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SILICA-RICH WASTE TO SUSTAINABLE NANOFIBERS VIA ELECTROSPINNING: A SYSTEMATIC REVIEW

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Abstract
Often overlooked in conventional waste management systems, silica-rich waste holds untapped potential as a sustainable precursor for advanced nanomaterials. This systematic review critically examines how diverse industrial and agricultural silica-rich residues such as rice husk ash, glass waste, and geothermal sludge can be valorized into functional nanofibers via electrospinning. Applying the PRISMA framework, 150 peer-reviewed studies (2014–2024) were synthesized to map current research on waste selection, silica extraction methods, electrospinning parameters, and end-use performance. The review highlights that tailored purification routes can yield high-purity silica suitable for stable, defect-free nanofibers. Electrospinning success hinges on a fine-tuned interplay of solution properties, operational settings, and ambient conditions. Resulting nanofibers demonstrate outstanding performance in air/water filtration, biomedical scaffolding, and energy storage systems. However, raw material variability, process reproducibility, and scale-up potential persist. By integrating material science with circular economy principles, this work positions waste-derived nanofibers as a strategic pathway toward greener, high-value applications in resource-constrained settings.
Keywords: silica-rich waste, nanofiber, electrospinning, circular economy, sustainable materials, systematic review

INTRODUCTION

In recent decades, attention to environmental and sustainability issues has increased significantly. It is due to the increasing global awareness of the negative impacts of human activities on ecosystems. In this context, one of the challenges faced is waste management, especially waste often generated from various industries, including agriculture, construction, and manufacturing. Ineffective waste management can result in soil, water, and air pollution, impacting human health and the survival of other living things. Silica waste, such as rice husk ash, silica dust, and glass waste, has great potential for utilization in diverse uses, one of which is as a raw material during the fabrication of nanoscale fibers, better known as nanofibers. Nanofibers have diameters that are less than 100 nanometers and exhibit unique features that render them highly desirable across multiple uses in technology and industry. Among the top prominent characteristics of nanofibers is their extensive surface area relative to size. It indicates that the nanofiber has expanded surface exposure versus internal volume, which allows for more significant interactions with the surrounding environment (Anusiya & Jaiganesh, 2022).

As an illustration in healthcare, nanofibers can be applied to develop more efficient pharmaceutical distribution mechanisms, where drugs can be absorbed faster and more effectively by target cells due to a larger surface area (Gavande et al, 2024). In addition, the good mechanical strength of the nanofiber makes it an advantage. In the automotive industry, nanofibers combined with composite materials can reduce vehicle weight without sacrificing strength values, improving fuel efficiency, and reducing carbon emissions. Much research indicates that carbon nanofibers exhibit strong mechanical behavior that can replace the use of other fibers. The exceptional durability of carbon fibers renders them suitable for polymer-based composites. High-strength fibers can be used in short forms in composites and mass-produced to meet the high demands of automotive applications. These materials can fulfill mechanical demands in both core and peripheral car components. Due to the weight ratio of these durable and low-density materials applicable across sectors (Natrayan et al, 2021). The ability of nanofibers to function as filter media is also very important, especially in the environmental and medical fields.

Nanofibers can create more efficient air and water filters, filtering out microscopic particles and harmful pollutants (Al-Husaini et al., 2021; Cui et al, 2020). For example, filters made of nanofiber can capture PM2.5 particles, which are fine particles that can penetrate the human respiratory system and cause various health problems (Cui et al, 2021; Almeida et al, 2020). Nanofibers also serve a critical function in developing smaller and more efficient electronic devices. For example, nanofibers can create ultra-responsive detectors (Rosenberger et al, 2020). Moreover, nanofibers make more efficient batteries, where nanofiber structures can increase energy storage capacity and speed up the charging process (Cheng et al, 2020; Zhao et al, 2023; Li et al, 2019).

Nanofiber manufacturing technology can be carried out in various ways, such as electrospinning, molecular self-arrangement, gradient demixing, mold-guided growth, melt blowing, electro-blowing, cellulose nanofibers, etc. (Anusiya & Jaiganesh, 2022). Electrospinning remains a conventional process for nanofiber creation thanks to its cost-efficiency, versatility, and operational ease (Nune et al, 2017). Nanofibers formed this way offer superior properties like large interface exposure, finer thread size on the micro scale, and good porosity (Figen, 2020). Various studies have shown that silica waste in electrospinning simultaneously decreases ecological footprint and enhances the physical and chemical properties of the resulting nanofibers; however, challenges such as waste variability, precursor preparation, and optimization of electrospinning parameters remain unexplored. This analysis seeks to close the knowledge divide by synthesizing the research on using silica-rich waste for nanofiber fabrication via electrospinning. The objectives are to: identify and categorize the sources of silica-rich waste, analyze methods for preparing suitable silica precursors for electrospinning, evaluate electrospinning parameters and their impacts on nanofiber properties, and explore the applications and prospects of silica-based nanofibers.

METHOD

A structured review represents a rigorous approach to evaluating and synthesizing existing research. Unlike general reviews, systematic analyses follow pre-defined frameworks and protocols. A valid systematic review must allow independent verification and yield unique scientific contributions. It can enhance credibility by thoroughly identifying, analyzing, and synthesizing all relevant findings. Nonetheless, conducting a systematic review demands significantly more work than a standard literature review (Staples & Niazi, 2006).

This SLR adopts the PRISMA guidelines to maintain clarity and completeness throughout the review.

1. Research Questions is the first stage in the preparation of the SLR. The research questions in this paper include;
   - What are the primary sources of silica-rich waste used in nanofiber production?
   - What methods are employed to process silica-rich waste into electrospinnable precursors?
   - Which electrospinning parameters significantly influence nanofiber morphology and performance?
   - What are the key applications of silica-based nanofibers in various sectors?
2. The Search Strategy is the second stage to complete when compiling an SLR paper. At this stage, the search time was carried out in January 2025. The search was carried out on relevant literature, and the process involves identifying keywords for information search purposes. In this context, at least one database must be presented when conducting an SLR. This study employs four major scholarly indexing sources, including Scopus, Web of Science, SpringerLink, and Google Scholar, using the following keywords: "silica-rich waste," "electrospinning," "nanofiber," "waste valorization," and "silica nanofiber." The Boolean string used: ("silica-rich waste" OR "waste-derived silica)" AND ("nanofiber") AND ("electrospinning").
3. Inclusion and Exclusion Criteria assess the quality of articles or the screening process of articles obtained from search results in databases. Screening refers to selecting or excluding sources based on pre-established authorial benchmarks of certain databases. In the screening process, eligibility is assessed in a systematic review. The researcher establishes selection and omission standards for the review, as illustrated in Table 1.

Table 1. The Criteria for Inclusion and Exclusion

Criteria	Inclusion	Exclusion
Publication Time	Articles published between 2014 and 2024	Articles published before 2014
Document Type	Peer-reviewed articles published	Non-peer-reviewed or grey literature (conference proceedings, chapters in books, book series, etc.)
Language	English	Non-English

Open Access	Yes	Non

4. Data Extraction is an important process in research and analysis. This process involves collecting and recording important information from studies or articles selected for analysis. In the context of SLR, the extracted data serves as the foundation for answering the research questions that have been set. This process is not just about collecting numbers or facts but also involves a deep understanding of the context and relevance of the information obtained. When conducting data extraction, the first step that needs to be taken is to determine the sources that meet the inclusion criteria. These criteria usually include the source's relevance, quality, and reliability.

RESULTS AND DISCUSSION

In accordance with the initial literature search results with the keywords "nanofiber," "electrospinning", "silica-rich waste", "waste-derivate silica", "silica nanofiber", and "application" in the Scopus database, 14,648 articles were obtained. In the SpringerLink database, 3,936 articles were obtained. If the two databases are added together, the total number of articles obtained is 18,584. This significant finding shows how extensive research has been done in nanofibers, especially silica-related ones. These numbers show how vast the research that has been done in this field is, reflecting the great interest and attention from researchers worldwide. Each database not only presents numbers but also represents the collaborative efforts of researchers worldwide. Research conducted in various countries, with different approaches, creates a rich and diverse knowledge network. In this context, it is important to understand how nanofibers, especially silica-based ones, can be produced from silica-rich waste and their varied applications in various industries.

The next stage is to search according to the selection and omission standards. This screening process includes 18,584 articles obtained from the initial search. Based on the information in Table 1, which consists of the year of publication, type of publication, language used, and publication model (open access), 8,906 eligible articles were assessed, and an intensive selection of 150 highly relevant studies was made. The PRISMA flowchart for the search and inclusion/exclusion process is presented in Figure 1.

Silica-rich waste

Silica-rich waste is a material that has a high silica content. Silica is a compound consisting of one silicon atom (Si) and two oxygen atoms (O_2) with the chemical formula SiO_2. This compound ranks among the top common minerals found within the terrestrial lithosphere. The type of silica most often seen is usually in soil, gravel, or sand, better known as quartz. Silica-rich waste is produced from various industrial processes in different fields. Among them are mining, manufacturing, mineral processing, energy, and agriculture. Table 2 presents multiple examples of waste that is rich in silica content.

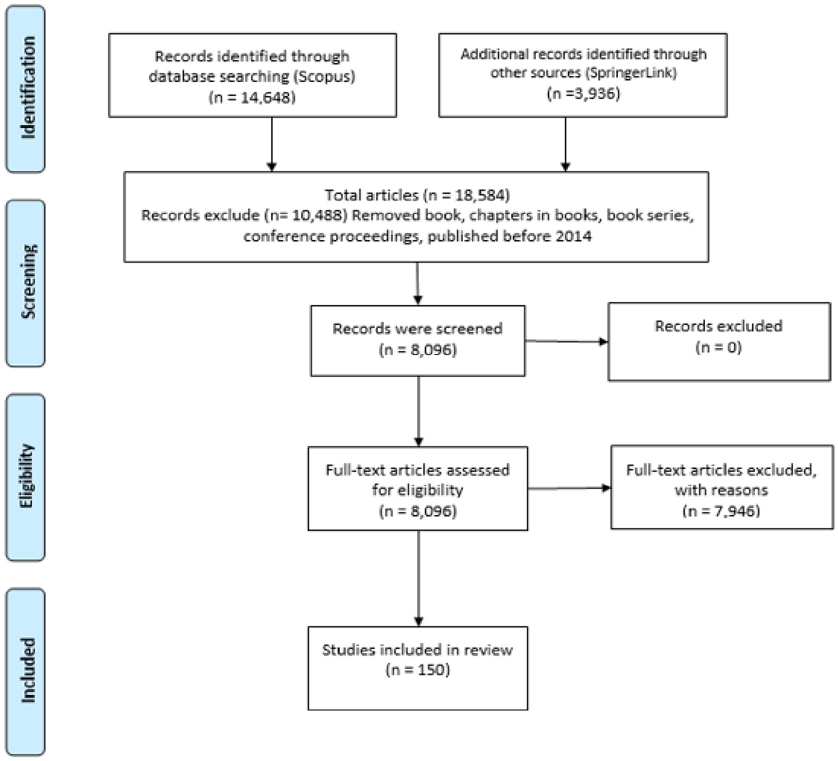

Figure 1. Article Selection and Screening Stages

Table 2. The waste source is rich in silica

Silica Rich Waste (Sources)	Reference	SiO_2 Content (wt%)
Mining/ mineral processing sector		
Iron ore tailings	(Zhao et al, 2021)	24,2 – 75,2
Coal gangue	(Zhang and Ling, 2019)	39,1 – 61,9
Red mud	(Wang and Liu, 2021)	17,4 – 25,9
Querry dust	(Hendronursito et al.,2020)	62,8
Manufacturing sector		
Waste/ bottle glass	(Mori, 2003)	60 - 80
Blast furnace slag	(Seggiani and Vitolo, 2003)	30 - 40
Metal silica residue	(Oliveira et al, 2020)	68,7 – 72,8
Ceramic waste	(Saif et al, 2024)	53,4 – 66,5
Silica furnace	(Liu et al, 2024)	95,7
Agricultural sector		
Rice husk ash	(Nzereogu et al, 2023)	87 – 97
Sugarcane baggase ash	(Rovani et al, 2018)	88,7
Bamboo lead ash	(Rangaraj and Venkatachalam et al, 2017)	49,9
Rice straw ash	(Abdel hamid et al, 2023)	84,5
Palm oil ash	(Olivia et al, 2024)	43,6 – 65,3
Energy sector		

Coal fly ash	(Anggara et al, 2024)	50 – 65
Geothermal sludge	(Panatarani et al., 2023)	95,7

Silica-rich waste method to become a nanofiber

Based on Table 2, various sources of silica-rich waste have the potential to be used as advanced materials. To achieve these results, appropriate methods must be applied in the processing and utilization of silica-rich waste into nanofibers. A structured extraction and purification process is required. This stage involves a series of systematic steps to ensure the quality and efficiency of the raw materials produced.

Based on Table 2, various sources of silica-rich waste have the potential to be used as advanced materials. Silica-rich waste, often produced from agricultural industries, mineral processing, and several other industrial processes, is rich in silica and has great potential for use in various applications, including as raw material for nanofibers.

Appropriate processing and utilization methods must be applied to achieve optimal results in utilizing silica-rich waste into nanofibers. This process involves physical and chemical processing and requires a deep understanding of the characteristics of raw materials and supporting environmental conditions. With a particular focus on conversion to nanofibers, we need to explore various approaches that can be used, such as sol-gel techniques, electrospinning, and other processing methods that have proven effective in producing high-quality nanofibers.

The first stage in utilizing silica-rich waste is the extraction and purification process of silica from garbage. This process is very important to ensure that the raw material produced is free from contaminants that can affect the quality of the nanofibers.

Table 3. Silica-rich waste processing method

Waste type	Method	Results	Reference
Iron ore tailing	Basic melting and acid treatment.	The porous silica specimens exhibited a remarkable measurable surface extension reaching 544.68 $m^2\ g^{-1}$, characterised by an irregular mesoporous structure. This significant surface area indicates the material's possible uses across domains like catalysis and capture. Overall, the unique structural properties of the samples suggest they could be highly beneficial for advanced material science applications.	(Han et al., 2021)
	Advanced magnetic segregation combined with acid dissolution.	Under the conditions that have been optimised, the silicon dioxide proportion in enriched quartz achieved a level of 92.06%, with a recovery rate of SiO2 standing at 43.54%. The quartz	(Li et al, 2023)

Waste type	Method	Results	Reference
		concentrate underwent a mixed acid leaching process to eliminate metallic impurities. As a result, the refinement level of silica in premium samples reached an impressive 99.51%. The efficiency of removal for various metallic impurities from the quartz concentrate was recorded as follows: Fe at 95.20%, Al at 85.60%, Mg at 97.99%, and Ca at 97.19%.	
	field-enhanced magnetic extraction method	The magnetic separation process yielded a notable increase in the SiO2 content of the products, rising from 61.38% to 95.23%. This enhancement in purity reflects the effectiveness of the separation technique employed. Furthermore, the recovery rate achieved during this process was 38.51%. Such results underscore the potential of magnetic separation in optimizing mineral processing outcomes.	(Zhang et al., 2024)
	Wet High-Intensity Magnetic Separation (WHIMS) with refined two-stage mixed acid leaching	An innovative methodology has been established, incorporating aqueous strong-field magnetic purification with a staged acid treatment. This technique has effectively diminished hazardous impurities, including heavy metals, leading to an impressive SiO2 purity level of 99.99%. Key achievements comprise attaining a SiO2 purity of 99.99%, a total recovery rate of 38.04% from the raw materials, and remarkable removal efficiencies for essential contaminants such as Fe (90.45%), Al (78.89%), and Ca (68.15%) following the two-stage acid treatment.	(Long et al, 2024)
Coal gangue	The process includes leaching, separation, simultaneous precipitation, selective dissolution, gel formation, and calcination.	The synthesized porous silica exhibited 0.33 cm^3/g of void space, 3.25 nm of mean cavity size, and a measurable surface area of 392.85 m2/g. The purity of mesoporous silica is 99.08%	(Sepehrian et al, 2024)
Red mud	Direct leaching and dry digestion	Silica extraction using HCL or H_2SO_4 and calcination resulted in a 92,3% silica purification. The final product showed mesoporous characteristics suitable for nanofiber synthesis. FTIR and XRD confirmed the formation of amorphous	(Wang & Liu.2021, Chandra et al, 2022)

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Waste type	Method	Results	Reference
		silica phases with good dispersion in polymer matrices.	
Quarry dust	Acid leaching and calcination	The findings indicated that the silica content rose in correlation with higher concentrations of HCl, smaller particle sizes, and increased rotational speeds. XRF analysis revealed that the highest purity of silica was obtained through leaching with 9.6 M HCl, utilizing a particle size of 400 mesh and a rotational speed of 750 rpm, achieving a purity of 73.49%. These results suggest that leaching with HCl effectively enhances the Si content compared to prior levels. Additionally, the XRD diffractogram confirmed that the granite powder resulted in the formation of the Quartz phase.	
Waste glass/bottle glass	Crushing, hydrothermal, sol-gel	The chemical makeup of the recycled glass is presented as stable oxides. It is noted that the recycled glass comprises 69.4 wt% % SiO2, signifying that it possesses a high silica content adequate for utilization as a silica precursor in the manufacture of sodium silicate.	(Owoeye et al, 2020)
Blast furnace slag	Leaching	The primary components of the slag are identified as CaO, SiO2, Al2O3, MnO, and BaO, along with several trace oxides including Fe2O3, SrO, ZrO2, and Y2O3. It is widely recognized that silica can be obtained from blast furnace slag through dissolution in acids such as hydrochloric acid, which catalyzes the gelation and polymerization of silica. However, this technique may yield comparatively lower purity (above 95%) silica, necessitating additional purification steps. Conversely, the method of extracting silica using sodium hydroxide, followed by precipitation with sulfuric acid, produces silica nanoparticles of high purity, as demonstrated in the current research.	(Abdelghaffar et al, 2019)
	High-temperature acid dissolution/leaching	Elemental analysis indicated that the residual solid predominantly comprised silica and a minor quantity of undissolved metal oxides, including aluminum and magnesium. The silica demonstrated a moderate surface area of	(Singh et al, 2024)

Waste type	Method	Results	Reference
		(100 m2 g−1) along with a broad pore size distribution between 4–20 nm, indicating its mesoporous nature. PXRD analysis revealed that the silica produced through synthesis is amorphous in structure.	
Metal silica residu	Leaching, sol-gel	Based on the extraction techniques employed, with and without HCl cleaning, yields of approximately 25% and 27% were achieved, respectively. These findings indicate that the method not utilizing HCl for residue cleaning yielded superior results, allowing for reagent savings and reducing extraction time, thereby enhancing the efficiency of SiO2 extraction. The analyses of dry silica gel's chemical composition (% mass) revealed a SiO2 content of 83.66% for the silica not subjected to HCl washing and 84.48% for the silica that underwent HCl treatment.	(Morais et al, 2020)
Ceramic waste	Crushing, milling, followed by alkaline leaching and calcination	Silica content of ceramic waste was increased to 66,5%. Post-processing results showed enhanced silica reactivity that is suitable for reuse in ceramic tile production. Machine learning optimization demonstrated its suitability for sustainable and circular material reuse.	(Saif et al, 2024)

Parameters Affecting the Electrospinning Process

The electrospinning procedure is largely shaped by factors divided into three principal types: chemical, operational, and environmental conditions. Each parameter determines the resulting nanofibers' morphology, diameter, and final quality.

1. Solution Parameters
   - Polymer Concentration and Viscosity

     Polymer concentration is directly related to the viscosity of the spinning solution. Insufficient chain entanglement leads to bead formation or droplet spray when the concentration is too low. On the other hand, overly high concentrations can increase viscosity to obstruct stable jet formation.

     For example, incorporating PVA with silica extracted from rice husk ash at concentrations of 8 – 10% has been shown to yield uniform, bead-free nanofibers. This concentration range provides sufficient viscosity to ensure jet stability and good spinnability (Nzereogu et al, 2023).
   - Conductivity and Surface Tension

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Conductivity is crucial in facilitating the transfer of electricity along the electrospinning jet. Solutions with higher conductivity typically respond more effectively to the applied electric field, generating thinner and consistent threads. On the other hand, surface tension resists the elongation of the foil jet. If it is too high, it can hinder fiber formation and increase the likelihood of bead defects.

For example, adding Triton X-100 surfactant to silica derived from sugarcane bagasse ash enhanced solution conductivity and improved fiber uniformity. Similarly, to overcome surface tension issues in silica solutions obtained from blast furnace slag, an ethanol-water co-solvent system facilitated better jet elongation and smoother fiber formation (Dhmees et al., 2019).

- Solvent Solubility and Polarity

  A suitable solvent for electrospinning should effectively dissolve the polymer, possess the right level of polarity, and evaporate at a sufficient rate during the jet's flight. If the solvent evaporates too slowly, fibers can remain wet or fail to solidify properly before reaching the collector.

  For example, a solvent mixture of ethanol and water in a 3:1 ratio was used to process PVA combined with silica derived from rice straw ash. This mixture facilitated rapid fluid loss, developing uniform, sleek strands (Abdel Hamid et al., 2023).

- Additives and Chemical Interactions

  Adding certain additives, such as surfactants, ionic salts, or functional agents, can improve the stability of the polymer solution and affect the resulting fiber morphology. Moreover, these additives may enhance the functional characteristics of the synthesized nano-threads.

  For example, incorporating amine compounds into silica solutions derived from blast furnace slag enhanced dispersion stability and yielded mesoporous fibers with promising performance for CO_2 adsorption.

- pH and Solution Stability (Singh et al, 2024).

  The acidity level of the mixture is essential in defining the compatibility between the silica and polymer phases. An inappropriate pH level can lead to particle agglomeration or trigger undesirable chemical interactions, hindering fiber formation.

  For example, the importance of pH control during silica matrix production from industrial by-products was highlighted, as it serves as a fundamental factor in shaping the homogeneity and spinnability of the resulting solution (Oliveira et al, 2020).

2. Process Parameters

   - Voltage

     Voltage supplies the electrostatic force required to overcome surface tension, enabling the emergence of a conical fluid tip and the initiation of a stable jet. Maintaining an optimal voltage, typically 10 to 30 kV, is essential for consistent fiber production. Under insufficient electrical charge, the stream may not form properly, whereas excessively high voltage can cause jet instability, resulting in bead defects or fiber breakage.

For example, an applied voltage of 20 kV was optimal for electrospinning nanofibers using silica derived from waste glass combined with PVA, resulting in uniform, bead-free fiber morphology (Dattilo et al, 2020).

- Tip to collector distance

The distance between the nozzle and the target influences the flight time of the polymer jet, providing the necessary duration for solvent evaporation before fiber deposition. A commonly used distance ranges from 10 to 20 cm. Fibers may not have enough time to solidify if the distance is too short, resulting in wet deposition that can cause fiber merging or structural collapse. On the other hand, an excessively long distance may reduce the magnitude of the applied electrostatic force, potentially destabilizing the jet and compromising fiber formation.

For example, a 15-centimeter emitter-to-collector gap was employed during the electrospinning of a silica PVA blend derived from rice straw ash, giving rise to uninterrupted generation of defect-free nanofibers (Hamid et al., 2023).

- Flow rate

Discharge rate regulates the polymer feed to the nozzle tip during electrospinning. If the flow rate is too high, the solution may accumulate at the tip, causing dripping and bead formation due to insufficient stretching. Conversely, a flow rate that is too low can lead to needle clogging or disrupt the continuity of the jet. In most electrospinning setups, an optimal flow rate typically falls within the 0.1 to 1 mL/h range.

For example, an optimal flow rate of 0.4 mL/h was identified for the electrospinning of PAN blended with silica extracted from coal fly ash, resulting in stable fiber formation (Anggara et al, 2024).

- Needle Diameter

The internal diameter of the nozzle strongly influences controlling the flow behavior and the initial formation of the electrospinning jet. Needle gauges commonly range from 21 G to 27 G. Smaller needle diameters are generally more suitable for low-viscosity solutions, as they help regulate the flow and produce finer, more uniform fibers.

For example, using a 22 G needle during the electrospinning of PES silica nanofibers enhanced jet control and stability (Cui et al, 2020).

- Collector type and Rotation

The configuration of the collector significantly influences the orientation of the electrospun fibers. A rotating drum or mandrel typically promotes fiber alignment along the direction of Rotation, whereas a stationary flat collector tends to produce randomly oriented fiber mats.

For example, a rotating drum speed of 1000 rpm was employed during the electrospinning process to fabricate silica-based membranes, resulting in enhanced mechanical strength and improved uniformity (Husaini et al, 2021).

3. Environmental Parameters

- Temperature

Temperature influences the solvent evaporation rate and the electrospinning solution's viscosity. Higher ambient temperatures generally promote fast solvent evaporation, accelerating fiber solidification and enhancing jet stretching, resulting in thinner threads. However, excessive heat may cause the Taylor cone to destabilize or cause the solution to dry prematurely near the needle tip, leading to bead formation or interruptions in fiber continuity.

For example, a rise in surrounding thermal conditions from 20˚C to 35˚C during the electrospinning of PVA/silica nanofibers derived from rice husk ash was found to reduce the average fiber diameter by 22%, indicating more efficient jet elongation under elevated thermal conditions (Zhuang et al, 2022).

- Relative Humidity

Humidity alters the external structure of spun nanofibers by influencing the phase separation process between the solvent and polymer during jet elongation. Elevated relative humidity can slow solvent evaporation, often resulting in porous structures, wrinkled fiber surfaces, or ribbon-like morphologies due to residual solvent retention. Conversely, extremely low moisture may accelerate solvent evaporation excessively, increasing the likelihood of nozzle clogging and producing brittle fibers with poor mechanical integrity.

For example, electrospinning silica-PAN nanofibers under high humidity (>60%RH) led to surface porosity due to water vapor condensation on the fiber surface. In contrast, optimal fiber morphology was achieved at relative humidity levels between 30 - 40% (Park et al., 2020).

- Airflow and Ventilation

Although sometimes underestimated, airflow within the electrospinning chamber can significantly affect the electrostatic field, altering the jet trajectory, fiber alignment, and deposition pattern. Maintaining a controlled laminar airflow is essential, as turbulent conditions may disrupt jet stability and lead to irregularities in the resulting fiber mats.

For example, applying perpendicular airflow to the collector surface during electrospinning enhanced fiber alignment when using a rotating drum collector, particularly in producing silica-based scaffolds for biomedical applications (Guo et al., 2021).

Applications of Silica-Based Nanofibers

Silica-based nanofiber derived from waste has gained prominence because of distinctive chemical-physical traits like superior surface, tunable porosity, integration within biological systems, and thermal stability. Applications include:

1. Filtration

   Silica nanofibers exhibit superior filtration efficiency for air and water treatment, particularly for PM 2.5 and heavy metal removal.

   For example, hydrophilic nanofiber membranes can effectively filter nanoparticles in contaminated water. In water purification, silica functionalized polyether sulfone (PES) nanofibers fabricated via electrospinning exhibited strong hydrophilicity and high removal efficiency of toxic elements like Pb and Cd.

2. Biomedical

   The compatibility and controllable degradation rates of silica nanofibers allow their use in dry delivery systems, wound healing, and tissue engineering scaffolds. Reviewed natural polymeric nanofibers for drug release, where silica composites enhance drug loading and release kinetics. Mesoporous silica/polycaprolactone (PCL) nanofibers have been developed for controlled drug delivery, demonstrating sustained release of antibiotics and anti-inflammatory drugs with minimal cytotoxicity. Additionally, silica-collagen composite nanofibers are used as wound healing scaffolds, promoting cell adhesion and proliferation due to their biomimetic structure.

3. Energy storage

   In lithium-ion batteries and supercapacitors, silica-based nanofibers are effective separators or electrodes. Discussed electrospun nanofiber electrodes with improved electrolyte diffusion and charge transport characteristics. Electrospun SiO_2 carbon composite nanofiber anodes enhanced specific capacity and cycle stability compared to conventional graphite anodes. The porous nature of silica aids in accommodating volume changes during lithiation/delithiation, while the carbon component improves electrical conductivity. Furthermore, electrospun SiO_2 PVDF-HFP nanofiber membranes have been proposed as advanced separators with enhanced thermal stability and electrolyte wettability.

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CONCLUSION

This systematic literature review highlights the significant potential of silica waste as an eco-friendly base component in nanofiber production via electrospinning. Various waste sources, such as rice husk ash, glass waste, and geothermal sludge, demonstrate high silica content, making them suitable for conversion into nanofibers after appropriate purification. Electrospinning efficiency is highly influenced by solution viscosity, conductivity, applied voltage, and ambient conditions, which must be optimized to achieve desirable fiber morphology.

Silica-based nanofibers derived from waste exhibit excellent functional properties for applications in filtration, biomedical devices, and energy storage systems. However, challenges remain, particularly regarding waste heterogeneity, process scalability, and consistency in nanofiber performance. Future research should prioritize improving process control and integrating these technologies into sustainable and circular material development frameworks.

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