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Review Article

The Role of Polysaccharide Aerogel in Tissue Regeneration and Repair

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Abstract

Aerogel-based biomaterials is an important subject in materials sciences due to their vast attention in different sectors. These materials possess unique properties that distinguish them such as low density. In the area of tissue engineering, there application has been documented in areas such as blood vessel, soft tissue, nerves, bone and cartilage. There are several steps involved in aerogel preparation. The first step involves the appropriate selection of a precursor material such as polymers, silica or carbon. Aerogels have a unique property which include the composition of mesoporous solid colloids that possess a light weight and a porous frame work structure. Aerogels also possess unique extraordinary physicochemical properties. Tissue engineering is a broad term that encompasses on using biocompatible materials to repair and replace damaged tissues. Notwithstanding, its diverse applications over the years, tissue engineering have had persistent hurdles which include the need to develop new novel biomaterials This article seeks to review the properties of aerogel and their preparation processes. The review also documented the challenges from current studies and future prospects were also discussed.

Keywords: Aerogel, Biomaterials, Biomedicine, Material science, Porosity

INTRODUCTION

The significant attention aerogels have gained over the years especially in the field of biomaterials cannot be over emphasized [1,2]. They have a unique property which include the composition of mesoporous solid colloids, which possess a lightweight and a porous frame work structure [3]. A definition given by Feng et al. defined an aerogel as a solid component that has a unique dispersion [4]. Aerogels are remarkable materials that possess extraordinary physicochemical properties [5]. Aerogel preparation involves several steps. They have diverse applications and ability to exist in different forms such as cylinders, spheres and monolithic shapes [6,7]. In the field of biomedicals, their application is widespread to other areas not limited to tissue engineering [8,9].

Tissue engineering is a broad term that encompasses on using biocompatible materials to repair and replace damaged tissues. Notwithstanding, its diverse applications over the years, tissue engineering have had persistent hurdles over the years which include the need to develop new novel biomaterials [10-14]. With these challenges in view, the promising avenue of aerogel-based biomaterials cannot be over-emphasized [15]. Some of the several reasons associated with the use of these materials include: its biocompatibility, biodegradability and mechanical strength [16]. Scientists have been able to incorporate the aerogel-based scaffolds in three-dimensional (3D) printing, thus enhancing its flexibility.

AEROGEL-BASED BIOMATERIALS AND THEIR UNIQUE PROPERTIES

Distinctive properties associated with aerogels include high porosity, low weight and surface area [17-20]. They help to increase their widespread applications in various fields. These exceptional qualities of the biomaterials to be easily handled and implemented in the human body is related to

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their low density and weight [21]. Some of the techniques used in the determination of aerogels include: scanning electron microscopy (SEM), small-angle scattering (SAXS), nuclear magnetic resonance (NMR) and X-ray diffraction (XRD) [22-26].

AEROGEL-BASED BIOMATERIALS AND THEIR PREPARATION TECHNIQUES

Several key steps are involved in aerogel preparation. The first step involves the appropriate selection of a material such as polymers, silica or carbon [27-28]. These precursor materials have their own unique properties. The sol-gel process is the first fundamental method employed in aerogel synthesis [29,30]. To enhance the strength of aerogels, there is to deploy various cross-linking strategies [31,32]. The production of nanofiber-derived aerogels (PNAs) by Qian [33], was based on the high porosity and surface area. The effect of aging on the aerogel's microstructure has been documented. According to Kawakami [34], he deployed the use of water vapor in optimizing the aging process. The most prevalent methods among the afore-mentioned techniques are freeze-drying and $SCCO_2$ drying [35-40]. **Table 1** summarizes the drying methods on aerogel characteristics, while **Tables 2 & 3** depicts the various strategies for aerogel preparation. Two unique characteristics mark out the supercritical drying technique. They include avoidance of structural collapse and mesopore shrinkage [40-42].

Table 1. Different characteristics of aerogels prepared by different drying techniques.

Technique	Aerogel	Raw material(s)	Characteristics	References
SCD	SiO_2 and carbon aerogels	Tetra-ethoxy silane, ethanol, water	Transparency, homogeneity, pore size (80 mm or less), ultra-low density, small mean particle size	[44-46]
SCD	Nanofibers	Ammonium sulfate, $CaCl_2$	33nm and 23 nm pore size	[47]
Freeze-drying	Carbon aerogels	Formaldehyde	Density of 0.112 g/cm^3	[48]
UAFD	Polyimide aerogels	N-N-dimethyl acetamide (DMAc)	Heightened thermal insulation and increased hydrophobicity	[49]

Note: SCD: Supercritical Drying; UAFD: Ultrasound Assisted Freeze Drying

Table 2. Applied strategies of aerogels in tissue engineering.

Aerogel	Applied strategy	Synthesis technology	Results	References
Photo-crosslink and methacrylate	3D printing of scaffolds	Wet chemical synthesis and self-assembly	Supports mesenchymal osteoblast differentiation	[66]
Alginate aerogel	3D printing of scaffolds	3D printing	Cell proliferation and migration are enhanced.	[67]
Nanofiber aerogel	Bone scaffolds	Freeze casting	Healing was achieved in a cranial defect of size 8 mm	[68]
Mixture of gelatin and chitosan aerogel	Dopamine release	Covalent grafting	Production of good mechanical properties	[69]
Nanofiber aerogel	Typical release strategy	Amination reactions	Formation of new bone cells	[70]

Table 3. Current perspectives of aerogel applications.

Tissue engineering application/direction	Aerogel-based biomaterials	Other added materials	Application advantages	References
Bone/tissue engineering	Scaffolds of nanowire origin	Hydroxyapatite	It enhances the growth and regeneration of bone cells	[76]
Nerve tissue engineering	Conductive cellulose/polypyrrole composite aerogels	Dodecyl-benzenesulfonic acid	It enhances the adhesion of PC 12 cells	[78]
Skin tissue engineering	Jackfruit aerogel	Derivatives of zinc	It enhances the regeneration of infected skin wounds	[79]
Muscle tissue engineering	Polydopamine aerogel	Tannic acid	It enhances the growth of myofibroblasts	[80]

CLASSIFICATION OF AEROGEL-BASED BIOMATERIALS

They are classified based on two distinct properties which include: constituent materials and chemical properties [9]. Nanomaterials is one of the materials used in biomedical application [50-54].

ORGANIC AEROGELS-BASED BIOMATERIALS

Unique characteristics associated with organic aerogels include: light weight, flexibility and biocompatibility [55-58]. Carbon based aerogels are constructed with the help of carbon-based nanomaterials. The materials exist in form of nano diamonds (NDs) [59-62]. Another component of the aerogel production are the organic polymer materials [63-65]. Cellulose has a well-known cellulose-based hydrogel derived from it [66].

INORGANIC AEROGEL-BASED BIOMATERIALS

The foundation of these biomaterials consists of inorganic materials like metal oxides [63-65]. The first synthesis of silicon aerogels was in the 19th century [58]. Inorganic aerogels have wide applications such as a thermal insulator in aerospace and construction. They are also used in industrial setting and in water purification [65].

HYBRIDIZED AEROGEL-BASED BIOMATERIALS

Distinct properties of aerogels are influenced by the selection between organic and inorganic types. They possess notable characteristics such as biodegradability, biocompatibility and light weight [69,70]. A significant milestone was achieved by Novak [71], when he prepared the first silica (SiO_2) hybridized aerogel for specific applications [71]. There are various techniques deployed in the characterization of organic-inorganic hybrid aerogels [71,72]. There are two main classes of organic-inorganic hybridized aerogels [73,74]. The choice of type I or type II hybridized aerogels depends on its application [75].

AEROGEL-BASED STRATEGIES FOR TISSUE REGENERATION

Properties such as biocompatibility, hydrophilicity and non-cytotoxicity are exhibited by aerogels.

CONCLUSION AND FURTHER PERSPECTIVE

The new characteristics of aerogels make them stand out as a unique material. There is need to pay critical attention on the synthesis protocols and porosity regulation of aerogels. Inherent properties of aerogels can be further explored by researchers in areas of aerogel-based biomaterials.

AUTHORSHIP CONTRIBUTION

Ezegbe Chekwube Andrew: Writing, review, supervision, Ezegbe Amarachi Grace: Writing, review, Odo Kenechi Benjamin: Writing, review, Onyia Oluebube Chisom: Review, writing, Agu-Kalu Amarachi: Writing, review.

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CONFLICT OF INTEREST

Authors declare no conflict of interest

REFERENCES

1. Hüsing N, Schubert U (1998) Aerogels-Airy Materials: Chemistry, Structure, and Properties. Angew Chem Int Ed 37(1-2): 22-45.
2. Kistler SS (1931) Coherent Expanded Aerogels and Jellies. Nature 127 (3211): 741.
3. Du A, Zhou B, Zhang Z, Shen J (2013) A Special Material or a New State of Matter: A Review and Reconsideration of the Aerogel. Materials (Basel) 6(3): 941-968.
4. Feng J, Su BL, Xia H, Zhao S, Gao C, et al. (2021) Printed aerogels: Chemistry, processing, and applications. Chem Soc Rev 50(6): 3842-3888.
5. Vareda JP, Lamy-Mendes A, Duraes L (2018) A reconsideration on the definition of the term aerogel based on current drying trends. Microporous Mesoporous Mater 258: 211-216.
6. Xie J, Niu L, Qiao Y, Chen P, Rittel D (2022) Impact energy absorption behavior of graphene aerogels prepared by different drying methods. Mater Des 221: 110912.
7. Ferreira-Gonçalves T, Constantin C, Neagu M, Reis CP, Sabri F, et al. (2021) Safety and efficacy assessment of aerogels for biomedical applications. Biomed Pharmacother 144: 112356.
8. Nita LE, Ghilan A, Rusu AG, Neamtu I, Chiriac AP (2020) New Trends in Bio-Based Aerogels. Pharmaceutics 12(5): 449.
9. Chen Y, Zhang L, Yang Y, Pang B, Xu W, et al. (2021) Recent Progress on Nanocellulose Aerogels: Preparation, Modification, Composite Fabrication, Applications. Adv Mater 33(11): 2005569.
10. Wan W, Zhang R, Ma M, Zhou Y (2018) Monolithic aerogel photocatalysts: A review. J Mater Chem A 6(3): 754-775.
11. Wei N, Ruan L, Zeng W, Liang D, Xu C, et al. (2018) Compressible Supercapacitor with Residual Stress Effect for Sensitive Elastic-Electrochemical Stress Sensor. ACS Appl Mater Interfaces 10(44): 38057-38065.
12. Shabangoli Y, Rahmanifar MS, El-Kady MF, Noori A, Mousavi MF, et al. (2018) Thionine Functionalized 3D Graphene Aerogel: Combining Simplicity and Efficiency in Fabrication of a Metal-Free Redox Supercapacitor. Adv Energy Mater 8(34): 1802869.
13. Zheng L, Zhang S, Ying Z, Liu J, Zhou Y, et al. (2020) Engineering of Aerogel-Based Biomaterials for Biomedical Applications. Int J Nanomed 15: 2363-2378.
14. Esquivel-Castro TA, Ibarra-Alonso MC, Oliva J, Martínez-Lu´evanos A (2019) Porous aerogel and core/shell nanoparticles for controlled drug delivery: A review. Mater Sci Eng C 96: 915-940.

15. Wu Y, Jin M, Huang Y, Wang F (2022) Insights into the Prospective Aerogel Scaffolds Composed of Chitosan/Aramid Nanofibers for Tissue Engineering. ACS Appl Polym Mater 4 (7): 4643-4652.

16. Follmann HD, Oliveira ON, Lazarin-Bidoia D, Nakamura CV, Huang X, et al. (2018) Multifunctional hybrid aerogels: Hyperbranched polymer trapped mesoporous silica nanoparticles for sustained and prolonged drug release. Nanoscale 10(4): 1704-1715.

17. Hosseini H, Zirakjou A, Goodarzi V, Mousavi SM, Khonakdar HA, et al. (2020) Lightweight aerogels based on bacterial cellulose/silver nanoparticles/polyaniline with tuning morphology of polyaniline and application in soft tissue engineering. Int J Biol Macromol 152: 57-67.

18. Maleki H, Durães L, García-González CA, Gaudio PD, Portugal A, et al. (2016) Synthesis and biomedical applications of aerogels: Possibilities and challenges. Adv Colloid Interface Sci 236: 1-27.

19. Amani H, Arzaghi H, Bayandori M, Dezfuli AS, Pazoki-Toroudi H, et al. (2019) Controlling Cell Behavior through the Design of Biomaterial Surfaces: A Focus on Surface Modification Techniques. Adv Mater Interfaces 6(13): 1900572.

20. Stergar J, Maver U (2016) Review of aerogel-based materials in biomedical applications. J Sol-Gel Sci Technol 77(3): 738-752.

21. Karamikamkar S, Yalcintas EP, Haghniaz R, de Barros NR, Mecwan M, et al. (2023) Aerogel Based Biomaterials for Biomedical Applications: From Fabrication Methods to Disease-Targeting Applications. Adv Sci 10(23): 2204681.

22. Li VC, Dunn CK, Zhang Z, Deng Y, Qi HJ (2017) Direct Ink Write (DIW) 3D Printed Cellulose Nanocrystal Aerogel Structures. Sci Rep 7(1): 8018.

23. Chen H, Wang X, Xue F, Huang Y, Zhou K, et al. (2018) 3D printing of SiC ceramic: Direct ink writing with a solution of preceramic polymers. J Eur Ceram Soc 38(16): 5294-5300.

24. Smirnova I, Gurikov P (2018) Aerogel production: Current status, research directions, and future opportunities. J Supercrit Fluids 134: 228-233.

25. Qiao H, Qin W, Chen J, Feng L, Gu C, et al. (2023) AuCu decorated MXene/RGO aerogels towards wearable thermal management and pressure sensing applications. Mater Des 228: 111814.

26. Cheng X, Chang X, Wu F, Liao Y, Pan K, et al. (2024) Advanced nanofabrication for elastic inorganic aerogels. Nano Res 17(10): 8842-8862.

27. Yu S, Budtova T (2024) Creating and exploring carboxymethyl cellulose aerogels as drug delivery devices. Carbohydr Polym 332: 121925.

28. Milovanovic S, Markovic D, Castvan JI, Lukic I (2024) Cornstarch aerogels with thymol, citronellol, carvacrol, and eugenol prepared by supercritical CO2- assisted techniques for potential biomedical applications. Carbohydr Polym 331: 121874.

29. Saldin LT, Cramer MC, Velankar SS, White LJ, Badylak SF (2017) Extracellular matrix hydrogels from decellularized tissues: Structure and function. Acta Biomater 49: 1-15.

30. Tan Y, Chen D, Wang Y, Wang W, Xu L, et al. (2022) Limbal Bio-Engineered Tissue Employing 3D Nanofiber-Aerogel Scaffold to Facilitate LSCs Growth and Migration. Macromol Biosci 22(5): 2270014.

31. Zhang M, Li M, Xu Q, Jiang W, Hou M, et al. (2022) Nanocellulose-based aerogels with devisable structure and tunable properties via ice-template induced self-assembly. Ind Crop Prod 179: 114701.

32. Duan X, Shi X, Li Z, Pei C (2024) Preparation of nitrocellulose/nitro chitosan composite aerogel with mesoporous and significant thermal behavior on the basis of precursors synthesized by homogeneous reaction. Cellul 31(3): 1641-1658.

33. Qian Z, Wang Z, Zhao N, Xu J (2018) Aerogels Derived from Polymer Nanofibers and Their Applications. Macromol Rapid Commun 39(14): 1700724.

34. Kawakami N, Fukumoto Y, Kinoshita T, Suzuki K, K.I (2002) Preparation of Highly Porous Silica Aerogel Thin Film by Supercritical Drying. Jpn J Appl Phys 39 (3A): L182.

35. Pirard R, Blacher S, Brouers F, Pirard JP (1995) Interpretation of mercury porosimetry applied to aerogels. J Mater Res 10(8): 2114-2119.

36. Lee D, Kim J, Kim S, Kim G, Roh J, et al. (2009) Tunable pore size and porosity of spherical polyimide aerogel by introducing swelling method based on spherulitic formation mechanism. Microporous Mesoporous Mater 288: 109546.

37. Ganesan K, Budtova T, Ratke L, Gurikov P, Baudron V, et al. (2018) Review on the Production of Polysaccharide Aerogel Particles. Materials 11(11): 2144.

38. Chen M, Xie J, Xiong C, Wang H (2021) Synthesis and characterization of hexagonal BN-based aerogels for absorbing oils. Ceram Int 47(14): 19970-19977.

39. Groen JC, Peffer LA, Perez-Ramırez J (2023) Pore size determination in modified micro- and mesoporous

materials. Pitfalls and limitations in gas adsorption data analysis. Microporous Mesoporous Mater 60(1): 1-17.

40. Thommes M, Kaneko K, Neimark AV, Olivier JP, Rodriguez-Reinoso F, et al. (2015) Physisorption of gases, with special reference to the evaluation of surface area and pore size distribution (IUPAC Technical Report). Pure Appl Chem 87(9-10): 1051-1069.

41. Beaumont M, Kondor A, Plappert S, Mitterer C, Opietnik M, et al. (2017) Surface properties and porosity of highly porous, nanostructured cellulose II particles. Cellul 24(1): 435-440.

42. Vesel P Riikonen J, Nissinen T, Lehto VP, Slov V (2015) Optimization of thermoporometry measurements to evaluate mesoporous organic and carbon xero-, cryo- and aerogels. Thermochim Acta 621: 81-89.

43. Hao L, Fei X, Peiyun Y, Man Z, Sujan S, et al. (2024) Multifunctional aerogel: A unique and advanced biomaterial for tissue regeneration repair. Mater Design 243: 113091.

44. Maleki H, Shahbazi MA, Montes S, Hosseini SH, Eskandari MR, et al. (2019) Mechanically Strong Silica-Silk Fibroin Bioaerogel: A Hybrid Scaffold with Ordered Honeycomb Micromorphology and Multiscale Porosity for Bone Regeneration. ACS Appl Mater Interfaces 11(19): 17256-17269.

45. Zhao S, Siqueira G, Drdova S, Norris D, Ubert C, et al. (2020) Additive manufacturing of silica aerogels. Nature 584(7821): 387-392.

46. Olsson RT, Azizi Samir, Salazar-Alvarez G, Belova L, Strom V, et al. (2010) Making flexible magnetic aerogels and stiff magnetic nanopaper using cellulose nanofibrils as templates. Nat Nanotechnol 5(8): 584-588.

47. Mazraeh-Shahi TZ, Mousavi A, Shoushtari AR, Bahramian M (2015) Synthesis, pore structure and properties of polyurethane/silica hybrid aerogels dried at ambient pressure. J Ind Eng Chem 21: 797-804.

48. Feinle A, Elsaesser MS, Hüsing N (2016) Sol-gel synthesis of monolithic materials with hierarchical porosity. Chem Soc Rev 45(12): 3377-3399.

49. Franco P, Pessolano E, Belvedere R, Petrella A, De Marco I (2020) Supercritical impregnation of mesoglycan into calcium alginate aerogel for wound healing. J Supercrit Fluids 157: 104711.

50. Van Nguyen TT, Yang GX, Phan AN, Nguyen T, Ho TG, et al. (2022) Insights into the effects of synthesis techniques and crosslinking agents on the characteristics of cellulosic aerogels from Water Hyacinth. RSC Adv 12(30): 19225-19231.

51. Capadona LA, Meador MA, Alunni A, Fabrizio EF, Vassilaras P, et al. (2006) Flexible, low-density polymer crosslinked silica aerogels. Polymer 47(16): 5754-5761.

52. Wang H, Cao M, Zhao HB, Liu JX, Geng CZ, et al. (2020) Double-cross-linked aerogels towards ultrahigh mechanical properties and thermal insulation at extreme environment. Chem Eng J 399: 125698.

53. Zhang X, Li W, Song P, You B, Sun G (2020) Double-cross-linking strategy for preparing flexible, robust, and multifunctional polyimide aerogel. Chem Eng J 381: 122784.

54. Françon H, Wang Z, Marais A, Mystek K, Piper A, et al. (2020) Ambient-Dried, 3D-Printable and Electrically Conducting Cellulose Nanofiber Aerogels by Inclusion of Functional Polymers. Adv Funct Mater 30(12): 1909383.

55. Chen Y, Shafiq M, Liu M, Morsi Y, Mo X (2020) Advanced fabrication for electrospun three-dimensional nanofiber aerogels and scaffolds. Bioact Mater 5 (4): 963-979.

56. Dilamian M, Joghataei M, Ashrafi Z, Bohr C, Mathur S, et al. (2021) From 1D electrospun nanofibers to advanced multifunctional fibrous 3D aerogels. Appl Mater Today 22: 100964.

57. Zhang J, Zheng J, Gao M, Xu C, Cheng Y, et al. (2023) Nacre-Mimetic Nanocomposite Aerogels with Exceptional Mechanical Performance for Thermal Superinsulation at Extreme Conditions. Adv Mater 35(29): 2300813.

58. Shao G, Hanaor DAH, Shen X, Gurlo A (2020) Freeze Casting: From Low-dimensional Building Blocks to Aligned Porous Structures-A Review of Novel Materials, Methods, and Applications. Adv Mater 32(17): 1907176.

59. Aizawa M (2020) How elastic moduli affect ambient pressure drying of poly (methyl silsesquioxane) gels. J Sol-Gel Sci Technol 104(3): 490-496.

60. Nagel Y, Sivaraman D, Neels A, Zimmermann T, Zhao S, et al. (2023) Anisotropic, Strong, and Thermally Insulating 3D-Printed Nanocellulose-PNIPAAM Aerogels. Small Structures n/a(n/a) 2300073.

61. García-Gonzalez CA, Camino-Rey MC, Alnaief M, Zetzl C, Smirnova I (2012) Supercritical drying of aerogels using CO2: Effect of extraction time on the end material textural properties. J Supercrit Fluids 66: 297-306.

62. M´endez DA, Schroeter B, Martínez-Abad A, Fabra MJ, Gurikov P, et al. (2023) Pectin-based aerogel particles for drug delivery: Effect of pectin composition on aerogel structure and release properties. Carbohydr Polym 306: 120604.

63. Zhu H, Yang X, Cranston ED, Zhu S (2016) Flexible and Porous Nanocellulose Aerogels with High Loadings of Metal–Organic-Framework Particles for Separations Applications. Adv Mater 28 (35): 7652-7657.

64. Cui S, Cheng W, Shen X, Fan M, Russell A, et al. (2011) Mesoporous amine modified SiO2 aerogel: A potential CO2 sorbent. Energ Environ Sci 4 (6): 2070-2074.

65. Pirzada T, Ashrafi Z, Xie W, Khan SA (2020) Multifunctional Aerogels: Cellulose Silica Hybrid Nanofiber Aerogels: From Sol-Gel Electrospun Nanofibers to Multifunctional Aerogels. Adv Funct Mater 30(5): 2070031.

66. Zou F, Wang Y, Tang T, Zheng Y, Xie Y, et al. (2023) Synergistic strategy constructed hydrogel-aerogel biphasic gel (HAB-gel) with self-negative-pressure exudate absorption, M2 macrophage-polarized and antibacterial for chronic wound treatment. Chem Eng J 451: 138952.

67. Li F, Xie L, Sun G, Kong Q, Su F, et al. (2019) Resorcinol-formaldehyde based carbon aerogel: Preparation, structure and applications in energy storage devices, Microporous Mesoporous Mater 279: 293-315.

68. Rahmanian V, Pirzada T, Wang S, Khan SA (2021) Cellulose-Based Hybrid Aerogels: Strategies toward Design and Functionality. Adv Mater 33 (51): 2102892.

69. Shang QG, Wang K, Li LG, He Z, Jiang HJ, et al. (2021) A Metallic Ion-Induced Self-Assembly Enabling Nanowire-Based Aerogels. Small 17 (44): 2103406.

70. Yang J, Lu J, Xi S, Wang H, Han D, et al. (2024) Direct 3D print polyimide aerogels for synergy management of thermal insulation, gas permeability and light absorption. J Mater Chem A 112: 456-467.

71. Novak BM, Auerbach D, Verrier C (1994) Low-Density, Mutually Interpenetrating Organic-Inorganic Composite Materials via Supercritical Drying Techniques. Chem Mater 6(3): 282-286.

72. Hense D, Büngeler A, Kollmann F, Hanke M, Orive A, et al. (2021) Self-Assembled Fibrinogen Hydro- and Aerogels with Fibrin-like 3D Structures. Biomacromolecules 22(10): 4084-4094.

73. Zhang S, Zhao K, Zhao J, Liu H, Chen X, et al. (2018) Large-sized graphene oxide as bonding agent for the liquid extrusion of nanoparticle aerogels. Carbon 136: 196-203.

74. Yi G, Tao Z, Fan W, Zhou H, Zhuang Q, et al. (2018) Copper Ion-Induced Self-Assembled Aerogels of Carbon Dots as Peroxidase-Mimicking Nanozymes for Colorimetric Biosensing of Organophosphorus Pesticide. ACS Sustain Chem Eng 12(4): 1378-1387.

75. Ciftci D, Ubeyitogullari A, Huerta RR, Ciftci ON, Flores RA (2017) Lupin hull cellulose nanofiber aerogel preparation by supercritical CO2 and freeze drying. J Supercrit Fluids 127: 137-145.

76. Zhang M, Si Z, Yang G, Cao L, Liu X, et al. (2022) Facile Synthesis of Dual Modal Pore Structure Aerogel with Enhanced Thermal Stability. Coatings 12 (10): 1566.

77. Jung HN, Choi H, Kim SH, Jung WK, Park HH (2023) The effect of surfactant type and concentration on the pore structure of alumina aerogels. J Non Cryst Solids 610: 122325.

78. Shi B, Ma B, Wang C, He H, Qu L, et al. (2021) Fabrication and applications of polyimide nano-aerogels. Compos A Appl Sci Manuf 143: 106283.

79. Konuk PO, Alsuhile AM, Yousefzadeh H, Ulker Z, Bozbag CA, et al. (2023) The effect of synthesis conditions and process parameters on aerogel properties. Front Chem 11: 1294520.

80. White RJ, Brun N, Budarin VL, Clark JH, Titirici MM. (2014) Always Look on the “Light” Side of Life: Sustainable Carbon Aerogels. Chem Sus Chem 7(3): 670-689.