A Perspective on the Supersonic Solution Blowing: Nanofibers at the Forefront of Energy Storage and Conversion, and Environmental Remediation

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Nanofibers play a crucial role in energy storage and conversion, catalysis, and environmental remediation applications. These nanomaterials, characterized by their high surface-to-volume ratio and porous structure, exhibit exceptional properties that render them ideal for various energy applications such as in fuel cells, lithium-ion batteries, supercapacitors, catalysis, and hydrogen production. This discussion outlines the historical context of electrospinning (ES), acknowledging its limitations in terms of commercial viability. Introducing the supersonic solution blowing (SSB) technique as a promising alternative, its energy-efficient process holds potential for commercial feasibility. The ES has remarkable advantages in nanofiber fabrication but faces limitations due to high operating costs. Solution blow spinning (SBS) offers speed and versatility; however, fibers have a broad distribution of diameters. SSB therefore overcomes some of the limitations of both ES and SBS techniques to produce defect-free nanofibers with smaller diameters at higher throughput rates. In this concise perspective paper, we emphasize the primary contributions of nanofibers to the development and optimization of materials used in energy applications. Drawing parallels with the prevalent ES and SBS techniques in the literature, we conclude with a discussion on the potential benefits that may arise as researchers increasingly explore this emerging and more efficient technique.

Keywords: nanofibers, energy storage and conversion, environmental remediation, SSB, SBS

1. Introduction

Nanofibers are structures that have been extensively investigated due to their novel physical properties.[1] They have a high surface-area-to-volume ratio, excellent flexibility, and superior mechanical properties. These unique characteristics make nanofibers suitable for a wide range of applications in various fields.[2,3] In energy storage and conversion, nanofibers are used due to their large specific surface area and excellent flexibility. They are also used in environmental monitoring and treatment. Furthermore, nanofibers are used in the production of electronic, optical, and semiconductor devices. They are also used as sensors, polymer fillers, and nonwoven porous membranes. The ease of tuning their structures, functionalities, and properties makes nanofibers a promising material for emergent applications[4] (Figure 1).

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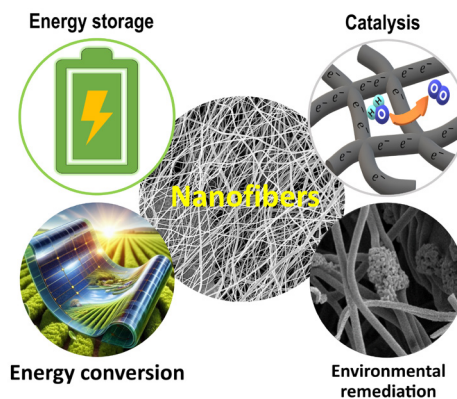Editor handled this article: Aldo José Gorgatti Zarbin (Guest)

Figure 1. Nanofibers and their possible applications in the field of energy storage and conversion, and environmental remediation.

Electrospinning (ES) is the oldest technique for obtaining micro- and nanofibers with high quality and control of the average diameter distribution. However, its main disadvantage is the need for high electrical voltages (normally 10-40 kV, but can reach 100 kV), which limits its viability on an industrial scale, which in addition to

safety risks increases production costs.[5] On the other hand, solution blow spinning (SBS) was firstly introduced in 2009[6] offering a productivity rate dozens of times higher than ES, however, in general, this technique produces micro and nanofibers with diameters larger than those produced by ES.[6] In 2013, Sinha-Ray *et al.*[7] reported supersonic blowing spinning (SSB), which combined elements from the two previous techniques, enabling the production of nanofibrous membranes with ultra-low diameters (20-50 nm), using only ca. 40-30% of the energy consumed by the ES technique.[8]

Since the first report, the SSB has been applied in some fields, including energy conversion and storage[8] as well as environmental remediation,[9] for example. The SSB technique allows to produce nanofibers that can be used as electrode materials in heterogeneous catalysis and electrochemical energy storage devices, such as double-layer supercapacitors and battery-type electrodes, and filtration membranes for environmental remediation.[10-13] The focus of this technique is on large-scale application, and it often involves the synthesis of nanofibers from abundant, low-cost materials with good electrochemical properties. The results of the properties of electroactive materials when produced using the SSB technique have been superior to those produced by conventional ES.

Thus, our intention is to highlight the main advances that the SSB technique must contribute to the development of new materials and devices based on nanofibers. We aim to underscore the primary challenges that remain for the scalability of the process, as well as the key parameters of the technique that directly influence the properties of the obtained nanomaterials. It is important to emphasize that the exploration of SSB to produce energy materials is still in its initial stage, particularly when compared to more established techniques such as electrospinning. Despite the promising potential of SSB, the field is relatively underexplored, which contrasts with electrospinning, a technique that has been extensively studied and widely applied in the production of nanofibers for several decades in the energy field. However, SSB research presents both challenges and opportunities. On one hand, the limited depth of research underscores that various facets of the technique remain not fully understood, demanding further exploration to optimize process parameters, improve scalability, and enhance the properties of the resultant nanofibers. On the other hand, the novelty of the field presents abundant opportunities for pioneering research and the potential to make substantial contributions to the advancement of next-generation energy materials grounded in nanofibers.

2. Nanofibers

Nanofibers are classified as one-dimensional (1D) materials, which means that one of their three dimensions must be at the nanoscale. Nowadays, materials with a diameter less than 1 μm are considered nanofibers, although they were previously defined as materials with a diameter less than 100 nm.[14] Another distinctive feature of these materials is their high aspect ratio, that is, the L/D (length-to-diameter) ratio, which generally should be greater than 50. This is crucial to differentiate these materials from other 1D nanostructures such as nanofibrils, nanowires, nanorods, and nanotubes.[15] The properties of nanofibers strictly depend on their diameter (mainly), length, and surface features, such as roughness, porosity, and the presence or absence of defects.[4] These are the minimum parameters to be considered in the design and applications of nanofibers, since the surface area, conductivity (electrical, ionic, and thermal), diffusion coefficient, reactivity, selectivity (in sensors), and general mechanical properties can be adjusted during the synthesis stage.[4,5]

As previously mentioned, the properties of nanofibers are intrinsically linked to the morphological characteristics of their surface and structure. Therefore, nanofibers with intentionally rough, porous, and hollow structures have been produced to achieve better performance, as these changes contribute to the increase in surface area. The aspect ratio of nanofibers allows the creation of other nanostructures (0D-3D) on these materials, making them platforms with additional functionalities.[16,17] Figure 2 presents some examples of nanofibers with modified surface and structure.[18] Considering the various possibilities that can be achieved by synthesis, surface modification, and compositional changes, nanofibers of polymers, ceramics, carbon, metals, and composites have been produced for a wide variety of applications. This includes environmental remediation, sensors, biomedical applications, tissue engineering, agriculture, catalysis and photocatalysis, wearable electronic devices, as well as energy generation and storage.[17]

Specifically, nanofibers have been the subject of considerable interest for applications such as electrodes in devices aimed at energy conversion and storage.[3] This is attributed to the ability of nanofibers, when randomly distributed, to form a self-sustaining three-dimensional network, resulting in a highly porous membrane that enhances the transport properties of the electrodes.[19] In energy storage devices, these one-dimensional materials have demonstrated greater efficiency compared to zero-dimensional materials, such as nanoparticles. In the manufacture of electrodes for lithium-ion batteries,[20] for
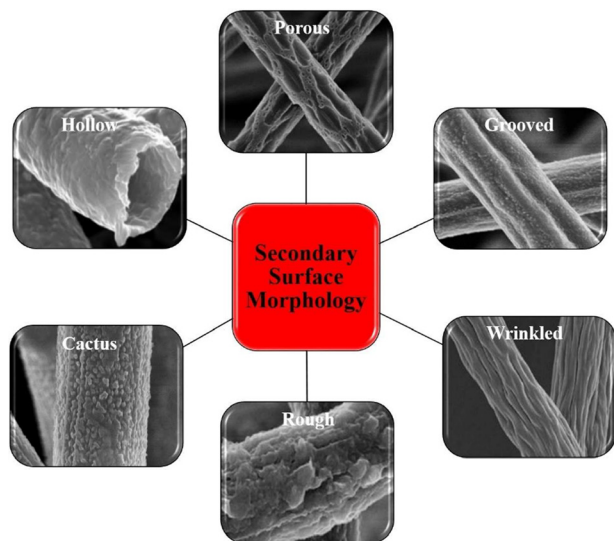
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Figure 2. Examples of surface-modified nanofibers (reprinted from Zaarour *et al.*[18] with copyright permission 2020 from Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim).

example, nanoparticles present inherent disadvantages due to their morphology. This includes a low volumetric capacity, due to the large interparticle space, and the need for additives and binders in the preparation of an ink, which increases the internal resistance of the battery, generates agglomerations and non-uniformity, thus compromising the performance of the device.[20] These problems can be overcome by nanofibers, due to their ability to function as self-sustaining electrodes, eliminating the need for any ink production in the electrode manufacturing.[21]

3. Supersonic Solution Blowing (SSB)

Nanofibers have garnered significant attention given the possibilities of applications, leading to advancements in their production processes. Various techniques have been employed for synthesizing nanofibers, which can be broadly categorized into two main groups based on the spinning methods:[4] electrospinning and non-electrospinning techniques. The first one, the electrospinning techniques, where electrostatic forces are responsible for the production process of micro-and nanofibers.[22] This technique tends to produce nanofibers with better quality (absence of defects); however, it has been economically unfeasible due to high energy consumption. The second, non-electrospinning techniques, rely on mechanical forces (centrifugation or aerodynamic forces) to produce micro- and nanofibers. These non-electrospinning methods encompass solution blowing spinning, centrifugal spinning, melt blowing, phase separation, and others.[1] The latter category often yields micro- and nanofibers at a larger scale, albeit with a slightly increased average diameter and the occasional

presence of defects. Until recently, it was necessary to use one of the two categories to produce nanofibers. When selecting among these techniques, factors such as desired diameter range, cost, required quantity, and the specific fibrous material play a crucial role in decision-making.

In 2013, Yarin and co-workers[7] introduced the SSB, also known as supersonic nanoblowing and electrically-assisted supersonic solution blowing. In the SSB system, an electrospun polymer jet is directed towards a Laval nozzle, which acts as a counter electrode. Simultaneously, the nozzle emits an air flow at a supersonic speed (above 560 m s^{-1}). This accelerated air flow causes the forced evaporation of the solvent and imposes a stretch of the order of 10^{10} s^{-1} due to the shear forces of the air. The intense force of the supersonic blow can break the van der Waals bonds between the polymeric chains, resulting in a marked stretch in the direction of the jet flow and, consequently, a drastic reduction in the diameter of the fibers.[23] This allows the reduction of the average diameter of the fibers by up to an order of magnitude compared to the ES and SBS techniques, as was reported to produce nanofibers of nylon 6,[7] poly(acrylonitrile) (PAN),[9] and natural rubber.[24] More detail about the operating principle (experimental and video) can be seen in the works of Silva *et al.*[8,25] Therefore, the main advantage of SSB over other more traditional techniques is the ability to produce nanofibers with smaller diameters which, consequently, allows a larger surface area (> 4000 m^2 g^{-1}).[8] In direct comparison with the most used technique in the literature, SSB requires only about 30-40% of the energy required by electrospinning to produce nanofibers with similar characteristics.[25] Furthermore, SSB enables the spinning of natural polymers, which is difficult to achieve by ES due to the need for volatile and environmentally friendly solvents.[26] Figure 3 presents a schematic of the configurations of the three techniques: ES, SBS and SSB.

4. Nanofibers in Energy Storage

Nanofibers based on carbon, metal oxides, polymers, and composite, have shown great potential in energy storage and conversion systems due to their unique properties such as their nanoscale diameter, large surface area, excellent thermal and electrical conductivity, and mechanical flexibility. As previously discussed, the engineering of these nanostructures, along with the introduction of surface modifications, results in substantial enhancements in their surface and transport properties. Consequently, these materials become highly appealing for a wide range of applications. For example, for energy storage systems such as supercapacitors and batteries, nanofibers enhance the
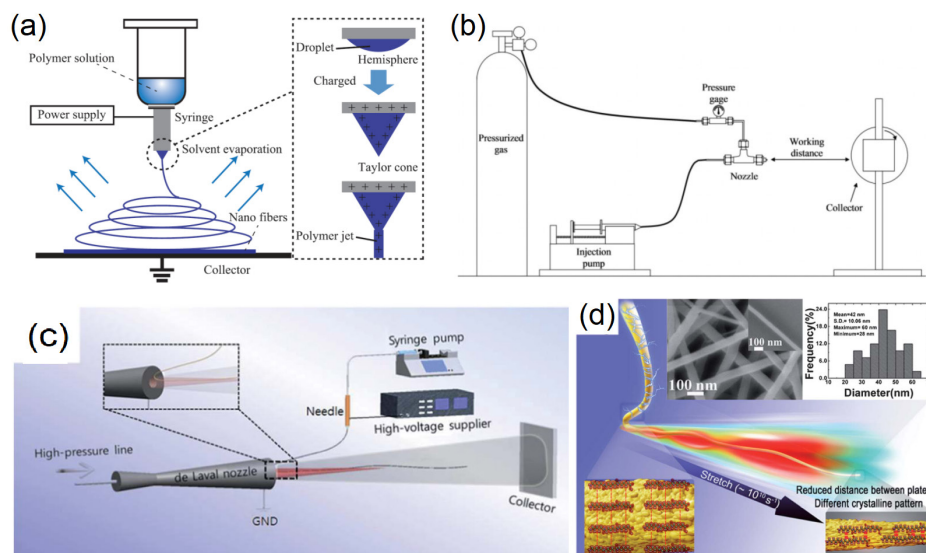
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Figure 3. (a) Classical electrospinning (ES) setup (reprinted from Maeda *et al.*[27] with copyright permission 2015 from Copyright Clearance Center); (b) classical SBS setup (reprinted from Medeiros *et al.*[6] with copyright permission 2009 from Wiley Periodicals, Inc.); (c) SSB setup and (d) effect of supersonic blowing on stretching the polymer chain and, consequently, reducing the fiber diameter (reprinted from Sinha-Ray *et al.*[7] with copyright permission 2013 from Royal Society of Chemistry).

adsorption and diffusion process of electrolyte ions due to their high surface area, porous structure, and short diffusion range. Their nanoscale diameter exposes more active sites for better adsorption of species, favoring electrochemical reactions and improving battery performance. On the other hand, their interconnected porous structure accelerates ion transport, drastically increasing the capacity of electrical double-layer capacitors (EDLCs). Thus, the one-dimensional nature shortens the ion/electron diffusion pathways, improving the kinetics of the intercalation/deintercalation processes. These properties make nanofibers ideal materials for applications in energy storage devices.

Recently, our group[8] reported for the first time the synthesis of carbon nanofibers with an ultra-high surface area (> 4000 m^2 g^{-1}) with a fiber diameter of 60 nm using the SSB technique. These nanofibers were investigated as electrodes for self-supporting EDLC-type supercapacitors. When employed as electrodes in symmetric cells (coin cells), we observed supercapacitance values in the range of 117-242 F g^{-1} in aqueous electrolyte (17 m NaClO$_4$, seventeen molal). The symmetric device, built based on the ultra-porous sample, delivered high energy density, and output power (27.2 Wh kg^{-1} at 0.77 kW kg^{-1} and 13.6 Wh kg^{-1} at 192.6 kW kg^{-1}). Based on these results, we confirmed that the SSB technique can be employed to obtain carbon nanofibers with ultra-high surface area, serving as new functional materials for self-supporting energy storage devices, without the need for physical or chemical activation of the nanofibers to achieve a microporous structure.

Joshi *et al.*[12] employed the SSB technique to fabricate reduced graphene oxide (rGO) loaded Fe–Fe$_3$C nanofibers

as anodes for lithium-ion batteries. The primary objective of their work was to explore a novel synthesis approach that could enhance battery performance using this unique nanofibrillar composite. The authors observed that the supersonic spinning process facilitated rapid and simultaneous coupling of exfoliated rGO within the nanofibers, a feat challenging to achieve using traditional electrospinning methods. This critical step significantly improved the conductivity, surface area, and stability of rGO-based electrodes, ultimately leading to more efficient energy storage. The electrochemical evaluation revealed an outstanding reversible capacity of 558 mA h g^{-1} at a current density of 1500 mA g^{-1} after the 200th cycle. Remarkably, this performance surpasses previously reported[12] values for other morphologies of the same composition. These findings position the nanofibrillar anodes as promising candidates for advanced lithium-ion battery applications.

Exploring new high-performance self-supported nanofibrillar composites as anodes for lithium-ion batteries, our group[25] recently reported a study on the synthesis of carbon nanofiber (CNF) composites containing varying concentrations of silica (SiO$_2$) nanoparticles. These composites serve as anodes for lithium-ion batteries. The resulting nanofibers exhibited an average diameter ranging from 86 to 271 nm and specific surface areas (SSA) between 619-1981 m^2 g^{-1}. Notably, the nanofibers displayed a well-defined tri-modal micropore-size distribution pattern. It was observed that the SiO$_2$ content significantly influenced several key parameters (diameter, SSA, pore-size). Regarding electrochemical performance, the addition of SiO$_2$ nanoparticles (up to 2.5%

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concentration by weight) led to an enhanced capacity of 305-444 mA h g^{-1} at 0.1 A g^{-1}. However, when the silica content exceeded 10-20 wt.%, performance declined due to increased nanofiber diameter, reduced SSA, and decreased porosity caused by nanoparticle agglomeration which led to an increase in charge transfer resistance. An interesting finding emerged from the diffusion length calculations. These calculations aligned with the average nanofiber diameters observed via field-emission scanning electron microscopy (FESEM). This alignment suggests that the diffusing lithium species can fill the entire interior of the nanofibers. Furthermore, the composite demonstrated mechanical robustness. After subjecting it to cyclability testing, was verified that the nanofibrillar morphology remained intact.[25]

Thus, this innovative approach of using SSB to create self-supported nanofibers holds promise for advancing supercapacitors, and lithium-ion battery technology. As can be seen, a limited number of studies have investigated the SSB technique for energy storage, it is evident that several other energy storage technologies could derive significant advantages from adopting the SSB method to enhance the development of technologically advanced electrodes.

5. Nanofibers in Energy Conversion

Heterogeneous catalysis serves as a pivotal component in the realm of clean energy conversion, facilitating the proficient transformation of raw materials into utilizable energy forms.[28] It underpins a multitude of energy conversion processes, encompassing hydrogen production, methane reforming, water electrolysis, and CO$_2$ reduction.[29] Within this context, the incessant research and development in catalysts are indispensable for surmounting the challenges concomitant with clean energy conversion, such as conversion efficiency, catalyst durability, and the mitigation of undesirable by-products.

The efficiency of catalysts can be enhanced through the adjustment of composition and morphology, with the latter being crucial for heterogeneous catalysis. It is known that nanostructures, due to their reduced size and high surface area, can offer highly active catalytic sites. However, some drawbacks may occur, such as the deactivation of the catalyst due to the high reactivity of the nanomaterial.[30] Therefore, precise control and investigation of the morphology of nanostructures are fundamental for the development of more efficient and robust heterogeneous catalysts for applications in clean energy conversion and generation.

Silva *et al.*[31] investigated the effect of the morphology of nickel oxide (NiO) nanostructures on their catalytic activity

toward the oxygen evolution reaction (OER) in an alkaline medium. One-dimensional hollow nanofibers (NiO-NFBs) synthesized by SBS were compared with 3D nanoparticles (NiO-NPTs) synthesized by a well-known citrate method (Figures 4a and 4b). Results confirm the superiority of NiO-NFBs, with a remarkable difference of 133 mV *versus* reversible hydrogen electrode (RHE) to generate a current density (j) of 10 mA cm^{-2} (Figure 4c). The NiO-NFBs showed a turnover frequency (TOF) value 122 times higher than NiO-NPTs (Figure 4d). The Tafel analysis and electrochemical impedance spectroscopy (EIS) revealed that the hollow structure favors kinetics through a more efficient process of mass and charge transfer. Overall, results corroborate the thesis that the morphology imposes the main rule on the electrocatalyst performance, since the morphology of NiO-NFBs is fully preserved after the electrolysis test, while NiO-NPTs degrade through a nanoparticle coalescence mechanism.[31] As a strategy to mitigate the effect of nanoparticle degradation during OER, the same authors later reported[32] an efficient method to produce nickel-nickel oxide nanoparticles embedded in carbon nanofibers (Ni–NiO/C), using the conventional SBS process. Where the carbon nanofibrillar matrix acting as a robust support, with well-dispersed nickel nanoparticles on the surface acting as active site (Figures 4i-4l). Only a small fraction of nickel on the fiber surface (ca. 1.2-5.3%) was found to promote substantial improvement in performance (overpotential (η) = 278 and 309 mV *vs*. RHE at j = 10 mA cm^{-2}) and significant turnover frequency (TOF) values of 1.38 (η = 278 mV *vs*. RHE) and 1.30 s^{-1} (η = 309 mV *vs*. RHE) (Figures 4m-4p).[32]

The valorization of CH$_4$ and CO$_2$ through dry reforming of methane is of great industrial interest, however, one of the main limitations of this process is the deactivation of the catalyst by carbon deposition. Therefore, the development of catalysts stable at high temperatures is crucial. Herminio *et al.*[33] explored the SBS technique to produce hollow and porous composite nanofibers of Ni/CeO$_2$ and studied it as a catalyst to produce syngas with a H$_2$/CO ratio close to 1 (Figures 5a-5d). The stability assessment of the self-supported catalyst was conducted at an operational temperature of 700 °C. The data obtained indicated insignificant deactivation after a continuous flow period of 30 h, with a reduction of only 4.5% in catalytic activity. This result was notably superior when compared to a conventional catalyst, which exhibited a severe deactivation of 84.2% after just 5 h of flow (Figure 5e). Furthermore, thermal analysis and X-ray diffraction of the Ni/CeO$_2$ nanofiber-based catalyst suggest that the deposition of carbon species did not compromise the stability of the catalyst. In terms of rate at 700 °C, the
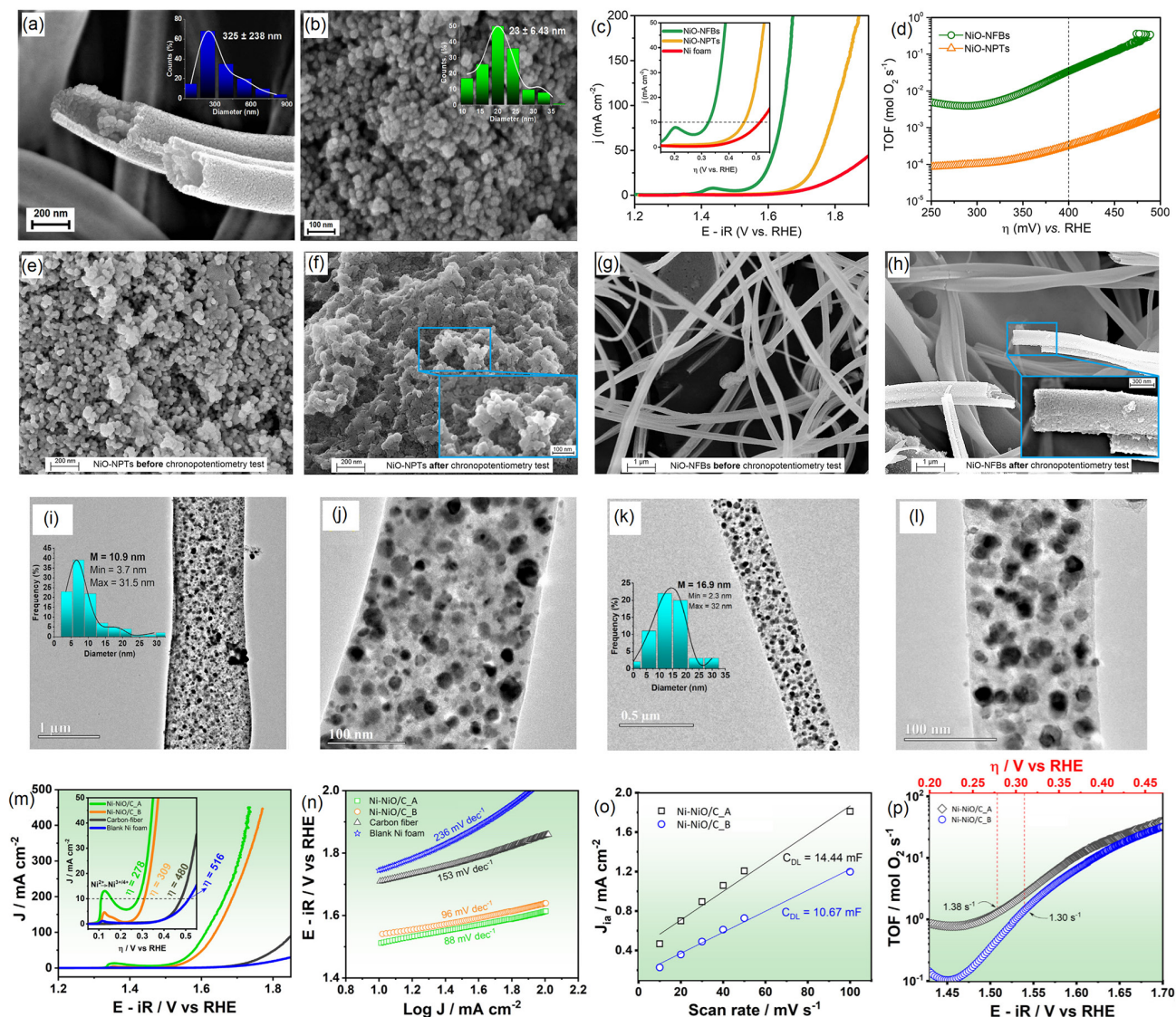
Figure 4. FESEM images of (a) NiO-NFBs and (b) NiO-NPTs; (c) linear sweep voltammetry (LSV) curve collected at 5 mV s^{-1} using as electrolyte 1 M KOH; (d) logarithm of turnover frequency (TOF) *versus* overpotential (η) in the OER regime; FESEM images before and after stability test for (e,f) NiO-NPTs and (g,h) NiO-NFBs (reprinted from Silva *et al.*[31] with copyright permission 2020 from Springer Nature); (i-l) TEM images of nickel-nickel oxide nanoparticles-embedded in carbon nanofibers (Ni-NiO/C) with different size of nanoparticles; (m) LSV curves and correspondent (n) Tafel slopes; (o) anodic current as function of the scan rate to determine the double layer capacitance (C_{DL}); (p) TOF *versus* overpotential (η) (reprinted from Silva *et al.*[32] with copyright permission 2021 from Elsevier).

H_2/CO ratio showed conversions after 1 h of 44 and 57% for methane and carbon dioxide, respectively (Figure 5e), resulting in a H_2/CO ratio of 0.66 at this temperature. These results reinforce the effectiveness and robustness of the self-supported nanofibrous catalyst under the required operational conditions.

Sekar *et al.*[34] conducted an evaluation of two metallic oxides (*p*-Cu_2O and *n*-TiO_2), with the objective of exploring the synergy between these materials in pursuit of simultaneous activity for photocatalytic H_2 production and environmental remediation. Titanium dioxide nanofibers (TiO_2-NF) were employed as a homogeneous support for the stabilization of Cu_2O nanoparticles on their surface

(Figures 5f-5h). This enabled the synthesis of Cu_2O nanoparticles with an average diameter of approximately 60 nm and high dispersibility. The integration of Cu_2O nanoparticles and TiO_2 nanofibers resulted in a remarkable synergistic photocatalytic performance. This was corroborated by a H_2 production rate of 48 μmol g^{-1} h^{-1} with an apparent quantum efficiency (AQE) of 3.6% (Figure 5i). Notably, this H_2 production rate was substantially higher, by a factor of approximately 6.5 times, when compared to the unmodified TiO_2-NF (Figure 5j). Additionally, the synergistic photocatalyst Cu_2O/TiO_2-NF exhibited notable oxidative degradation of sulfamethoxazole, with a degradation rate of 7×10^{-2} mmol g^{-1} min^{-1}, demonstrated

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high stability. Furthermore, the authors attributed these promising results to the composition and nanofibrillar morphology of the catalyst.

Continuing with the strategy of developing nanofibers as a support for metallic nanoparticles to act as active catalytic sites, Lai *et al.*[35] employed the electrospinning technique to fabricate atomically dispersed Co–N$_4$/C porous carbon nanofiber (Co–N–PCNF) as support for intermetallic L1$_0$-PtCo nanoparticle for fuel cells applications. The nanofiber-supported catalyst exhibits excellent performance in a proton exchange membrane fuel cell (PEMFC) reducing drastically the O$_2$ transport resistance (pressure-independent) with higher dry proton accessibility, and excellent durability with 99 and 73% mass activity retentions after 50,000 and 100,000 cycles, respectively. Using density function theory (DFT) calculations the authors suggest that the nanofiber structure plays a crucial role in the kinetics of the oxygen reduction reaction.[35]

6. Nanofibers in Environmental Remediation

Environmental remediation is closely linked to sustainable energy. It involves site cleanup, ecosystem restoration, and safe waste disposal. Notably, it directly impacts renewable energy infrastructure, allowing projects to thrive in areas that were once polluted.

Moreover, it contributes to improved water quality, efficient management of solar panel waste, and carbon sequestration.[36] By addressing environmental challenges, we open the way for cleaner and greener energy systems. Nanofibers have been applied to various environmental remediation challenges that englobes some examples as the air filtration, water treatment, antimicrobial treatment, and heavy metal removal.[4]

Sinha-Ray *et al.*[23] investigated the filtration efficiency of commercially available filter media. Traditionally, electrospun nanofibers are added to enhance filtration. However, this study introduces the SSB technique to deposit nanofibers onto commercial filter membranes (Figures 6a and 6b). By incorporating a layer of ultrafine 20-50 nm nanofibers, the filtration efficiency of filter media with fiber/pore sizes around 10 μm is dramatically increased. As a result, an increase of up to 25% in efficiency was observed in the filtration of 0.2-2 ppm aqueous suspensions containing 50-300 nm copper nanoparticles. The authors proposed a theory, which was experimentally verified, suggesting that the smaller nanofibers (the 20-50 nm supersonically solution-blown ones) are more efficient collectors of nanoparticles than the larger (300-500 nm) electrospun nanofibers due to attractive forces imposed by van der Waals interactions in the nanofibers with diameter smaller than 100 nm. From their theoretical
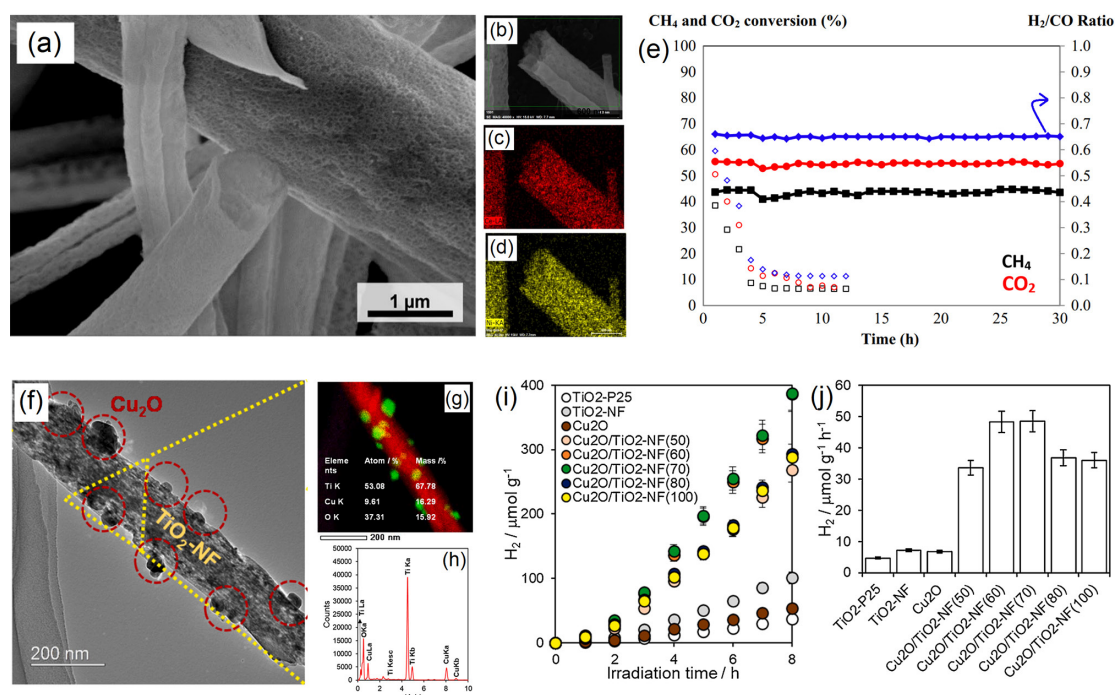

Figure 5. (a) FESEM of the fibers; (b-d) EDS mapping showing the uniform distribution of Ce and Ni; (e) stability test at 700 °C for 30 h, where the full symbols are assigned to the Ni/CeO$_2$ fibrous catalyst, and empty symbols to the classical (reprinted from Herminio *et al.*[33] with copyright permission 2020 from Springer Nature); (f) HR-TEM images of Cu$_2$O/TiO$_2$-NF; (g) elemental mapping and (h) corresponding EDX; (i) amount of H$_2$ produced via photocatalysis and (j) corresponding rates of H$_2$ production across various catalysts (reprinted from Sekar *et al.*[34] with copyright permission 2021 from Elsevier).

findings, the authors observed that nanofibers of such dimensions can create an interaction field with a radius of up to 100 nm for capturing nanoparticles through the van der Waals forces. The efficiency in the number of nanoparticles captured decreases with the increase in the diameter of the nanofiber that constitutes the filtration membrane (Figure 6c). This research sheds light on a promising method for improving nanoparticle filtration processes, which is applied across various industries such as biomedical, cosmetics, food processing, and semiconductor manufacturing.[23] Posteriorly, Chen *et al.*[9] combined the van der Waals and electric forces effects to improve the filtration of commercial gassy fiber membranes (GFM). They also used the SSB to deposit in filter membranes nanofiber with 80 nm diameter, then it was sputter coated with a thin Pt layer of 10 nm to improve the conductivity. When they used the electric forces, the filtration efficiency increased by the factor of ca. 2.3-fold compared to the van der Waals forces by itself. In comparison to filter membranes with approximately 500 nm fibers operating solely under van der Waals forces, the combined van der Waals-electric filter membrane with approximately 90 nm fibers exhibits a ca. 4-fold increase in filtration efficiency.[9]

In an innovative work, Kakoria *et al.*[11] developed nanofiber mats using waste plastic bottles (polyethylene terephthalate, PET) produced by ES and SSB to be applied as filtration of particulate matters (PM). The initial tests confirmed the superior efficiency of nanofiber

membranes obtained through SSB compared to ES. This was because the finer SSB fibers allowed for a smooth airflow, enhancing the interaction between fibers and particles, with a focus on PM capture through diffusion. The porosity and hydrophobicity parameters have been contributed as well for performance of the SSB mats. When a prototype facemask using SSB mat was made, it maintained particle filtration efficiency (PFE) for PM even after 21 days of regular use, with only a 4% reduction in particle filtration efficiency. Surprisingly, the facemask was washed and retained over 99% PFE for PM after 10 cycles of handwashing and sun drying (Figure 6d). Thus, this research transforms waste PET bottles into high-performance nanofiber filters, contributing to both environmental conservation and public health.[11]

Thus, nanofibers play a crucial role in addressing environmental issues, offering innovative solutions for cleaner air, water, and soil. Several studies[5,37-40] have employed the techniques of ES or SBS for the removal of oil, and water purification, for example. However, for these mentioned applications using nanofibers, no studies have yet explored the SSB technique in the literature. Considering the advantage of SSB in producing fibers predominantly with a diameter below 100 nm, theoretically, we would expect better results with this approach due to the benefits imposed by the significant reduction in the diameter of these nanomaterials, as previously mentioned in Nanofibers section.
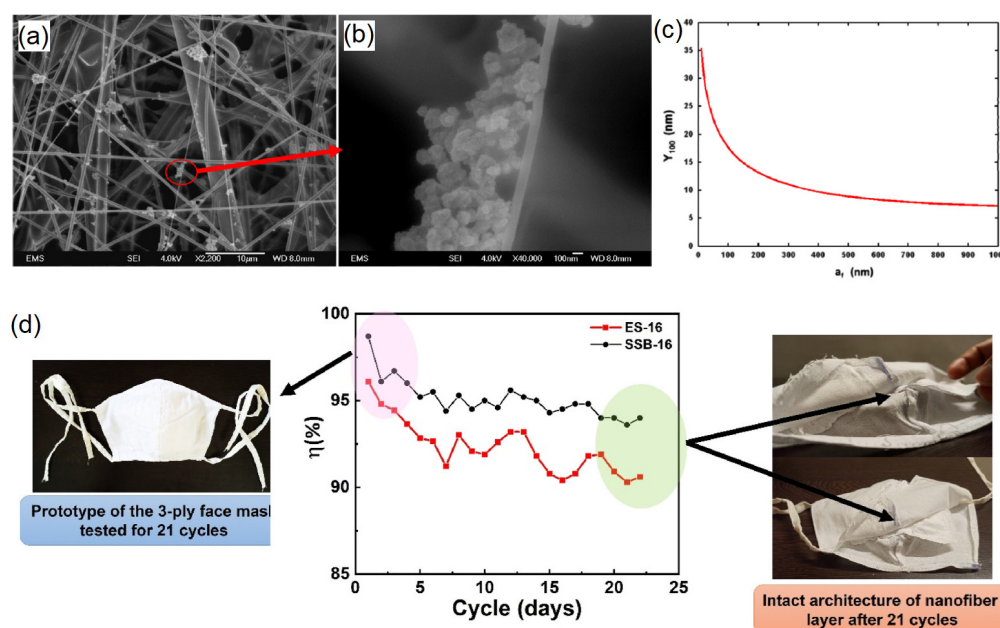

Figure 6. (a) FESEM image of a dual-coated filter with thick nanofibers (obtained by ES) and thin (obtained by SSB); (b) detailed images of nanoparticles agglomerated (captured) by a nanofiber produced by SSB; (c) result of theoretical calculations for the correlation between the capture of nanoparticles by van der Waals attraction with the variation in the length and diameter of the nanofibers (reprinted from Sinha-Ray *et al.*[23] with copyright permission 2015 from Elsevier); (d) results of 21-day cyclic efficiency measurement of mats (ES and SSB) designed in prototypes of 3-ply face mask. The architecture was intact after a heavy test protocol (reprinted from Kakoria *et al.*[11] with copyright permission 2021 from Elsevier).

In summary, the ES offers remarkable advantages in nanofiber fabrication, but it also has limitations. Although it is the oldest technique for producing nanofibers, its large-scale application is still limited by the high operating cost due to the substantial amount of energy required. On the other hand, the SBS provides speed, simplicity, and versatility. However, the distribution of larger diameters can be a problem. Lastly, the SSB offers advantages in terms of speed, nanofibers without defects, and smaller diameters. Nevertheless, research should also consider its limitations when selecting it for specific applications (such as biomedical applications for *in situ* spinning). Table 1 makes a complete comparison of the advantages and disadvantages of the ES, SBS, and SSB techniques, and as can be seen, there is still a range of applications that can be explored by the SSB technique.

7. Outlook

Looking to the future, the significance of nanofibers in fields such as energy storage and conversion, heterogeneous catalysis, and environmental remediation is profound. Their extraordinary attributes, including ultra-high surface area and flexibility, render them ideal materials for cutting-edge energy storage and conversion systems like supercapacitors. Nanofiber capacity to deliver high energy density and power output could revolutionize our energy infrastructure, ushering in more efficient and compact energy storage and conversion mechanisms. Furthermore, the potential to fabricate self-supporting energy storage devices using nanofibers could simplify the production process and lower costs by eliminating the need for physical or chemical activation. In the context of heterogeneous catalysis, the high surface area of nanofibers can provide many active sites, enhancing the catalytic efficiency. For environmental remediation, the adsorptive properties of nanofibers could be exploited for effective pollutant removal. As we continue to explore these applications, it is evident that nanofibers will play a central role in sustainable energy solutions and environmental cleanup. Ongoing research and innovation are crucial to fully unlock the potential of these materials and tackle any associated challenges.

Table 1. Comparison of the advantages and disadvantages of ES, SBS, and SSB techniques

Technique	Advantage	Disadvantage	Recent applications[a]
Electrospinning (ES)	consolidated technique; fibers with smaller diameters (≤ 100 nm); narrower diameter distribution range; core-shell system; high surface area nanofibers	limited to the use of polar solvent; higher cost (high energy consumption); safety risk due to high voltages (kV); limitations regarding the use of solvents; jet instability; *in situ* spinning is not possible due to high electrical voltage	batteries;[41] supercapacitors;[42] fuel cells;[43] catalysis;[5] photocatalysis;[19] solar energy;[41] steam reforming;[41] water purification;[37] filtration;[44] green hydrogen[45]
Solution blow spinning (SBS)	low cost; production in large-scale; speed in the process; safer technique; high surface area nanofibers; no limitations on the types of solvents; low surface area nanofibers; adaptation to industrial scale; core-shell system; *in situ* spinning onto biological systems (tissue and organs); no needs electric tension	fibers with a slightly larger diameter (≤ 1 μm); less control over diameter distribution; it is sensitive to humidity variations; instability in the nozzle	batteries;[46] supercapacitors;[47] fuel cells;[48] catalysis;[49] photocatalysis;[50] solar energy;[51] steam reforming;[33] water purification;[40] green hydrogen[31]
Supersonic solution blowing (SSB)	fast fiber generation; fiber with smaller diameter (< 100 nm) and uniform; ultra-high surface area nanofibers; superior yield than ES; more economic (60-70%) and safe than ES; self-supporting electrodes; more sustainable than ES	limited morphology control; reduced control over fiber alignment; still needs high voltage but less than ES; challenges in large scale	batteries;[12,25] supercapacitors;[8] filtration;[23,52] water purification[11]

[a]Refers to some applications reported in the literature for each technique. However, the SSB technique refers to all applications found in the literature until the publication date of this paper related to the proposal of this work.

However, it is important to note that the effectiveness of nanofibers in the abovementioned applications depend on factors such as the type of nanofiber (composition and secondary surface morphology), the specific design of the energy storage system, and the methods used to incorporate the nanofibers into the system. For example, the induction of porosity can increase the capacity of nanofibers to store more ions, however, this can compromise their flexibility and, consequently, mechanical resistance. Therefore, the modifications induced on the nanofibers to increase some properties must be carried out through a systematic study in order not to sacrifice the others, or at least, reduce the negative effects on the other properties to the minimum possible.

An analysis of the studies shown here revealed that the predominant techniques for producing these nanomaterials are ES or SBS. In contrast, the alternative technique, SSB, which is a further development of ES and SBS,[6] and produces fibers with smaller diameters and an extremely high surface area, is still little explored (see Table 1). Therefore, it is reasonable to predict that, as the SSB technique is further explored, we will be able to achieve results superior to those currently reported in the literature.

8. Conclusions

In conclusion, the SSB technique holds great promise to produce nanofibers, potentially revolutionizing their application in energy generation and storage, catalysis, and environmental remediation. The supersonic solution blowing technique offers several advantages over traditional nanofiber production methods. Firstly, it allows to produce nanofibers with smaller diameter, which is beneficial for a range application. Secondly, it provides greater control over the morphology of the nanofibers, enabling the production of nanofibers with specific properties tailored for energy applications. Despite electrospinning's historical importance in nanofiber production, its commercial viability is still limited. The energy efficient SSB technique, however, holds potential for future commercial feasibility. Nevertheless, further research and development are needed to fully realize the potential of this technique and to overcome the challenges associated with its scaleup.

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Author Contributions

Vinícius D. Silva was responsible for the conceptualization, writing, review and editing; Eliton S. Medeiros for the writing, review and editing; Roberto M. Torresi for the conceptualization, writing, review and editing, project administration, funding acquisition.

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