



A Comprehensive Review Of Nanosponges: Materials, Synthesis, And Space Science Applications

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Abstract

Nanosponges, a novel class of porous nanomaterials, have garnered significant attention due to their high surface area, tunable porosity, and remarkable adsorption properties. These unique characteristics make them highly versatile for a range of applications, including environmental remediation, drug delivery, catalysis, and energy storage. In this review, we explore the fundamental attributes of nanosponges, the essential building blocks utilized in their synthesis, and the diverse fabrication techniques employed to tailor their structural and functional properties. A key focus is placed on their emerging role in space science, where nanosponges have shown great potential in addressing critical challenges such as water purification, gas capture, radiation shielding, and controlled drug delivery for astronauts. Their ability to efficiently trap and release molecules makes them promising materials for sustainable resource management in extraterrestrial environments. Furthermore, advancements in nanosponges technology offer prospects for developing lightweight, high-performance materials suitable for space applications. By critically examining the current research landscape, we provide a comprehensive overview of nanosponges, highlighting their advantages, existing limitations, and the future directions necessary for optimizing their performance. The insights presented in this review aim to guide the development of next-generation nanosponges, fostering innovative solutions for both terrestrial and space-based applications.

Keywords: Nanosponges, Porous Nanomaterials, Synthesis Strategies, Adsorption, Space Science, Water Purification, Gas Capture, Radiation Shielding, Drug Delivery, Extraterrestrial Sustainability

1. Introduction

Nanosponges, a class of porous nanoparticles, have emerged as one of the most exciting materials in recent years due to their unique combination of properties, which include high surface area, tunable porosity, and biocompatibility [1]. These materials are garnering attention across a range of fields, from drug delivery and biomedicine to environmental remediation and space science. As nanotechnology continues to evolve, the versatility of nanosponges and their potential for diverse applications make them a subject of intense research, particularly when considering their suitability for extreme environments like those found in space [2]. Nanosponges are a type of cross-linked polymeric material characterized by their sponge-like architecture, which gives them a highly porous structure that can encapsulate a wide range of molecules, including drugs, proteins, and even gases. Their versatility is rooted in the ability to fine-tune their synthesis methods, allowing for the manipulation of their size, porosity, and surface chemistry. These features make nanosponges particularly effective as carriers for controlled release applications, including targeted drug delivery systems, where their high surface area facilitates loading of large amounts of active compounds [3]. The development of nanosponges began with the desire to overcome the limitations of traditional drug delivery systems, which often face challenges such as poor solubility, lack of specificity, and issues with

the controlled release of therapeutic agents. In contrast, nanosponges offer a unique advantage due to their structural properties that allow for the encapsulation of a variety of compounds, as well as the ability to release them in a controlled manner over time [4]. Their polymeric nature and ease of modification make them ideal candidates for a wide range of biomedical applications, from targeted therapies for cancer to the development of nanodevices for diagnostic purposes.

Nanosponges are typically created through a process known as "cross-linking," where polymer chains are chemically bonded to form a three-dimensional network. This process results in a material that is not only porous but also stable, resistant to degradation, and capable of withstanding environmental conditions. Several materials are used to create nanosponges, including biodegradable polymers such as poly (lactic-co-glycolic acid) (PLGA), as well as more robust synthetic polymers like polyvinyl alcohol (PVA) and cyclodextrin-based polymers [5]. The choice of material significantly influences the properties of the resulting nanosponges, such as their biodegradability, drug-loading capacity, and release kinetics. One of the key factors driving research in nanosponges is their potential for space science applications. Space missions, particularly long-duration ones, face unique challenges that traditional materials often struggle to address. For instance, astronauts in space must contend with a microgravity environment, increased radiation exposure, and limited access to medical supplies. These factors pose significant challenges for sustaining human health during extended missions, such as those to Mars or beyond. In this context, nanosponges offer promising solutions to some of these challenges. Their ability to encapsulate and release drugs in a controlled manner makes them ideal for use in space medicine, where astronauts may require on-demand treatments for a variety of health conditions. Furthermore, nanosponges have been proposed as potential solutions for mitigating the effects of radiation exposure in space, by providing a means to deliver radioprotective agents that can protect cells from damage [6].

Beyond space medicine, nanosponges also hold great promise for use in other aspects of space science, including environmental monitoring, waste management, and the development of novel materials for spacecraft construction. For example, the porous structure of nanosponges could be employed to capture toxic gases or pollutants in confined spaces, providing a means of maintaining a safe and breathable environment for astronauts. In waste management, nanosponges can potentially be used to absorb hazardous materials, preventing contamination and reducing the environmental footprint of space missions [7]. Additionally, the development of nanosponges with specific surface properties may lead to the creation of new materials for advanced space exploration technologies, such as energy-efficient thermal insulation or radiation-resistant shielding. Despite their potential, the use of nanosponges in space science presents several challenges. The extreme conditions of space, such as radiation, vacuum, and temperature fluctuations, demand that materials used in space exploration exhibit exceptional stability and performance. Furthermore, the lack of gravity in space can affect the behavior of nanoparticles in ways that are not fully understood. As a result, further research is needed to optimize the synthesis of nanosponges for space applications, ensuring that they are not only effective but also safe and reliable in these harsh environments [8].

In addition to space science, the versatility of nanosponges also extends to other fields, such as environmental science, where they are used for water purification, air filtration, and soil decontamination. In the pharmaceutical industry, nanosponges are being explored as carriers for controlled drug release, as well as for the targeted delivery of bioactive agents. Their ability to improve the solubility and stability of drugs, especially those with poor bioavailability, has sparked significant interest in their use for enhancing the efficacy of various therapies [9]. The growing body of research on nanosponges reflects their potential to revolutionize a variety of fields. As our understanding of nanotechnology continues to advance, it is likely that nanosponges will play an increasingly important role in addressing some of the most pressing challenges in science and technology, including those in the harsh and unforgiving environment of space. In this review, we will explore the salient features of nanosponges, the building blocks used in their synthesis, the various techniques employed in their preparation, and their potential applications in space science. By examining the current state of research on nanosponges, we aim to provide a comprehensive overview of this exciting material, highlighting both its challenges and its vast potential for future innovations.

2. Salient features of Nanosponges

Nanosponges are an emerging class of nanoscale drug delivery systems known for their distinctive three-dimensional, porous structure, typically measuring less than one micron in size, with pore diameters ranging between 1 and 2 nanometers [10]. Their highly porous architecture enables them to encapsulate a diverse range of therapeutic agents, including hydrophilic and hydrophobic drugs, making them a versatile

platform for drug delivery. One of the key advantages of nanosponges is their ability to enhance the solubility of poorly water-soluble drugs, thereby improving their bioavailability and therapeutic effectiveness [11]. This property is particularly beneficial in cases where conventional drug formulations face solubility challenges, limiting their absorption and bioactivity.

A significant feature of nanosponges is their capacity to regulate drug release in a controlled and targeted manner. By modulating drug action duration and residence time, they help achieve sustained therapeutic effects while minimizing adverse side effects. Their composition, made from biodegradable and bioerodible polymers, ensures stability across a wide range of temperature and pH conditions, reducing toxicity concerns and enhancing biocompatibility. The efficiency of drug encapsulation depends on the structural voids present within the nanosponges, as well as the molecular size of the drug being incorporated. This ability to entrap and protect bioactive molecules extends beyond small-molecule drugs to larger biomolecules such as enzymes, proteins, vaccines, and antibodies, highlighting their potential for various biomedical applications. Additionally, nanosponges are suitable for both oral and topical drug delivery, providing flexibility in their administration routes [12].

Beyond pharmaceutical applications, nanosponges have shown promise in diverse fields, including environmental remediation. Their high absorption efficiency makes them effective in water purification, metal ion removal, wastewater treatment, and gas adsorption. Their ability to act as sensors further broadens their scope, offering applications in detecting environmental contaminants and pollutants. Furthermore, nanosponges play a crucial role in addressing oil spills by efficiently absorbing hydrocarbons, contributing to ecosystem health and sustainability [13]. Given their multifunctional nature, nanosponges continue to attract interest in drug delivery, biotechnology, and environmental sciences, offering innovative solutions for both medical and industrial challenges.

3. Building Blocks for Nanosponges Synthesis

A multitude of substances has demonstrated encouraging outcomes and can be employed for the synthesis of Nanosponges, contingent upon the specific type of Nanosponges desired and the requisite level of crosslinking. The fundamental constituents of nanosponges predominantly encompass polymers, copolymers, cross-linking agents, and particular solvents, which collectively establish a porous architecture that enables the regulated release and targeted delivery of pharmaceuticals or contaminants. These configurations are meticulously engineered to encapsulate an array of substances, rendering them adaptable for utilization in both drug delivery systems and environmental remediation efforts. Different components used in the preparation of nanosponges are discussed below

3.1. Polymers

Polymers are macromolecules consisting of repetitive structural units. In the preparation of nanosponges, they function as the fundamental constituents, facilitating the development of a three-dimensional architecture through crosslinking, which is critically important [14]. Generally, the polymers utilized in the synthesis of nanosponges can be classified into synthetic and organic (natural) polymers, each presenting unique advantages and applications as delineated in Table 1.

Table 1: Overview of synthetic and natural polymers with their key properties and applications in biomedical and environmental fields

Polymer Type	Polymer Name	Key Properties	Common Applications	References
Synthetic Polymers	Polycaprolactone (PCL)	Biodegradable, hydrophobic, slow degradation	Controlled drug release, tissue engineering	Dash et al., 2012 [15]
	Poly(lactic-co-glycolic acid) (PLGA)	FDA-approved, tunable degradation rate	Drug delivery, cancer therapy	Dash et al., 2013[15]
	Polyurethane	Strong mechanical stability, customizable porosity	Drug carriers, environmental applications	Song et al., 2011 [16]

	Hyper-crosslinked Polystyrene	High surface area, excellent adsorption ability	Water purification, pollutant removal	Castaldo et al., 2010[17]
	Poly (methyl methacrylate) (PMMA)	Biocompatible, rigid, non-biodegradable	Drug carriers, biosensors	Koh et al., 2021[18]
	Polyvinyl Alcohol (PVA)	Water-soluble, biocompatible, highly stable	Wound healing, drug delivery	Jin et al., 2021 [19]
	Poly(ϵ-caprolactone-co-lactide)	Slow degradation, flexible	Sustained drug release, regenerative medicine	Dash et al., 2013[15]
Natural (Organic) Polymers	Cyclodextrins (CDs)	Hydrophobic cavity, high drug-loading ability	Drug solubilization, sustained release	Song et al., 2011[16]
	Chitosan	Biodegradable, antimicrobial, mucoadhesive	Mucosal drug delivery, wound healing	Koh et al., 2021[18]
	Alginate	Natural gel-forming ability, highly biocompatible	Drug encapsulation, wound dressing	Koh et al., 2021[18]
	Gelatin	Flexible, biodegradable, tissue-friendly	Drug carriers, tissue engineering	Dash et al., 2013 [15]
	Cellulose Derivatives (Ethyl Cellulose, HPMC)	Biocompatible, excellent film-forming properties	Controlled drug release, drug coatings	Castaldo et al., 2010[17]
	Pectin	Gel-forming, colon-targeted drug delivery	Oral drug release, nutraceuticals	Koh et al., 2021[18]
	Starch	Natural, hydrophilic, modifiable structure	Drug carriers, wound healing, pollutant absorption	Dash et al., 2013[15]
	Modified Starch (Carboxymethyl Starch, Cyclodextrin-Starch Complexes)	Enhanced solubility, better drug release control	Sustained drug release, biomedicine	Song et al., 2011[16]

3.2. Copolymers

Copolymers are defined as polymers that consist of two or more distinct monomeric units. In the synthesis of nanosponges, these materials play a critical role in regulating the stability, uniformity, and charge characteristics of nanoparticles, thereby augmenting their efficacy across a range of applications by offering steric stabilization and promoting interactions with the nanoparticle interface [19]. The composition of the nanosponges gives use not only to synthetic copolymers but also to natural copolymers, depending on the specific requirements for distinct applications. Synthetic copolymers favor reproducible and customizable attributes such as controlled degradation rates and drug release profiles, with poly(lactide-co-glycolide) (PLGA) and poly(caprolactone-co-lactide) being prime examples. These syntheses are good for use where controlled drug delivery and tissue engineering are concerned. Conversely, natural copolymers such as chitosan and gelatin are greatly valued for their biocompatibility and biodegradability and find applications in biomedicine where minimizing toxicity and immune response is of prime importance [20]. The choice then between synthetic or natural copolymers ultimately would depend on the specific demands of the envisaged application while weighing the performance aspects of the materials against their biocompatibility and aimed release characteristics of the active agents.

3.3. Crosslinkers

In the preparation of nanosponges, crosslinkers play a crucial role in the formation and stabilization of the nanostructured system. These crosslinkers are typically small molecules or polymers that covalently bond the polymer chains of nanosponges, creating a three-dimensional network that enhances their polymeric network, porosity, mechanical strength, structural integrity, loading capacity, and controlled release properties [21]. Various crosslinkers, including epichlorohydrin (ECH), citric acid, glutaraldehyde, sodium tripolyphosphate (STPP), phosphoryl chloride (POCl_3), diepoxybutane (DEB), divinyl sulfone (DVS), toluene-2,4-diisocyanate (TDI), urea-formaldehyde, succinic anhydride, and boric acid, are commonly employed based on the desired properties of the nanosponge. ECH and glutaraldehyde are widely used due to their ability to form strong covalent bonds, enhancing mechanical stability and drug-loading capacity [22]. Citric acid and succinic anhydride, being biodegradable crosslinkers, are preferred for eco-friendly applications, while STPP and POCl_3 improve resistance to enzymatic degradation. Boric acid, on the other hand, interacts with hydroxyl groups to form borate ester linkages, providing tunable swelling properties and biocompatibility. The choice of crosslinker significantly impacts the nanosponge's performance, influencing factors such as drug release kinetics, stability, and environmental sustainability, making it essential to select an appropriate crosslinking agent based on the intended application [23]. The table 2 below provides an overview of the different crosslinkers used in the preparation of nanosponges, detailing their chemical bonding mechanisms, advantages, and specific applications in various fields.

Table 2: Common Crosslinkers, Their Bond Types, Advantages, and Applications in Biomedical and Environmental Fields

Crosslinker	Type of Bond Formed	Key Advantages	Applications	Reference
Epichlorohydrin (ECH)	Ether linkages	Strong mechanical stability, high drug-loading	Drug delivery, adsorption of pollutants	Sikder et al., 2019 [24]
Citric Acid	Ester bonds	Biodegradable, eco-friendly	Biomedical, food industry	Pooja et al 2025 [25]
Glutaraldehyde	Schiff base, acetal bonds	Strong crosslinking, improves durability	Drug delivery, enzyme immobilization	Jia et al., 2021 [26]
Sodium Tripolyphosphate (STPP)	Ionic crosslinking	Enhances stability and biocompatibility	Chitosan-based nanosponges, biomedicine	Wu et al., 2020 [27]
Phosphoryl Chloride (POCl_3)	Phosphate ester bonds	Increases resistance to enzymatic degradation	Tissue engineering, sustained drug release	Pooja et al 2025 [25]
Diepoxybutane (DEB)	Ether bonds	Enhances water resistance, durability	Coatings, pharmaceutical applications	Jia et al., 2021 [26]
Divinyl Sulfone (DVS)	Covalent crosslinking	Improves porosity and stability	Adsorption, drug encapsulation	Sikder et al., 2019 [24]
Toluene-2,4-diisocyanate (TDI)	Urethane linkages	High mechanical strength, hydrophobicity	Industrial and biomedical applications	Komez et al., 2019 [28]
Urea-Formaldehyde	Covalent network	High crosslinking density, thermosetting	Packaging, drug release	Wu et al., 2020 [27]
Succinic Anhydride	Ester bonds	Biodegradable, improves water resistance	Sustainable nanosponges, medical uses	Pooja et al 2025 [25]
Boric Acid	Borate ester linkages	Tunable swelling, biocompatibility	Controlled drug release, wastewater treatment	Komez et al., 2019 [28]

3.4. Solvents

Solvents are essential in the preparation of nanosponges as they aid in dissolving the polymeric materials and ensuring efficient crosslinking for the formation of nanosponge networks. Water is one of the most widely used solvents due to its eco-friendliness, non-toxicity, and biodegradability. It is especially suitable for pharmaceutical and biomedical applications where biocompatibility is a critical requirement. Water is

often preferred in formulations aimed at controlled drug delivery as it supports the formation of hydrophilic nanosponge structures. Additionally, ethanol is commonly used as a solvent due to its ability to dissolve both hydrophilic and hydrophobic compounds, allowing for the preparation of nanosponges with diverse properties. It is also favored in combination with other solvents to optimize the solubility of different polymeric materials during synthesis. Dimethyl sulfoxide (DMSO) is another solvent of choice, particularly when working with highly hydrophobic polymers or crosslinkers, as it is known for its high solubility power [29].

In addition to these, acetone is frequently employed in the preparation of nanosponges due to its high volatility, which is beneficial during the solvent evaporation stage. Acetone is commonly used when rapid solvent removal is desired, ensuring that the nanosponge matrix forms efficiently. Chloroform is utilized for dissolving certain biopolymers, such as polyvinyl alcohol (PVA), which are integral in the creation of stable nanosponges with enhanced mechanical properties. Chloroform is particularly effective in maintaining the integrity of polymeric solutions during crosslinking. Moreover, tetrahydrofuran (THF) is a versatile solvent used to dissolve hydrophobic polymers and facilitate the formation of nanosponge structures, especially when high drug-loading capacity is desired. The choice of solvent plays a pivotal role in determining the morphology, surface characteristics, and release profiles of nanosponges, making it a critical factor in their design and application.

4. Techniques for Nanosponge Preparation:

Nanosponge synthesis involves various advanced techniques that enable the formation of porous, nanoscale structures with high surface area and tunable properties. These techniques typically rely on polymeric or inorganic precursors, which undergo processes such as crosslinking, precipitation, or self-assembly to create a stable nanosponge network. Factors such as reaction conditions, choice of solvents, catalysts, temperature, and processing methods play a crucial role in determining the final characteristics of the nanosponges, including their porosity, size, and functional properties. The different methods for the preparation of nanosponges are discussed below [30].

4.1. Solvent method

The solvent method is a widely used approach for preparing nanosponges, which are cross-linked polymeric nanocarriers designed for drug delivery applications. This method involves dissolving a polymer such as β -cyclodextrin, poly(lactic-co-glycolic acid) (PLGA), or polyvinyl alcohol (PVA) in an organic solvent like dimethyl sulfoxide (DMSO), acetone, or ethanol. A cross-linking agent, such as diphenyl carbonate or glutaraldehyde, is then introduced to the polymer solution under controlled stirring, facilitating the formation of covalent bonds between polymer chains and leading to the formation of a nanosponge structure. After the cross-linking reaction is complete, the mixture is subjected to solvent removal through evaporation or filtration, followed by washing to eliminate any unreacted materials [31]. The final nanosponge particles are then dried using vacuum or lyophilization to obtain a stable and free-flowing powder suitable for pharmaceutical application (Fig1).

Nanosponges prepared using the solvent method exhibit significant advantages, including improved drug stability, enhanced solubility of poorly water-soluble drugs, and controlled drug release properties. The porous nature of the nanosponge matrix allows for efficient drug encapsulation, making them ideal for sustained-release formulations [32].

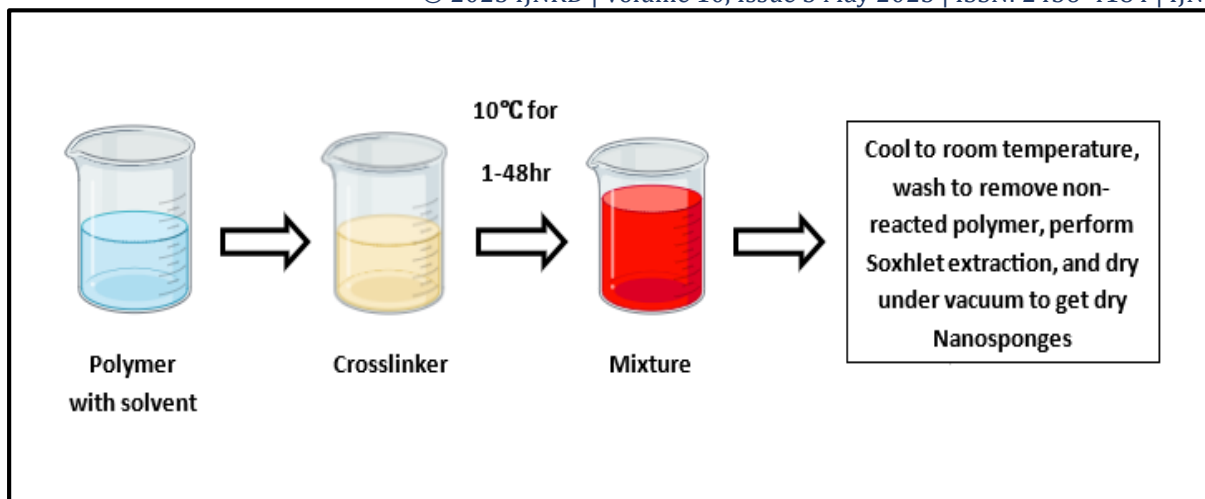


Fig 1: Schematic representation of nanosponge synthesis involving polymer dissolution, crosslinking reaction at 10°C for 1–48 hours, and post-processing steps including washing, Soxhlet extraction, and vacuum drying to obtain dry nanosponges.

4.2. Ultrasound-assisted method

In this method, nanosponges are synthesized through a reaction between polymers and cross-linkers without the need for solvents, utilizing sonication. The resulting nanosponges are spherical and uniform in size. In this procedure, the polymer is combined with cross-linkers, such as di-phenyl carbonate or pyromellitic anhydride, at a specific molar ratio in a flask. Once the mixture cools, it is heated to 90°C in a water-filled ultrasonic bath. After the reaction, the mixture is rinsed with water to remove any unreacted polymer, followed by a prolonged Soxhlet extraction with ethanol for purification. This method, which does not require solvents, can also be employed for creating nanosponges through sonication, allowing for a simple reaction between the polymer and cross-linkers. Trotta et al. detailed the process using this approach, where a combination of β -cyclodextrin and diphenyl carbonate was placed in a flask, which was then subjected to ultrasonic heating at 90°C for 5 hours (Fig2). The crystallization and purification steps were similar to those in melt/solvent methods. High-energy input methods, such as probe sonication, may also be used in place of ultrasonication. The major advantage of this approach is the elimination of organic solvents, making it a safer and more environmentally friendly technique for drug delivery. Taleb et al. demonstrated the use of ultrasound-assisted synthesis for quercetin-loaded nanosponges, highlighting that this method's lack of organic solvents offers a safer drug delivery system [33].

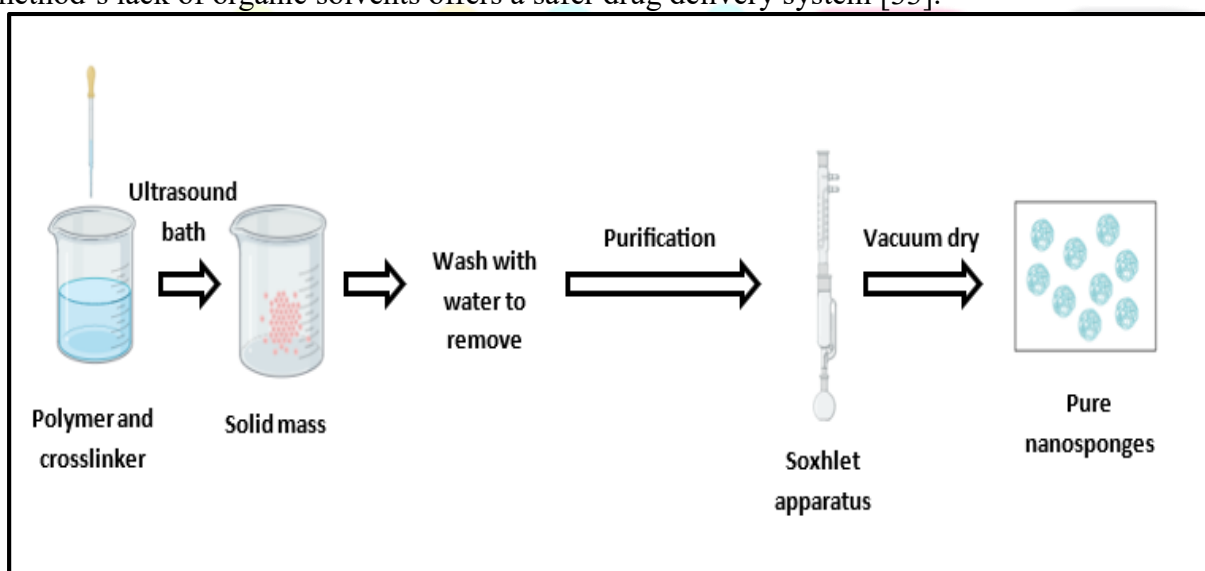


Fig 2: Schematic representation of nanosponge synthesis using an ultrasound-assisted method, followed by washing, Soxhlet purification, and vacuum drying to obtain pure nanosponges.

4.3. Melt method

In the melt method for nanosponge (NS) preparation, the polymer and cross-linker are melted together at a specific temperature, allowing them to form a homogeneous mixture. The ingredients are finely homogenized to ensure uniformity in the final product. Once the mixture is melted and homogenized, the resulting material is cooled to solidify, forming a solid, porous structure. After cooling, the nanosponges are collected by repeatedly washing the acquired product with a suitable liquid, such as water or ethanol.

This washing step is crucial as it removes any unreacted polymer and cross-linker, leaving behind the purified nanosponge structure [34]. The washing process also helps to separate the product into the nanosponge form. Once the blank nanosponges are obtained, they can be further utilized for drug encapsulation (Fig3). The clean nanosponges are exposed to narcotics or other therapeutic agents, enabling the efficient loading of drugs into the nanosponges.

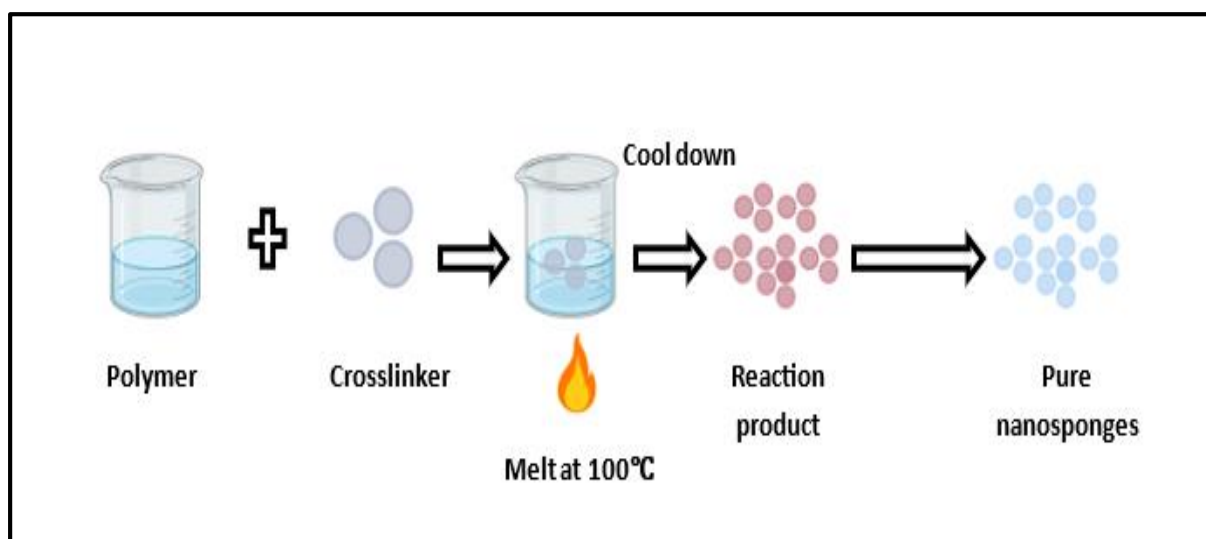


Fig 3: Schematic representation of Nanosponges synthesis via a thermal crosslinking method, where the polymer and crosslinker are melted at 100°C, followed by cooling to obtain the reaction product, which is further processed to yield pure nanosponges.

4.4. Quasi-emulsion diffusion method

The quasi-emulsion diffusion method is a widely used technique for preparing nanosponges, particularly for drug delivery applications. In this method, an organic phase containing a polymer and a cross-linker is prepared by dissolving them in a volatile, water-immiscible solvent such as dichloromethane or ethyl acetate. This organic phase is then emulsified into an aqueous phase containing a stabilizing agent, such as polyvinyl alcohol, under continuous stirring. The emulsification process leads to the formation of oil-in-water (O/W) droplets, where the polymer and cross-linker are confined within the dispersed phase. Once a stable emulsion is formed, the system undergoes solvent diffusion, where the organic solvent gradually diffuses into the aqueous phase, leading to nanoparticle precipitation and nanosponge formation [35]. The solidified nanosponges are then collected by filtration or centrifugation, followed by multiple washing steps to remove any unreacted components or residual solvents. Finally, the purified nanosponges are dried, typically through lyophilization or vacuum drying, to obtain a stable nanosponge formulation Fig 4.

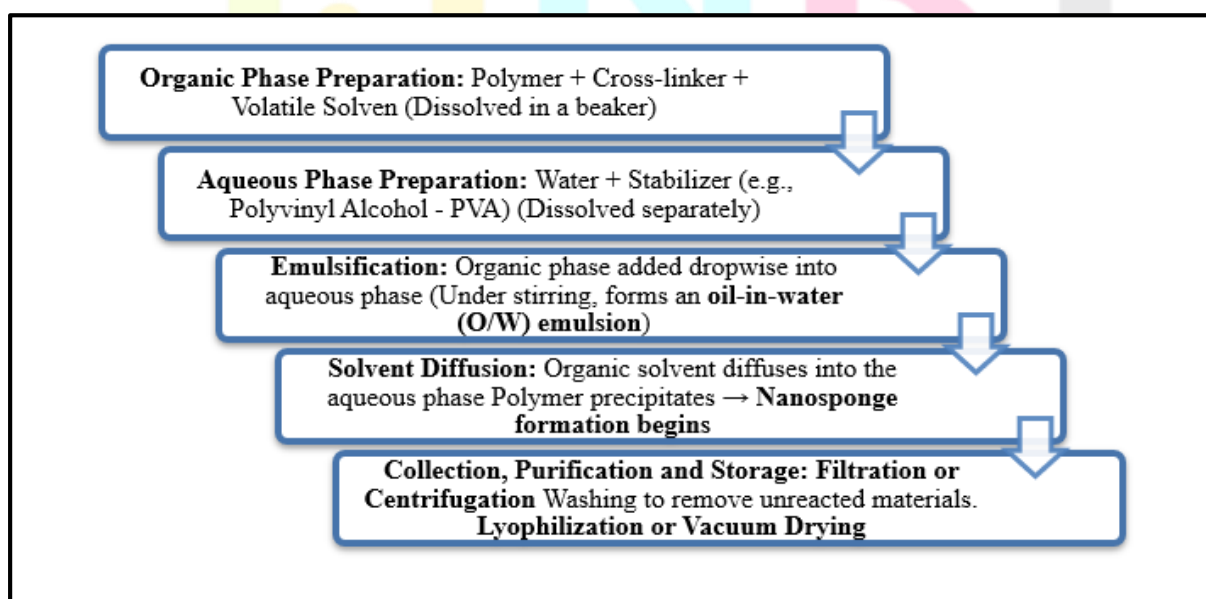


Fig 4: Schematic representation of the emulsification-solvent diffusion method for Nanosponges synthesis. The process involves organic and aqueous phase preparation, emulsification to form an oil-in-water (O/W) emulsion, solvent diffusion leading to Nanosponges formation, followed by purification and drying through lyophilization or vacuum drying.

4.5. Microwave-Assisted Method

The Microwave-Assisted Method is an advanced technique for nanosponge preparation that utilizes microwave irradiation to enhance the crosslinking reaction between the polymer and cross-linker. In this method, the polymer and cross-linker are dissolved in an appropriate solvent and subjected to controlled microwave energy, which facilitates rapid and uniform heating, promoting efficient polymerization and nanosponge formation. The use of microwave irradiation significantly reduces reaction time compared to conventional thermal methods while improving reaction efficiency and product uniformity [36]. Additionally, microwave energy provides precise temperature control, preventing excessive degradation of the polymer and ensuring the formation of nanosponges with well-defined porosity and size. Once the reaction is complete, the formed nanosponges are collected by filtration or centrifugation and purified through repeated washings to remove unreacted materials. The purified nanosponges are then dried using lyophilization or vacuum drying to obtain a stable final product (Fig5). This method is advantageous due to its energy efficiency, reduced solvent consumption, and the ability to produce highly uniform nanosponges with enhanced physicochemical properties.

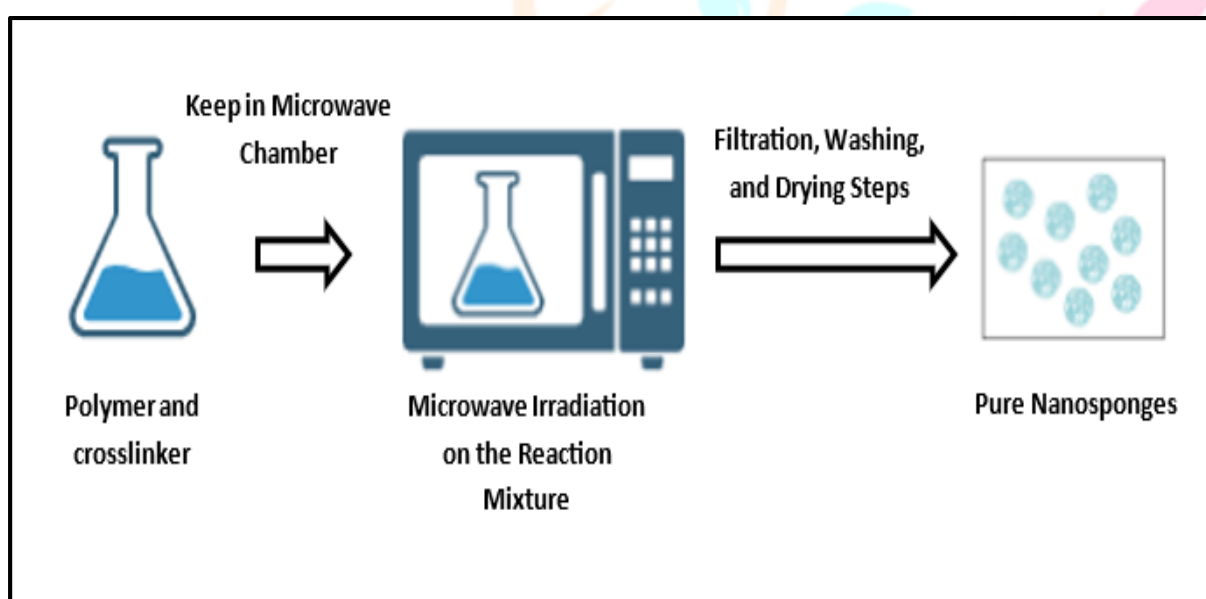


Fig 5: Schematic representation of the microwave-assisted synthesis of nanosponges. The process involves mixing a polymer with a crosslinker, subjecting the reaction mixture to microwave irradiation, followed by filtration, washing, and drying to obtain pure nanosponges.

5. Evaluation and Analysis of Nanosponges

Nanosponges (NS) are gaining significant attention in various fields due to their unique properties, including their large surface area, high loading capacity, biocompatibility, and ability to encapsulate a wide range of bioactive compounds. Evaluating and analyzing these nanostructures is critical for assessing their performance and suitability for diverse applications, particularly in drug delivery, biomedical, and environmental sectors. This section discusses the methods and techniques commonly used for the evaluation and analysis of nanosponges.

5.1. Morphological and Structural Characterization

The first step in evaluating nanosponges is understanding their morphological and structural properties. This can be achieved through several imaging and characterization techniques. SEM is widely used to visualize the surface morphology and size distribution of nanosponges. SEM can provide high-resolution images of the nanosponges, allowing for the observation of their spherical shape, porous structure, and uniformity. TEM provides deeper insights into the internal structure of the nanosponges, enabling the visualization of their core-shell structure, porosity, and the arrangement of polymeric matrices at the nanoscale. AFM can be used to assess the surface topology, roughness, and size distribution of nanosponges in three dimensions. AFM analysis is helpful in confirming the nanoscale dimensions of the particles and in evaluating their surface properties. XRD analysis is used to study the crystalline nature of the nanosponges and the physical state of the encapsulated drug or bioactive compound. It helps in confirming

whether the nanosponges are amorphous or crystalline in nature, which is crucial for determining their release characteristics [37].

5.2. Particle Size and Zeta Potential

DLS is a commonly used technique to measure the hydrodynamic diameter of nanosponges in suspension. The particle size distribution, including polydispersity index (PDI), is an essential parameter in assessing the stability and uniformity of the nanosponges. The zeta potential, measured by electrophoretic light scattering, provides an indication of the stability of colloidal systems. Nanosponges with a high zeta potential (either positive or negative) tend to exhibit better dispersion stability due to electrostatic repulsion between particles. The zeta potential also impacts the interaction of nanosponges with biological systems, influencing their cellular uptake and biodistribution.

5.3. Surface Area and Porosity

BET analysis is used to determine the specific surface area of nanosponges, which is a critical factor in determining their loading capacity. A high surface area is generally associated with better drug loading and release profiles. The porosity of nanosponges is important for their ability to encapsulate and release drugs. Techniques like nitrogen adsorption-desorption isotherms can be used to measure the pore size, volume, and distribution of nanosponges, which are essential for evaluating their efficiency in drug delivery applications.

5.4. Drug Loading and Release Studies

One of the primary applications of nanosponges is drug delivery, and evaluating their drug loading capacity and release behavior is crucial. The efficiency with which a drug is loaded into nanosponges is measured by determining the amount of drug encapsulated compared to the initial amount added. Drug loading is influenced by the polymeric matrix and the nature of the drug. Techniques such as UV-Visible spectroscopy, High-Performance Liquid Chromatography (HPLC), or fluorescence spectroscopy are used to quantify the encapsulated drug. In vitro release studies are conducted to evaluate the drug release profile of nanosponges. The release can be measured under different conditions (e.g., pH, temperature, and ionic strength) to simulate physiological conditions. The release kinetics are often evaluated using models like zero-order, first-order, and Higuchi models to understand the mechanism of drug release (e.g., diffusion-controlled, swelling-controlled, or degradation-controlled release) [38].

5.5. Stability Studies

Stability studies are essential to ensure that nanosponges retain their structural integrity, size, and drug loading over time. These studies typically involve storing nanosponges under various temperature and humidity conditions and monitoring their physical and chemical stability. In vivo stability can be assessed through pharmacokinetic studies, which involve tracking the circulation time, bioavailability, and tissue distribution of the nanosponges in animal models. The ability of nanosponges to maintain their structure in biological systems and the extent of their degradation or accumulation in tissues are crucial factors in determining their suitability for medical applications.

5.6. Biocompatibility and Toxicity

The biocompatibility of nanosponges is assessed through cytotoxicity studies, where the effects on different cell lines (e.g., fibroblasts, hepatocytes, or cancer cells) are evaluated. MTT or XTT assays, which measure cell viability, are commonly used to determine whether the nanosponges induce any adverse effects on cells. For biomedical applications, the hemocompatibility of nanosponges must be evaluated to ensure that they do not cause hemolysis, thrombosis, or platelet aggregation. In vitro assays such as hemolysis assays and platelet aggregation studies can be used to assess these parameters. Animal models are used to evaluate the toxicity of nanosponges. Acute and chronic toxicity studies provide insights into potential side effects, organ toxicity, and safe dosage ranges for clinical use [39].

5.7. Mechanism of Action and Interaction Studies

Understanding how nanosponges interact with cells is crucial for their application in drug delivery. Fluorescence microscopy or confocal microscopy can be used to study the cellular uptake and internalization mechanisms of nanosponges in different cell types. The interaction of nanosponges with proteins, DNA, or other biomolecules is assessed through techniques like surface plasmon resonance (SPR), circular dichroism (CD) spectroscopy, and fluorescence quenching assays. These studies help in understanding the biological interactions that determine the efficacy and toxicity of the nanosponges.

5.8. Environmental and Ecotoxicity Evaluation

Nanosponges are also being explored for environmental applications, such as pollution control and water treatment. The ecotoxicity of nanosponges can be assessed through tests on aquatic organisms, plants, and soil bacteria. Understanding their behavior in environmental settings is critical for ensuring they do not cause long-term ecological damage. The evaluation and analysis of nanosponges require a multifaceted approach that includes structural characterization, drug loading and release studies, stability analysis, biocompatibility testing, and understanding their mechanisms of action [40]. These evaluations are essential for ensuring the practical applicability of nanosponges in fields such as drug delivery, environmental remediation, and other biomedical applications. Proper assessment of these factors will help optimize their design and functionality, paving the way for their successful integration into therapeutic and industrial applications.

6. Application of Nanosponges in Space Science:

Space science has witnessed significant advancements with growing focus on addressing the numerous challenges faced during space exploration. Among these challenges, ensuring the safety, health, and overall well-being of astronauts on long-duration missions, as well as improving the efficiency of various space systems, has become a top priority. Nanosponges, with their remarkable properties such as high surface area, controlled porosity, biocompatibility, and ability to encapsulate and release a wide range of substances, have shown immense potential for revolutionizing several areas of space science. This section delves into the application of nanosponges in key areas of space science, including life support systems, drug delivery, radiation protection, environmental monitoring, and extraterrestrial exploration.

6.1. Nanosponges in Life Support Systems

Life support systems are vital for ensuring the survival of astronauts during long-duration space missions, especially for those venturing to distant destinations like Mars. Nanosponges offer a variety of solutions that can help maintain a safe and sustainable environment in spacecraft and space habitats. In the context of oxygen generation, nanosponges can be engineered to carry oxygen-generating compounds that release oxygen as needed. This allows for a more efficient supply of breathable air, especially in situations where oxygen levels might deplete due to extended missions [41]. Similarly, in water purification, nanosponges, with their large surface area and porous structure, can adsorb contaminants from wastewater and facilitate the removal of pollutants, providing a continuous supply of clean water. These nanosponges can be customized to capture heavy metals, organic pollutants, or even microbial organisms, making them ideal for water recycling in space. Furthermore, nanosponges can play a key role in food preservation. Space missions often rely on freeze-dried or specially packaged food for long-term storage. Nanosponges can encapsulate essential nutrients, vitamins, and bioactive compounds, preserving the quality and stability of these food supplies. This would not only enhance the nutritional value but also protect food from degradation, oxidation, and contamination from space radiation, ensuring the safety and sustainability of food supplies during extended missions.

6.2. Drug Delivery and Therapeutics in Space

Space travel poses numerous health challenges, including the effects of microgravity, radiation, confinement to small spaces, and exposure to limited medical resources. The need for reliable drug delivery systems that are efficient, adaptable, and effective in the space environment is crucial. Nanosponges have emerged as ideal candidates for controlled drug delivery systems. They can be engineered to release therapeutic agents in a controlled and sustained manner, ensuring astronauts have access to the right treatment over extended periods without needing frequent administration. This is particularly advantageous for treating conditions like muscle atrophy, bone loss, or chronic inflammation, which are common during long-duration space flights. Moreover, nanosponges can encapsulate bioactive compounds that are critical for astronauts' health. These include antioxidants, anti-inflammatory agents, and other therapeutic molecules that counteract the adverse effects of space travel. When released gradually, these compounds can work to maintain astronauts' immune functions, reduce oxidative stress, and support overall well-being in the harsh space environment. Nanosponges also have the potential to provide radiation protection by encapsulating radioprotective agents. These agents can be gradually released to protect astronauts' cells from radiation-induced damage [42]. Radiation in space, particularly from solar particle events and cosmic rays, poses a significant risk to astronauts' health, and nanosponges could provide an effective means of mitigating this threat. By neutralizing reactive oxygen species (ROS) that result from radiation exposure, these agents can help to minimize oxidative damage and reduce the risk of radiation-related illnesses.

6.3. Radiation Protection

Space radiation is one of the most significant risks for astronauts, with cosmic rays and solar radiation capable of causing DNA damage, increasing cancer risk, and inducing other harmful health effects. Traditional radiation shielding materials tend to be heavy and impractical for deep-space missions, making them unsuitable for long-term use. Nanosponges, with their lightweight yet effective radiation-shielding capabilities, offer an innovative solution. By incorporating materials with high atomic numbers, such as metals or metal oxides, within the nanosponges, they can act as a shield against radiation. These materials are able to interact with and absorb radiation, providing effective shielding without significantly increasing the weight of the spacecraft or habitat. The large surface area of nanosponges also allows for the inclusion of a higher density of these radiation-absorbing materials. Moreover, nanosponges can be tailored to shield against specific types of radiation, such as alpha, beta, and gamma rays, which pose different threats in space [43].

Another application of nanosponges in radiation protection is the encapsulation of radioprotective compounds. These compounds, such as antioxidants and free radical scavengers, can be slowly released from the nanosponges to neutralize the harmful effects of radiation. By reducing oxidative stress and protecting cellular structures from damage, these compounds can play a critical role in ensuring astronaut health during extended space missions. This targeted release of radioprotective agents offers a means to counteract the damaging effects of space radiation over time.

6.4. Environmental Monitoring and Pollution Control

Maintaining a controlled and safe environment is crucial for the success of space missions. Space habitats, such as the International Space Station (ISS), are confined spaces where air quality, water purity, and waste management must be continuously monitored and managed. Nanosponges can play an integral role in this environmental monitoring, helping to ensure the health and safety of astronauts. In gas detection, nanosponges can be engineered to selectively adsorb specific gases, such as carbon dioxide (CO₂), ammonia (NH₃), or methane (CH₄). By monitoring the interaction between the nanosponges and these gases, it is possible to detect harmful gas build-up in the habitat and address the issue promptly. Changes in the physical properties of nanosponges, such as their color or fluorescence, can be used as indicators of gas concentrations, allowing for real-time monitoring [44]. Similarly, nanosponges can be used for microbial detection and deactivation. In a closed environment like a spacecraft, the accumulation of microorganisms can pose serious health risks. Nanosponges can be functionalized with antimicrobial agents that allow them to capture and neutralize harmful bacteria, fungi, and viruses. This will help maintain a sterile and safe environment for astronauts throughout the mission. In addition to their role in gas and microbial detection, nanosponges can assist in water quality monitoring and filtration. Functionalized nanosponges can be used to absorb contaminants such as heavy metals, organic pollutants, and microbial organisms from water. They can be incorporated into water filtration systems, providing a continuous means of purifying water to ensure its safety for consumption during space missions.

6.5. Extraterrestrial Exploration

As space agencies prepare for future missions to the Moon, Mars, and beyond, the ability to conduct sustainable operations on extraterrestrial bodies has become paramount. Nanosponges offer a range of potential applications for supporting human exploration beyond Earth, including in-situ resource utilization, habitat construction, and radiation protection. One of the key challenges in extraterrestrial exploration is the need to utilize local resources for long-term sustainability [45]. Nanosponges can play a significant role in in-situ resource utilization (ISRU) by helping extract valuable resources, such as water, from lunar or Martian soil. With their porous structure and surface functionalization, nanosponges can be designed to selectively capture water molecules from the environment, providing astronauts with a reliable and efficient means of extracting and purifying water from extraterrestrial sources. Nanosponges could also be used in the development of construction materials for extraterrestrial habitats. The lightweight, flexible nature of nanosponges makes them ideal for creating durable, adaptable materials for habitat construction on the Moon or Mars. When combined with local materials like regolith, nanosponges could help produce strong, yet lightweight, building materials that could withstand the harsh conditions of extraterrestrial environments. From life support systems to drug delivery, radiation protection, environmental monitoring, and extraterrestrial exploration, nanosponges offer innovative solutions that can significantly improve the efficiency, safety, and sustainability of space missions. As research continues to evolve, nanosponges hold the potential to play an increasingly important role in advancing human exploration of space.

7. Conclusion

In conclusion, nanosponges are highly versatile materials with exceptional adsorption properties, making them valuable for various applications, including environmental remediation, drug delivery, catalysis, and energy storage. Their emerging role in space science, particularly in water purification, gas capture, radiation shielding, and controlled drug delivery, highlights their potential for addressing critical challenges in extraterrestrial environments. Despite their advantages, further research is needed to enhance their stability, efficiency, and scalability for real-world applications. Advancing Nanosponges technology will open new possibilities for sustainable solutions both on Earth and in space.

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Data Availability

The datasets generated and analyzed during this study are available from the corresponding author upon reasonable request.

Ethics approval

This study does not involve human participants or animals and does not require ethical approval.

Consent to participate

Not applicable.

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