reported that they did not determine the structural properties of the material. Among the remaining 38 studies, morphology and microstructure were the most frequently investigated properties. Specifically, 19 studies characterized these features using SEM (Aboulkhair et al., n.d.; Aminipour et al., 2017; Fry et al., 2018; Gontarczyk et al., 2017; Hartmann et al., 2024; Ivanets et al., 2016; Kılınç et al., 2021; Kucuk & Oge, 2018; Pandis et al., 2014; Rewatkar et al., 2018; Zarka et al., 2020), tomography (Trevisan et al., 2022), SEM-EDX (Sirkiä et al., 2021), digital light microscope (Vogel et al., 2017), SEM-EDS (Akmal et al., 2020; Arrabal et al., 2015; Voicu et al., 2016), TEM (Huang et al., 2016), and FESEM (Kostoglou et al., 2016). These techniques revealed important structural characteristics such as pore morphology, pore interconnectivity, particle shape, and surface roughness, which are closely associated with the functional performance of porous materials. For example, SEM and FESEM images were widely used to confirm the formation of interconnected porous networks and to evaluate pore uniformity after different fabrication processes, whereas TEM provided high-resolution observations of internal nanostructures and particle interfaces. Furthermore, SEM-EDS and SEM-EDX analyses enabled simultaneous examination of surface morphology and elemental composition, confirming the homogeneous distribution of constituent elements and verifying the successful incorporation of functional additives. In addition, two studies determined particle size distribution using a laser diffraction analyzer (Hartmann et al., 2024) and laser scattering (Kılınç et al., 2021), demonstrating that particle size uniformity plays an important role in controlling pore formation and the overall structural characteristics of porous materials. Nineteen studies determined structural and microstructural characteristics using a light microscope (Zhang & Malzbender, 2015), TEM (Yoon et al., 2016), FESEM (Mishra & Sharma, 2016; Palmero et al., 2015; Yuse et al., 2018), optical microscope (Akmal et al., 2020; Hartmann et al., 2024; Mishra & Sharma, 2016), SEM (Fry et al., 2018; Hartmann et al., 2024; He et al., 2017; Ravariu et al., 2017; Sun et al., 2016; Trevisan et al., 2022), SEM-EDS (Bansal et al., 2014; Carrasco-amador et al., 2017; Rankouhi et al., n.d.; Salehi et al., 2017), tomography (Fry et al., 2018). Five studies report determining surface structure using mid-IR OCT (Zorin et al., 2022), SEM (Fraga et al., 2016; Ivanets et al., 2016), surface analyser (Huang et al., 2016), static dynamic contact angle (Santos et al., 2014). Five studies report determining phase composition using XRD (Arrabal et al., 2015; Ivanets et al., 2016; Sirkiä et al., 2021), SEM-EDS (Kaspar et al., 2018), raman spectrometer (Sun et al., 2016). There are two studies that report the use of XRD to determine phase analysis (Mishra & Sharma, 2016; Salehi et al., 2017), Two studies report the use of textural using a digital video microscope (Izzo et al., 2016) and using N_2 adsorption/desorption isotherms at 77 K (Kostoglou et al., 2016). Six other studies reported determining phase structure using XRD (Kılınç et al., 2021), determining elemental analysis using XRD-EDS (Zarka et al., 2020), structural quality determination using optical microscopy (Justo, 2018), penetuan phase constituent menggunakan XRD (He et al., 2017), penetuan structural quality menggunakan optical microscopy (Carrasco-amador et al., 2017), phase fraction determination using XRD (Zalaoglu et al., 2017) and elemental composition determination using EDS (Mishra & Sharma, 2016).

Characterization of thermal properties of porous materials

Of the 41 studies reported, there were 8 studies that determined thermal properties. Of the eight studies reported, there were seven studies that used thermogravimetric analysis to determine thermal behavior (Gontarczyk et al., 2017; Kılınç et al., 2021; Kucuk & Oge, 2018; Pandis et al., 2014; Salehi et al., 2017; Voicu et al., 2016) and determine thermal conductivity (Rewatkar et al., 2018). One study reported using calorimetry (Vogel et al., 2017).

Characterization of optical properties of porous materials

In the 41 studies reported, only 5 studies determined optical properties. The optical properties determined are refraction index using a spectroscopic ellipsoid (Kaspar et al., 2018) and UV-VIS (Carrasco-amador et al., 2017), determining the degree of polarization using a spectroscopic ellipsometer (Rosu et al., 2016), determining optical inspection using optical microscopy (Ravariu et al., 2017), determining opacity using a color touch reflectometer (Santos et al., 2014), determining yellowness index using a color touch reflectometer (Santos et al., 2014) and brightness using a color touch reflectometer (Santos et al., 2014).

Interrelationship between VOSviewer and PICO analysis

The PICO results found are related to the results of the VOSviewer analysis. Based on VOSviewer analysis, material structure characterization is the largest cluster. Among 41 studies based on PICO analysis, 38 studies characterized the structural properties of materials. This shows that structural properties are the most commonly determined properties in terms of material characterization, and SEM is the most commonly used tool for characterization. In the VOSviewer SEM study, it is included in the second-largest cluster. Based on pico analysis, countries in Europe have conducted the most research on the characterization of porous materials, and the VosViewer study shows that Germany is the country that has been most significant in conducting research on the characterization of porous materials. Spain is the country with the most citations. This linkage is significant as future research implementation can offer a comprehensive framework.

The result and discussion are presented together so that the relationship between the two can be clearly illustrated. The use of graphics and photos should be presented with quality. Tables and Figures should be numbered and cited in the manuscript (see Figure 1). Repeating the information that has been conveyed in the method and introduction should be avoided.

CONCLUSION

VOSviewer was used to show research trends and theme links, and a systematic review utilizing the modified PICO framework thoroughly examined the characterization of porous materials and their related material properties. Characterization emerged as the predominant research theme in eight research clusters published between 2014 and 2024, followed by porosity, pore size, and SEM. 41 papers were analyzed using the modified PICO framework. Of these, 38 research described the structural characteristics of porous materials, 25 analyzed porosity, 20 looked at mechanical properties, 8 looked at thermal properties, and just five evaluated optical qualities, suggesting that optical characterization is still largely unexplored.

The reviewed research consistently showed that complementary information on pore shape, pore interconnectivity, particle size, elemental composition, phase composition, and internal microstructure may be obtained from structural characterisation techniques, including SEM, FESEM, TEM, EDS, and XRD. The mechanical, thermal, optical, and functional performance of porous materials were found to be significantly influenced by these structural features. The results also show that a more thorough understanding of structure-property connections can be obtained by integrating several characterization techniques rather than depending just on one analytical methodology.

All things considered, this review offers a thorough synthesis of current characterization methods, points out current research trends and knowledge gaps, and identifies areas for further investigation, especially in the quantitative comparison of material properties and the incorporation of sophisticated characterization techniques for porous materials.

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