

# Safe Applications of Aerogels

Subjects: [Materials Science](#), [Biomaterials](#)

Contributor: Antonella Caterina Boccia , Alfio Pulvirenti , Carlos A. García-González , Fabia Grisi , Monica Neagu

An increasing number of aerogels as nanostructured highly porous materials are entering the market in every day products, with an attractive portfolio of properties for emerging applications ranging from health care and leisure to electronics, cosmetics, energy, agriculture, food and environmental.

best practices

safety regulatory compendium

aerogels

## 1. Introduction

Aerogels are a special class of nanostructured materials generally with an ultra-light weight and high porosity, associated with tunable physicochemical properties [1]. Kistler reported, for the first time, the term aerogel in 1931, defining it as a low-density, porous solid gel derived from gel [2]. To date, the definition of aerogels lies in a sort of “limbo”, considering that IUPAC defines aerogels as “a gel comprised of microporous solid in which the dispersed phase is gas” [3], but the scientific community stated that aerogels are not strictly microporous solids as there are commonly reported mesoporous and nanofibril aerogels [4]. In the meantime, aerogels cannot be considered nanoforms, based on the REACH Annexes definition [5][6], and they are also exempted from the need to report to national nanomaterials product inventories such as those in France, Belgium, the USA or Canada [7][8]; but, they can be included in the nanomaterials category considering that they are constituted by nanomaterials [9]. Typically, aerogels are obtained through a sol-gel process [10], meaning that a colloidal suspension of precursors was converted by applying a gelling process, after which the replacement of the solvent with gas into materials characterized by a three-dimensional network follows. According to the nature of the solvent occupying the solid scaffold, as well as on the procedure commonly used for the solvent replacement, it is possible to produce: (i) aerogels (usually obtained by CO<sub>2</sub> supercritical drying) [2][11]; (ii) xerogels (usually obtained by atmospheric pressure drying) [12][13]; and (iii) cryogels (usually obtained by freeze drying) [14], which are materials characterized by different properties and are accepted with the general term “aerogel”. The main sources for fabricating the aerogels are silica, alumina and carbon, but synthetic polymers, biopolymers and other organic precursors need to be considered as emerging sources. In recent years, aerogels are increasingly being studied considering the appealing applications in food, for the controlled release of active compounds, biomedical, textile, packaging, energy storage devices, aerospace engineering, and solar-steam generation [15][16][17], as illustrated in **Figure 1**, but the full potential of aerogels is still to be assessed for other technological sectors [18][19]. As materials for biomedical applications, they are able to respond to the requirement for tissue engineering applications, such as in designing implantable cardiovascular devices, as well as for nerve repair implant applications, bone grafting and biosensing [20]. The adaptable surface area, together with the surface functionalization, makes them valuable candidates to be used as a platform for adsorbing and controlling the release of active compounds. For specific administration routes, aerogels are capable to improve the delivery of low water soluble drugs and deliver, in situ, the drug enhancing the bioavailability [21]. Concerning aerogels in textiles, they received attention in this century for producing protective clothing for space exploration, as the first application, and successively for thermal insulation textiles [22]. Recently, the new emerging applications include aerogels as textiles for wound care medical applications [23][24], face masks [25] and tissue engineering applications [26][27], thermal insulating [28], smart clothes, prevention of electromagnetic radiation, protection against chemicals, flame retardancy and treatment of textile process wastes [29][30]. Regarding the environmental applications, aerogels are ideal materials for thermal insulations which can save energy and help to reduce carbon emissions due to their low thermal conductivity. Another aspect to be considered is that aerogels generally possess a high porosity and specific surface area, enabling them to be

ideal materials useful to adsorb toxic molecules or ions in the air and water, which can be applied to protect the environment [31]. As a consequence, the aerogels market has recently seen a surge in the number of patents filed on aerogels, demonstrating the incredible increase on these materials in recent years. Even considering that the market is mainly driven by the increasing demand for construction applications, the new emerging trend, together with increases in R&D investment and a global aerogel market size projected to reach USD 1045 million by 2025, suggests that the market believes aerogels will become increasingly important [32][33].



**Figure 1.** Aerogel-based materials for biomedical, textile, packaging, energy storage devices, solar-steam generation, and aerospace engineering applications.

To date, there is a lack of information concerning the toxicity of aerogels; ecotoxicity and cytotoxicity and regarding the health risk assessment and other regulatory aspects are not extensively addressed as aerogels do not require registration as nanoforms but their nanostructures raise concerns about a possible hazard assessment which needs to be addressed. The reason for this may be partially due to an uncertainty about which aspects should be approached for regulatory purposes. However, producers cannot neglect that even if the toxicity inherent to aerogel exposure is not expected in general, an increased bioactivity may derive from inhalable or ingestible fragments due to their high inner surface area [34]. One of the most critical routes of exposure to aerogel nanoparticles is the unintended inhalation of material dust and the consequent pulmonary deposition, which is an existing scenario in the industrial insulation production of silica and PU-based (PU = polyurethanes) aerogel materials [35], as well as during the installation and removal activities of insulation materials in houses, considering that this is one of the most frequent applications. It is important to keep in mind that for the industrial implementation of aerogels all workers involved in the production process and application of aerogels may be involved in the exposure to these nanostructures and the dispersion into the surrounding environment, and, consequently, global regulation is highly necessary to prevent any risks to human health.

## 2. Risks Assessment of Nanomaterials

## 2.1. Health Risks

As aerogels have different properties than their bulk compounds, there is less knowledge available as to how they will react in an environment with human contact [36] and it would be reasonable to measure the concentration of aerogel particles for better establishing exposure limits and the right safety equipment.

Ultrafine nanoparticles (size less than 100 nm) can be inhaled easily, leading to breathing problems, lung inflammation and distal organ involvement [37]. Ultrafine particles of carbon, silica and titanium are known for causing problems like mesothelioma, pulmonary toxicity, inflammation, genotoxicity and neurotoxicity, DNA damage and human embryo development [38][39][40][41]. The dimension of aerogel nanoparticles can increase the probability of entering into the human bloodstream, together with an increased likelihood of electrochemical reactivity [42].

## 2.2. Safety Aspects of Nanomaterials

The main components of occupational health and safety processes are information gathering, hazard assessment, determination of protection measures, review of the effectiveness of measures, and other documentation [43]. Possible ways of being exposed to nanomaterials are inhalation, dermal absorption and ingestion.

Nanomaterials should be kept in a designated area; cleanliness should be taken care of; and protective gear, like gloves or face masks, should be used. Containers should be labelled with the aerogel material to be used, indicating the properties of the materials. Sealed containers containing the material in free or dry form should be opened in a ventilated hood, fumed hood or closed glove box [44]. Anything previously in touch with the aerogel, meaning the container it was placed in, any wet wipes used to clean it, gloves handling it, masks and so on, is considered contaminated and should be disposed of properly [44]. In the case of protective clothing that can be recovered by cleaning, the effects deriving from disinfection and end-of-life disposal need to be considered in terms of the environmental impacts.

The best way to manage surfaces contaminated by aerogel particles is the adoption of wet wiping or, alternatively, the use of a tack roll mop or strippable decontamination agents [44]. HEPA (High-Efficiency particulate air filter) vacuuming should be used for the capture of airborne particles with diameters below 3  $\mu\text{m}$ .

Before disposal, aerogel materials should be either kept in a labelled waste container or labelled plastic bags and treated as hazardous waste to minimize the aeroparticles' dispersion into the environment, as well as the worker's exposure to the particles [45].

Incineration is one of the most common methods of treating aerogel material waste; additionally, it can be used in soil for construction purposes [46].

## 2.3. Life-Cycle Considerations for the Exposure Assessment and Risk Characterization

Due to the potential release of aerogel particles at different stages (manufacturing, transport, use and disposal), the exposure of the worker, consumer and environment to the nanoparticles should be monitored over the entire life-cycle of the products. In the event that aggregates or agglomerates are formed during a life-cycle step, a(n) (eco)toxicological risk analysis should be engaged considering their potential dissolution or disaggregation, even if the risk of aerogels in these forms is not considered relevant. According to EU recommendations for nanomaterials, all people involved in the exposure to aerogels should consider that "Agglomerated or aggregated particles may exhibit the same properties as the unbound particles" [47] consistent with their potential dissolution or disaggregation, and they have to evaluate the risk due to the potential exposure to constituent particles in the size range of 1–100 nm.

Finally, some studies evaluated the resultant products and production methods of aerogels from an environmental perspective concluding with a positive opinion in terms of net energy, greenhouse gas emissions and less solid waste generation when compared with polyurethane-based materials [48]. A case study also evidenced the beneficial impacts deriving from changing the procedure for aerogel preparation, in terms of reduced CO<sub>2</sub> emissions and pollution in general, as well as in terms of more ecofriendly adopted solvents [49]. Aside from this, the life-cycle consideration cannot neglect the environmental impact deriving from the production of protective masks, HEPA filters, etc.—which are mainly made of polypropylene (PP), polyethylene terephthalate (PET), glass microfiber, or melt blow glass fiber—due to the high energy consumption, high costs and the elevated emitted pollutants involved in their own production, which tremendously limit their wide and sustainable applications.

Furthermore, the toxicity effects on the environment as a result of incidental or natural dispersion of aeroparticles should be considered, also including possible toxic effects due to the chemical's release as this can induce a mismatch in ecosystems and cause a loss of biodiversity. Often, these chemicals are able to leach down the soil, seeping into the water table and killing, as a consequence, aquatic animals and vital soil symbionts, indirectly reaching agro- and animal products and entering the food chain, leading to acute or chronic impacts on human health [50].

## 2.4. Aerogels Disposal

This compendium has the ambition of becoming a successful guideline for safely managing aerogel products; but, considering the fact that a lack of knowledge on how to dispose of aerogel materials affects the literature, a brief paragraph has been introduced to raise awareness within the aerogel community and regulatory offices on the need to address this important issue.

Generally, instruction for aerogel disposal refers to silica-based products, adopting chemical, physical or thermal strategies [51]. Specifically, when a thermal degradation process for either the degradation or recycle step is adopted, the negative impact on the environment linked to the CO<sub>2</sub> emissions should be considered, thus, when possible, this approach should be avoided [52]. Actually, aerogel wastes end up in landfill or in an incinerator, which over time can lead to the release of volatile aeroparticles in the atmosphere, as well as to the deposit of and significant accumulation of dust which over time can affect the performance and safety of disposal plants, with direct and adverse environmental and human health impacts. These remarks should also be extended to bio-based aerogels, which are generally considered to be environmentally friendly and non-harmful because when they are disposed in landfills they can be subjected to breakage, thus emitting dust which negatively affects the environment and human health. Furthermore, considering aerogels can potentially contain additives [51], industrial waste landfills should be advised on the right waste procedures to be taken into account.

---

## References

1. Zubair, N.A.; Abouzari-Lotf, E.; Mahmoud Nasef, M.; Abdullah, E.C. Aerogel-based materials for adsorbent applications in material domains. *E3S Web Conf.* 2019, 90, 1003.
2. Kistler, S.S. Coherent expanded aerogels and jellies. *Nature* 1931, 127, 741.
3. McNaught, A.D.; Wilkinson, A. The IUPAC Compendium of Chemical Terminology. In *International Union of Pure and Applied Chemistry*, 2nd ed.; The “Gold Book”; Blackwell Scientific: Oxford, UK, 1997; ISBN 0-9678550-9-8.
4. Sonu, S.S.; Nisha, R.; Indu, C. Multifunctional Aerogels: A comprehensive review on types, synthesis and applications of aerogels. *J. Sol-Gel Sci. Technol.* 2023, 105, 324–336.

5. European Commission Recommendation on the Definition of Nanomaterial, Definition of Nanomaterial—European Observatory for Nanomaterials. 2011. Available online: <https://euon.echa.europa.eu/definition-of-nanomaterial> (accessed on 26 August 2023).
6. Mech, A.; Wohlleben, W.; Ghanem, A.; Hodoroaba, V.D.; Weigel, S.; Babick, F.; Brüngel, R.; Friedrich, C.M.; Rasmussen, K.; Rauscher, H. Nano or Not Nano? A Structured Approach for Identifying Nanomaterials according to the European Commission's Definition. *Small* 2020, 16, 2002228.
7. Ministère de l'Environnement, de l'Énergie et de la Mer. *Éléments Issus des d'Eclerations des Substances a l'état Nanoparticulaire—Exercice 2016: Rapport d'étude*. Direction Générale de la Prévention des Risques, Service des Risques Sanitaires Liés à l'Environnement, des Déchets et des Pollutions Diffuses. 2016. Available online: <https://www.ecologie.gouv.fr/sites/default/files/2016-11%20-%20Rapport%20R-nano%202016.pdf> (accessed on 3 July 2023).
8. Wigger, H.; Wohlleben, W.; Nowack, B. Redefining environmental nanomaterial flows: Consequences of the regulatory nanomaterial definition on the results of environmental exposure models. *Environ. Sci. Nano* 2018, 5, 1372–1385.
9. Rauscher, H.; Kestens, V.; Rasmussen, K.; Linsinger, T.; Stefaniak, E.; European Commission; Joint Research Centre. *Guidance on the Implementation of the Commission Recommendation 2022/C 229/01 on the Definition of Nanomaterial*; Publications Office of the European Union: Luxembourg, 2023; Available online: <https://data.europa.eu/doi/10.2760/143118> (accessed on 27 August 2023).
10. Dervin, S.; Pillai, S.C. An Introduction to Sol-Gel Processing for Aerogels. In *Sol-Gel Materials for Energy, Environment and Electronic Applications*; Pillai, S.C., Hehir, S., Eds.; Springer International Publishing: Berlin/Heidelberg, Germany, 2017; pp. 1–22.
11. Deshpande, R.; Smith, D.M.; Brinker, C.J. Preparation of High Porosity Xerogels by Chemical Surface Modification. U.S. Patent US5565142A, 15 October 1996.
12. Ziegler, C.; Wolf, A.; Liu, W.; Herrmann, A.K.; Gaponik, N.; Eychmüller, A. Modern inorganic aerogels. *Angew. Chem. Int. Ed. Engl.* 2017, 56, 13200–13221.
13. Smirnova, I.; Gurikov, P. Aerogels in chemical engineering: Strategies toward tailor-made aerogels. *Annu. Rev. Chem. Biomol. Eng.* 2017, 8, 307–334.
14. Chen, H.-B.; Hollinger, E.; Wang, Y.-Z.; Schiraldi, D.A. Facile fabrication of poly(vinyl alcohol) gels and derivative aerogels. *Polymer* 2014, 55, 380–384.
15. Zhu, F. Starch based aerogels: Production, properties and applications. *Trends Food Sci. Technol.* 2019, 89, 1–10.
16. Storer, D.P.; Phelps, J.L.; Wu, X.; Owens, G.; Khan, N.I.; Xu, H. Graphene and Rice-Straw-Fiber-Based 3D Photothermal Aerogels for Highly Efficient Solar Evaporation. *ACS Appl. Mater. Interfaces* 2020, 12, 15279–15287.
17. Lee, K.; Shabnam, L.; Faisal, S.N.; Gomes, V.G. Aerogel from fruit biowaste produces ultracapacitors with high energy density and stability. *J. Energy Storage* 2020, 27, 101152.
18. García-González, C.A.; Budtova, T.; Durães, L.; Erkey, C.; Del Gaudio, P.; Gurikov, P.; Koebel, M.; Liebner, F.; Neagu, M.; Smirnova, I. An Opinion Paper on Aerogels for Biomedical and Environmental Applications. *Molecules* 2019, 24, 1815.

19. Okeke, E.S.; Chidike Ezeorba, T.P.; Mao, G.; Chen, Y.; Feng, W.; Wu, X. Nano-enabled agrochemicals/materials: Potential human health impact, risk assessment, management strategies and future prospects. *Environ. Pollut.* 2022, 295, 118722.
20. Smirnova, I. Pharmaceutical applications of aerogels. In *Aerogels Handbook*; Aegerter, M.A., Leventis, N., Koebel, M.M., Eds.; Springer: New York, NY, USA, 2011.
21. García-González, C.A.; Jin, M.; Gerth, J.; Alvarez-Lorenzo, C.; Smirnova, I. Polysaccharide-based aerogel microspheres for oral drug delivery. *Carbohydr. Polym.* 2015, 117, 797–806.
22. Health and Safety Executive. EH40/2005 Workplace Exposure Limits. In *Containing the List of Workplace Exposure Limits for Use with the Control of Substances Hazardous to Health Regulations 2002 (as Amended)*, 4th ed.; TSO (The Stationery Office), Part of Williams Lea: Norwich, UK, 2020; ISBN 978-0-7176-6733-8. Available online: <https://www.hse.gov.uk/pUbns/priced/eh40.pdf> (accessed on 3 July 2023).
23. Stergar, J.; Maver, U. Review of aerogel-based materials in biomedical applications. *J. Sol-Gel Sci. Technol.* 2016, 77, 738–752.
24. Batista, M.P.; Gonçalves, V.S.S.; Gaspar, F.B.; Nogueira, I.D.; Matias, A.A.; Gurikov, P. Novel alginate-chitosan aerogel fibres for potential wound healing applications. *Int. J. Biol. Macromol.* 2020, 156, 773–782.
25. Uhljar, L.É.; Ambrus, R. Electrospinning of Potential Medical Devices (Wound Dressings, Tissue Engineering Scaffolds, Face Masks) and Their Regulatory Approach. *Pharmaceutics* 2023, 15, 417.
26. Yahya, E.B.; Jummaat, F.; Amirul, A.A.; Adnan, A.S.; Olaiya, N.G.; Abdullah, C.K.; Rizal, S.; Mohamad Haafiz, M.K.; Khalil, H.P.S.A. A Review on Revolutionary Natural Biopolymer-Based Aerogels for Antibacterial Delivery. *Antibiotics* 2020, 9, 648.
27. Lázár, I.; Čelko, L.; Menelaou, M. Aerogel-Based Materials in Bone and Cartilage Tissue Engineering—A Review with Future Implications. *Gels* 2023, 9, 746.
28. Li, C.; Chen, Z.; Dong, W.; Lin, L.; Zhu, X.; Liu, Q.; Zhang, Y.; Zhai, N.; Zhou, Z.; Wang, Y.; et al. A review of silicon-based aerogel thermal insulation materials: Performance optimization through composition and microstructure. *J. Non-Cryst. Solids* 2021, 553, 120517.
29. Tafreshi, O.A.; Mosanenzadeh, S.G.; Karamikamkar, S.; Saadatnia, Z.; Park, C.B.; Naguib, H.E. A review on multifunctional aerogel fibers: Processing, fabrication, functionalization, and applications. *Mater. Today Chem.* 2022, 23, 100736.
30. Zuo, X.; Fan, T.; Qu, L.; Zhang, X.; Miao, J. Smart multi-responsive aramid aerogel fiber enabled self-powered fabrics. *Nano Energy* 2022, 101, 107559.
31. Maleki, H. Recent advances in aerogels for environmental remediation applications: A review. *Chem. Eng. J.* 2016, 300, 98–118.
32. Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs. *Aerogels Getting Their Second Wind, Case of Study*; Business Innovation Observatory; European Commission: Brussels, Belgium, 2015.
33. MarketsandMarkets. *Aerogel Market—Global Forecast 2025*; Market Research Report; MarketsandMarkets: Pune, India; Available online: <https://www.marketsandmarkets.com/Market-Reports/aerogel-market-714.html> (accessed on 1 July 2023).
34. Steinhauser, K.G.; Sayre, P. Reliability of methods and data for regulatory assessment of nanomaterial risks. *NanoImpact* 2017, 7 (Suppl. C), 66–74.

35. Keller, J.G.; Wiemann, M.; Gröters, S.; Werle, K.; Vennemann, A.; Landsiedel, R.; Wohlleben, W. Aerogels are not regulated as nanomaterials, but can be assessed by tiered testing and grouping strategies for nanomaterials. *Nanoscale Adv.* 2021, 3, 3881–3893.
36. Kaur, A.; Singh, H. Nanomaterials in Environment: Sources, Risk Assessment, and Safety Aspect. In *Advanced Functional Nanoparticles “Boon or Bane” for Environment Remediation Applications. Environmental Contamination Remediation and Management*, 1st ed.; Kumar, R., Kumar, R., Chaudhary, S., Eds.; Springer: Cham, Switzerland, 2023; pp. 75–93.
37. CEN/TR 13205-3:2014; Workplace Exposure—Assessment of Sampler Performance for Measurement of Airborne Particle Concentrations—Part 3: Analysis of Sampling Efficiency Data. Available online: <https://store.uni.com/cen-tr-13205-3-2014> (accessed on 6 September 2023).
38. Dominici, F.; Peng, R.D.; Bell, M.L.; Pham, L.; McDermott, A.; Zeger, S.L.; Samet, J.M. Fine particulate air pollution and hospital admission for cardiovascular and respiratory diseases. *JAMA* 2006, 295, 1127–1134.
39. Baeza-Squiban, A.; Vranic, S.; Boland, S. Fate and health impact of inorganic manufactured nanoparticles. In *Nanomaterials: A Danger or a Promise?* Brayner, R., Fiévet, F., Coradin, T., Eds.; Springer: London, UK, 2013; Volume 9, pp. 245–268.
40. Zhang, L.; Jiang, Y.; Ding, Y.; Povey, M.; York, D. Investigation into the antibacterial behaviour of suspensions of ZnO nanoparticles (ZnO nanofluids). *J. Nanopart. Res.* 2006, 9, 479–489.
41. Shukla, R.; Sharma, V.; Pandey, A.; Singh, S.; Sultana, S.; Dhawan, A. ROS-mediated genotoxicity induced by titanium dioxide nanoparticles in human epidermal cells. *Toxicol. In Vitro* 2011, 25, 231–241.
42. Sudha, P.N.; Sangeetha, K.; Vijayalakshmi, K.; Barhoum, A. Nanomaterials history, classification, unique properties, production and market. In *Micro and Nano Technologies, Emerging Applications of Nanoparticles and Architecture Nanostructures*; Barhoum, A., Makhlof, A.S.H., Eds.; Elsevier: Amsterdam, The Netherlands, 2018; pp. 341–384.
43. Del Castillo, A.M.P. *Nanomaterials and Workplace Health&Safety: What Are the Issues for Workers?* European Trade Union Institute: Brussels, Belgium, 2013.
44. Seal, S.; Karn, B. Safety aspect of nanotechnology-based activity. *Saf. Sci.* 2014, 63, 217–225.
45. Dhawan, A.; Shanker, R.; Das, M.; Gupta, K. Guidance for safe handling of nanomaterials. *J. Biomed. Nanotechnol.* 2011, 7, 218–224.
46. Silva, G.L.; Viana, C.; Domingues, D.; Vieira, F. Risk assessment and health, safety, and environmental management of carbon nanomaterials. In *Nanomaterials—Toxicity, Human Health and Environment*; Clichici, S., Filip, A., Do Nascimento, G.M., Eds.; IntechOpen: London, UK, 2019; Available online: <https://www.intechopen.com/books/nanomaterials-toxicity-human-health-and-environment/risk-assessment-and-health-safety-and-environmental-management-of-carbon-nanomaterials> (accessed on 6 September 2023).
47. *Human Health and Environmental Exposure Assessment and Risk Characterisation of Nanomaterials—Best Practice for REACH Registrants; Third GAARN Meeting*; European Chemicals Agency: Helsinki, Finland, 2013; Available online: [https://echa.europa.eu/documents/10162/788325/best\\_practices\\_human\\_health\\_environment\\_nano\\_3rd\\_en.pdf/a368fe40-4673-a041-83b63cc9f50b?t=1395828950292](https://echa.europa.eu/documents/10162/788325/best_practices_human_health_environment_nano_3rd_en.pdf/a368fe40-4673-a041-83b63cc9f50b?t=1395828950292) (accessed on 27 August 2023).
48. Karatum, O.; Bhuiya, M.M.H.; Carroll, M.K.; Anderson, A.M.; Plata, D.L. *Life Cycle Assessment of Aerogel Manufacture on Small and Large Scales: Weighing the Use of Advanced Materials in Oil Spill Remediation.*

J. Ind. Ecol. 2018, 22, 1365–1377.

49. Huber, L.; Zhao, S.; Malfait, W.J.; Vares, S.; Koebel, M.M. Fast and Minimal-Solvent Production of Superinsulating Silica Aerogel Granulate. *Angew. Chem. Int. Ed.* 2017, 56, 4753–4756.
50. Brühl, C.A.; Zaller, J.G. Biodiversity decline as a consequence of an inappropriate environmental risk assessment of pesticides. *Front. Environ. Sci.* 2019, 7, 177.
51. Vareda, J.P.; García-Gonzalez, C.A.; Valente, A.J.M.; Simón-Vázquez, R.; Stipetic, M.; Durães, L. Insights on toxicity, safe handling and disposal of silica aerogels and amorphous nanoparticles. *Environ. Sci. Nano* 2021, 8, 1177–1195.
52. Cabrera, F.C. Eco-friendly polymer composites: A review of suitable methods for waste management. *Polym. Compos.* 2021, 42, 2653–2677.

---

Retrieved from <https://encyclopedia.pub/entry/history/show/115583>