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Nanofibers: where they are where we need them to be

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This perspective article focuses on polymeric and inorganic nanofibers and their synthesis. The reason for this material to be put in perspective is—with all the respect to those, who contributed to its development—it has not made it as far as people thought in past that it would and could. This article aims to put in perspective a summary and outlook, what remaining steps need to be done and overcome, so that these nanofibers become industrially viable and feasible to produce, and that end users can finally profit from their utilization in various applications.

KEYWORDS

nanofibers, polymeric, inorganic, synthesis, electrospinning technology, centrifugal spinning

General economic aspects and considerations about nanomaterials

Synthetic chemistry, chemical engineering (incl. catalysis) and materials sciences have been experiencing a huge growth over past few decades. Many different kinds of materials, including nanomaterials, in form of nanosheets (Wang et al., 2025), nanopowders (Talapin and Shevchenko, 2016), nanotubes (Lee et al., 2014), nanofibers (Huang et al., 2003; Jiang et al., 2018), etc. and various other complex shapes (including 3D printed ones), have been scientifically explored over these years for various applications, but mainly on the laboratory scale. Without any link to the industry and industrial scale!

In fact, thousands of scientific publications have been published on these materials, providing some good or less good glimpse on what the materials can do or could do. However, only a small portion of these materials made it to real products, as a whole, or as a part. The reasons for that are complex, but most likely, the commercial production and application any material can be only realized, if at least two of the following three conditions become fulfilled:

1. The materials can be made reproducibly on an industrial scale,
2. The material costs are significantly cheaper and/or balanced with current costs but compensated by improved performance compared to the currently used material (so-call benchmark),
3. The material is much more stable and thus it can provide higher performance and/or offer an extended function, or significantly increase the material lifetime, ensure multiple turnovers, cycles, etc.

Different types of materials (and synthetic technologies behind them) typically face difficulty with one or another conditions. However, in this perspective article, I want to focus solely on nanofibers, as they have a prospect to fulfil all three criteria, at least in some cases and some applications. They represent one-dimensional (1D) nanostructure, whose

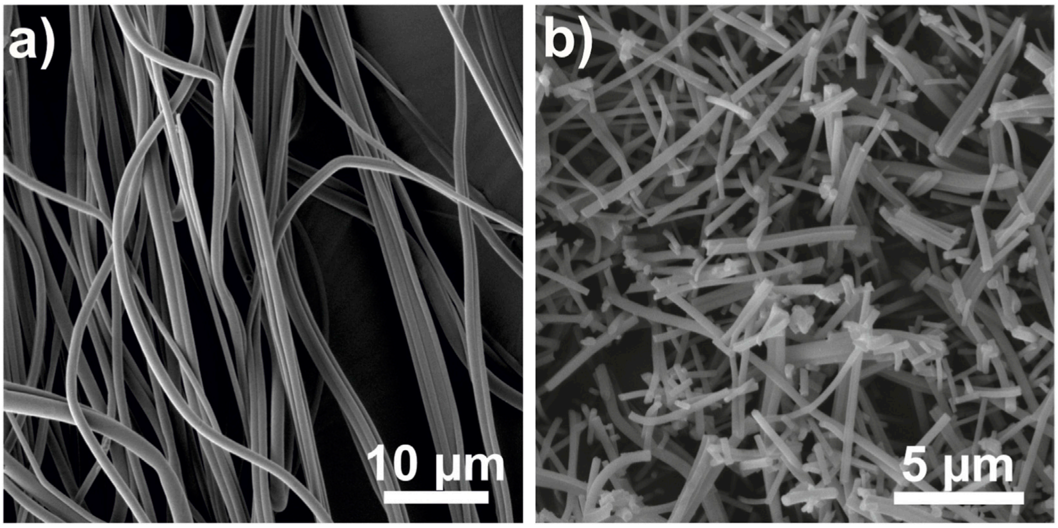

FIGURE 1
SEM images of **(a)** centrifugal spun polyvinylalcohol and **(b)** electrospun TiO_2 nanofibers. An average fiber diameter (and standard deviation) of these fibers is 9252 ± 310 nm and 292 ± 40 nm, respectively. Images taken with MIRA3 XMU TESCAN scanning electron microscope.

diameter is significantly short than their length. Figure 1 shows illustrative images of polymeric and inorganic nanofibers. It is generally accepted that even fibers with a diameter in the range of more than 100 nm up to 1 mm are entitled as nanofibers (Ramakrishna et al., 2005; Tan et al., 2005).

The reasons why we want to focus on nanofibers is that–in contrast to many other materials (that seemed even more interesting and many research groups rushed to get involved) – nanofibers really made it quite far in terms of their development, technologies behind to make them, and, finally, successful demonstration of excellent performance in various applications. But not far enough. For example, in cosmetics and filtration, the technology readiness level reached is already on the pilot scale demonstration. In other applications, the level has not reached this stage yet. However, the development needs to progress and this is the goal of this perspective.

The case of nanofibers

About 25 years ago, a massive wave of research in the synthesis and applications of nanofibers begun due to significant advancements and pushes in the electrospinning technology (Author Anonymous, 2027). Different groups around the globe advanced the electrospinning technology–in particular in terms of design of the spinneret, fiber collectors, fiber orientation, etc. (Ramakrishna et al., 2005; Tan et al., 2005; Barhate and Ramakrishna, 2007; Cengiz and Jirsak, 2009; Reneker and Yarin, 2008). Other groups focused on the development of polymers (incl. various copolymers) and search for their suitable solvents (Hiwrale et al., 2023; Mahalingam et al., 2015; Mit-Uppatham et al., 2004; Homaeigohar et al., 2012; Badrossamay et al., 2014; Wendorff et al., 2012; Agarwal et al., 2010).

Other groups focus on the process upscale and optimization and also on the fundamental understanding of the fiber formation process (Cengiz and Jirsak, 2009; Sivan et al., 2022; Pokorny et al., 2014; Guex et al., 2017). All these efforts have been valuable–they led to an extensive publicly available knowledge. But what is more, they led some pilot scale quantity of nanofibers that could be tested at that scale, which is a key condition for any company to be fulfilled before they can go on the market. The testing results - in particular in filtration and tissue engineering - turned out very positive. They underlined the expectations and that nanofibers do have really tremendous potential to be the materials of choice for these applications and no other material can beat them. But still, the move from “potential impact” to “groundbreaking and proven application” and “industrial production” has not happen yet. Some recent advancements, like alternating current (AC) electrospinning has expanded the technological options during the nanofiber synthesis, but the yield remains still rather low (Sivan et al., 2022; Pokorny et al., 2014; Al Saif and Cselkó, 2025).

In early 2010′s, intense efforts begun in a complimentary (and to a certain extent also competing) technology entitled centrifugal spinning (Sarkar et al., 2010; Vazquez et al., 2012; Xu et al., 2014). In that process, nanofibers are formed due to a high centrifugal force applied on the polymeric solution in the rotating spinneret, which has numerous nozzles with a certain diameter (typically a few hundreds of μm). Once the equilibrium between the surface tension of solution and the centrifugal force (which is significantly high for spinneret rotations of generally several thousands of rpm) is disrupted, the solution is expelled out from the nozzles of the spinneret in the form of many jets of fibers (Sarkar et al., 2010; Xu et al., 2015). Due to evaporation and strong air flow in the spinning chamber and the subsequent evaporation of the solvent, the newly born fibers reach the fiber collector and stay there for further collection (Sarkar et al., 2010; Vazquez et al., 2012). Theoretically, the fiber yield should be mainly affected by the speed of a spinneret, the distance of the collector and diameter of the spinneret nozzle (Naseri Joda et al., 2024). On the

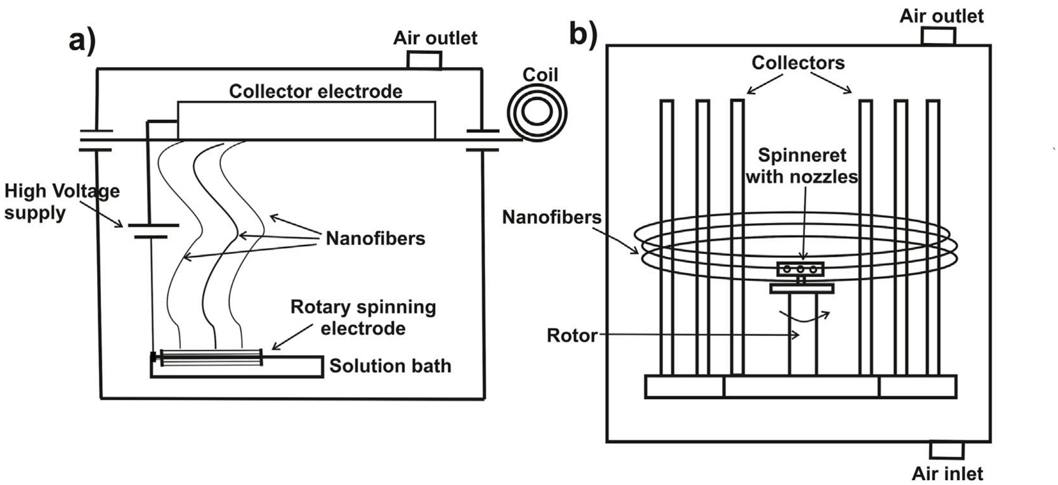

FIGURE 2
Schemes of **(a)** nozzle-less electrospinning and **(b)** centrifugal spinning technologies for nanofiber synthesis.

other hand, the fiber morphology and dimensions should depend primarily on the viscosity of solution, the rotational speed of the spinneret and the evaporation rate (Golecki et al., 2014). Depending on the process parameters and spinning solution, fiber with the diameter in the range of few hundreds of nm to few μm can be made (Sarkar et al., 2010; Rihova et al., 2021a). Depending on the design of the spinnerete, the entire solution can be spent into fibers, which has a positive cost figure for the process efficiency. Figure 2 provides an Illustrative comparison of electrospinning and centrifugal spinning technologies.

In recent literature, one can find experimental comparative studies between electrospinning and centrifugal spinning (Rihova et al., 2021a; Krifa and Yuan, 2016; Rogalski et al., 2018). The somewhat surprising outcome of these comparisons is that both technologies can be used to make to make high quality nanofibers from a whole range of polymers with relatively good control of nanofiber diameters. This is something that the electrospinning researchers probably would never trust that centrifugal spinning can do. The somewhat unsurprising outcome, and also verified from feedbacks from industries testing both technologies, is that centrifugal spinning, if done well and optimized, can have significantly higher yield of nanofibers per unit of time. And also that both techniques show significant sensitivity on atmospheric conditions, so they should be operated in some controlled atmospheres (hence the air outlets and inlets in Figure 2) (Rihova et al., 2021a).

While there are recent excellent academic reviews available, in particular for electrospinning (Xue et al., 2019), to the best of our knowledge, there are no studies that directly and comprehensively compare electrospinning and centrifugal spinning techniques in terms of the production rates versus the energy consumption versus the cost per gram in a comprehensive manner. Such comparison is challenging, as these parameters are highly system-dependent and vary significantly with the design of spinning heads, number of nozzles, collectors, and processing conditions. Such data set undoubtedly exist, but they represent companies´ secrets that are not to be shared.

Nevertheless, Table 1 below provides an illustrative summary, based on the extraction of publicly available data, comparing the yield, benefits, pros and cons for different technological configurations of both spinning systems. From this table, one can see that there are non-negligible differences in the production parameters among both techniques, in addition to other differences, such as in the quality and dimensions of the fibers.

It is also noteworthy to recognize “electro-centrifugal” spinning, a recently developed hybrid technique that merges electrospinning and centrifugal spinning in terms of integrating a high-voltage electrostatic field into a classical centrifugal spinning system, subjecting the ejected polymer jet to both centrifugal and electrostatic forces simultaneously (Khamforoush and Asgari, 2015; Xu et al., 2023). The addition of the electric field provides a very welcome stabilizing effect on the liquid jet, that leads to comparably lower number of defects (such as beads and droplets), hence offering promising improvements in the fiber fabrication efficiency. However, this technique still suffers from technical limitations, particularly the difficulty of ensuring a stable high-voltage supply to the rotating spinning head. But it can be expected that further research will lead to improvements.

Costs of nanofiber production go hand in hand with the costs of the chemical (raw materials) that are used to produce them. For the nanofiber synthesis, whether by electrospinning or centrifugal spinning, the major cost item has always been and will probably always be the cost of solvent, followed by the polymers itself. Many polymers are water insoluble, thus, one has to use alcoholic or other types of solvents that are costly, frequently also toxic (various types) and flammable. There was also a time, where researchers and industry thought that the melt spinning could do the job (Zander et al., 2017; O’Haire et al., 2016; Zander, 2015; Guo et al., 2025). However, after all trials and tests–it did not. Issues with limited polymer stability at elevated temperatures, their degradation and also clogging of parts of the spinning tools, rendered this approach also not very viable. In addition, the viscosity of polymer melts is much higher than that of polymer solutions, thus imposing challenges to draw the melted material into very fine fibers.

TABLE 1 Comparative table of important parameters and features of electrospinning versus centrifugal spinning processes.

Feature	Electrospinning	Centrifugal spinning
Driving force	Electrostatic field (high voltage)	Centrifugal force (mechanical rotation)
Primary mechanism	Electrohydrodynamic jet instability (whipping)	Mechanical jet ejection and stretching
Production rate (laboratory scale)	Very low (0.1–5 g/h) for single nozzle up to nozzle-less systems (Holopainen et al., 2015; Wang et al., 2009)	High (3–30 g/h) (Dotto et al., 2017; Ren et al., 2013)
Production rate (industrial scale)	Moderate (up to ~600 g/h), in particular for AC electrospinning (Elmarco, 2025; SKE, 2025)	Very high (up to 12,000 g/h)
Scalability	Challenging (electrical field interference, clogging)	Straightforward (mainly mechanical scaling)
Equipment cost	High (high-voltage supply, safety systems)	Lower (simpler mechanical setup)
Operational safety	High risk (high voltage)	Lower risk (mechanical hazards)
Material versatility	Limited (requires conductive/dielectric solutions)	High (independent of conductivity, melt-spinnable)
Typical fiber diameter	Very fine (10–500 nm)	Coarser (200 nm - 5 μm)
Fiber quality	High uniformity, fewer defects (beads)	Lower uniformity, prone to beading, droplets
Key advantages	Precision, ultra-fine fibers, high uniformity	High yield, low cost, safety, material versatility
Key limitations	Low yield, high cost, safety risk, material limits	Coarser fibers, lower uniformity

Furthermore, for inorganic nanofibers, even though they possess great properties and potential (e.g., in catalysis) a significant cost items is also the calcination of raw precursor nanofibers into fully inorganic nanofibers, which is done usually in a batch reaction way, rather than in continuous operation (H et al., 2017; Hromádko et al., 2021).

Without a big thinking, there are some applications, where nanofibers are really handy and can provide unique solutions that no other material from can offer.

In fact, so some applications, nanofibers and microfibers have already become an integral part of modern life. One of their most widespread and well-established applications is in filtration technologies, where nanofiber membranes are routinely employed in both liquid and air filtration units (Zhang et al., 2016; Hutten, 2025; Fahimirad et al., 2021; Yang, 2012). Aided with more than three thousand scientific publications on the research and development of fiber filters, numerous fiber-manufacturing now produce nanofiber filters on an industrial scale, owing to own development and efforts and also supported by extensive intellectual property portfolio. The filtration sector can be broadly classified into liquid filtration, primarily applied in water and wastewater treatment, and air filtration, which encompasses cleanroom filters, HVAC systems, and personal protective equipment. These materials represent one of the most advanced and mature stages of fiber commercialization, effectively reaching the highest Technology Readiness Levels (TRL) of 7–9.

For sorbents based on nanofibers, although their assemblies are similar to those of filtration units, there is quite some development too, however, they are not yet as far, having the TRL level on some 2-5 points (Zhang et al., 2016; Yasin et al., 2015).

Another industrially emerging segment involves cosmetic applications of fibers (Rihova et al., 2022; Rihova et al., 2025). Fiber-based facial masks have recently become available on the market, designed to deliver active compounds for skin nourishment and to prevent dermatological disorders. Although commercialized, there remains strong potential for further development through the incorporation of bioactive additives or controlled-release systems. While these materials demonstrate significant technological progress, their readiness level indeed remains somewhat lower (on the scale of 5–8) than that of filtration products, which are already fully industrialized.

In other biomedical applications, such as wound healing or drug delivery systems (Vocetkova et al., 2017; Dubský et al., 2012; Zajicova et al., 2010), the situation is more complex. Despite the existence of numerous scientific studies, industrial implementation is more challenging than in cosmetics, mainly because these products must undergo *in vivo* testing and extensive clinical validation. Such processes are time-consuming and typically take several years before market approval can be achieved. Consequently, although these materials are technologically promising, their readiness level remains lower compared to cosmetic or filtration applications. This reflects the additional regulatory and clinical hurdles required for biomedical commercialization. Overall, in this segment ´s TRL is on the scale to 3-6.

Finally, inorganic nanofibers have found applications in catalysis (Yasin et al., 2015; Ternero-Hidalgo et al., 2019; Yu et al., 2011; Sopha et al., 2021), energy storage, and high-temperature filtration. Although promising, their large-scale utilization remains limited due to higher production costs and the need for tailored annealing treatments that might be costly. As a result, their overall Technology Readiness Level is currently lower compared to polymer-based fibers. TRL in this segment is on the scale of 2-5.

The use of nanofibers in these lower TRL segments could generate billion USD annually, in addition to already very profitable filtration markets. However, the chemistry and the production scale do not allow that yet.

So what is next? What has to happen so that nanofibers can be produced at low price at a great scale, with great reproducibility and compositional and pore size and fiber layer thickness variability?

Challenges to overcome/outlook

Polymer vs. solvent interplay

The biggest challenge without any doubt. Traditional polymers, like polyamide 6, or polyacrylonitrile are not soluble in water, instead, they need toxic and costly solvent [dimethylformamide, formic acid, etc. (Mit-Uppatham et al., 2004; Rogalski et al., 2018; Dotto et al., 2017; Yu et al., 2010; Lu et al., 2013; Lu et al., 2015)]. Water soluble polymers are available and usually are significantly cheaper, however, problem is that they are not stable in aqueous environment. So for any application, where the stability of nanofibers in waters is required, this is no option, see also other point (Xu et al., 2014; Le et al., 2025; Hou et al., 2017; Theron et al., 2004). Even though the development of new polymers may be rather tedious and costly, is still going on, in particular towards biodegradable polymers (Bezrouk et al., 2020), conjugated polymers (Miranda et al., 2020), smart polymers (Zhang et al., 2025), etc. However, high molecular weight polymers, particularly natural polymers with branched structures, are often difficult to be processed by electrospinning, as the electrostatic force alone is insufficient to effectively stretch the fibers.

Another important role plays the choice of solvent, which allows the adjustment of polymer concentration and other solution properties (Tan et al., 2005; Mahalingam et al., 2015; Golecki et al., 2014; Zander, 2015). In terms of the management and recovery of solvents, there is probably the largest room for improvement on the spinning technology side. During the spinning (regardless technology), solutions are evaporated and not used further, in fact they are wasted without further use. In can easily be that for production of 1 kg of fibers, one needs 10 kg of solution with 10 wt% of polymer, for which the remaining 9 kg of solvent are wasted and represent a significant cost item. As already mentioned, melt spinning is currently not viable for reasons of either polymeric instability, when melted, and/or too large diameters. As it is hardly imaginable to develop entirely new class of solvents (which would be costly at the low scale production anyway), the only room on the solvent side is thus their recovery during processing. This could be achieved, for example, by a closed-loop spinning systems that could effectively capture and recover solvents for reuse, thereby minimizing both environmental emissions and operational costs. For a small scale production, the solvent adsorption on carbonaceous materials, followed by desorption, could be used (Bai et al., 2013). For a large scale production, the solvent condensation could be used by colling the exhausts below the dew point of the solvent vapour. Nevertheless, in most of cases nobody does that (typically because of even higher costs than in the case of wasted solvent) and it would be a significant step forward and would comply with circular economy principles. Therefore, the industry particularly aims to use the highest polymer concentration that is still spinnable, in order to minimize solvent waste.

Even though it can be energetically demanding, the ever increasing availability of green energy (e.g., from photovoltaic panels), in combination with smart capture protocols at the end of the spinning process (extraction, absorption, etc.) could be used to recover at least part of the solvents to further use (Singhal et al., 2019).

Stability of nanofibers in different environments

In relation to stability of polymers, there are also issues with stability of polymer-derived nanofibers. However, the concerns about stability depend on the final application and also on angle of view. For highly demanding, e.g., filtration applications, the nanofiber layers (typically placed on a non-woven substrate) should be stable enough, i.e., should not dissolve or disintegrate in time. But that means that they cannot be easily disposed, unless they are burnt. Fortunately, there are also applications, where their instability would not matter so much or not at all. These includes biomedical applications [e.g., tissue engineering (Mohanto et al., 2023; Flores-Rojas et al., 2023), or wound healing (Rihova et al., 2022; Dubský et al., 2012; Zajicova et al., 2010)] which are in essence bioresorbable applications. One could also think about employment of these nanofibers in a single-use respirators, which would still have the necessary filtration function during a limited period of time and then would degrade (depending on the disposal conditions). There is a large room for exploiting such nanofibers, and this is yet to be exploited.

There is also large room for post-modification of water-soluble nanofibers to make them less soluble, but still keep them somehow biodegradable. At first glance, various cross-linking approaches can be used (Xu et al., 2014; Mohanto et al., 2023), but also various other post-treatments, such as physico-chemical methods [e.g., plasma modification (Miroshnichenko et al., 2019; Manakhov et al., 2017), deposition of protecting overlayers (Kernell et al., 2008; Roy et al., 2010)]. There are pioneering efforts in the literature to infiltrate surface of polymeric nanofibers with various species–for example, inorganic oxides–to improve mechanical properties and chemical stability of nanofibers (Sureshkumar et al., 2010; Lee et al., 2009). Namely, researcher have introduced ultrathin coatings on the nanofibers´ surface to get them protected or stabilized (Kernell et al., 2008; Roy et al., 2010; Peng et al., 2007), or prepare nanotubes by subsequent removal of templating nanofibers (Peng et al., 2007; Rihova et al., 2021b; Kim et al., 2014). Moreover, metal oxide-infiltrated nanofibers may exhibit antibacterial effects and enable controlled drug release (Rihova et al., 2022; Rihova et al., 2025; Cheng et al., 2018). The primary technique of choice for these modifications include Atomic Layer Deposition, Vapour Phase Infiltration or plasma spray Physical Vapour Deposition. All in all, there is a large room for the synthesis of new types of polymeric and inorganic nanofibers with interesting surface properties. Last, but not least, recent trend is also to produce biodegradable nanofibers and nanofibers composites, whose limited stability is not an issue and is essentially welcome for various purposes, such as for the wound healing, cosmetic purposes, etc. (Zhou et al., 2024; Li et al., 2025). It can be expected that this trend will be even accelerated in soon future.

TABLE 2 Executive summary of main limitations and challenges in various aspects of fibers and solutions to tackle them.

Aspect/Challenge	Current limitation/issue	Proposed potential solution
Polymer vs. solvent interplay	Traditional polymers (e.g., polyamide 6, polyacrylonitrile) are insoluble in water and require toxic/costly solvents; water-soluble polymers are cheaper, but unstable in aqueous environments	Explore novel polymers and solvents, perform chemical modifications of current polymers, also to increase spinning solutions viscosities using less solvents, considerations of solvent recovery
Stability of nanofibers in different environments	Stability of polymer-derived nanofibers depends on the application: highly demanding uses like filtration require long-term stability, while biomedical or single-use applications can tolerate limited stability or even benefit from biodegradability	Stability can be enhanced via post-modifications, such as cross-linking, plasma treatment, protective coatings, or infiltration with inorganic species, which can also add functionalities like antibacterial activity or controlled drug release
Spinning process engineering	Electrospinning and centrifugal spinning often produce nanofibers with wide diameter distributions, occasional defects, and mean diameters around 1 μm, which can limit applications requiring precise pore sizes or high homogeneity, such as filtration	Improved design of spinnerets, nozzles, tailoring electrostatic fields, and real-time process monitoring, potentially combined with sensors, machine learning, and AI offers strong potential to optimize nanofiber uniformity and tailor properties to specific applications. Use of electro-centrifugal spinning bears also strong potential for specific applications
Production rates	Production rates of both electrospinning and centrifugal spinning remain insufficient for continuous or semi-continuous industrial operation, with water-based processes being particularly limited due to slow solvent evaporation and residual humidity	Optimizing spinneret design, solution rheology, airflow, utilizing multi-nozzle configurations, supported by high-tech sensors, cameras, and AI-driven process modeling, all requiring especially close collaboration between academia and industry
Conservativeness and skepticism in the use of nanofibers	Companies' conservative to replace their current materials with fibers, due to need to rebuilt/change their production lines, potential fear from the toxicity of fibers, limited number of champion cases of fibers	focus on extended toxicological research and careful environmental assessment of both biopolymer and inorganic fibers in various applications, understanding of degradation of biopolymeric fibers, champion performance of fibers compared to other materials that will overcome its cons (in particular lower - yet increasing - production rates) in applications (not only in filtration)

Spinning process engineering

Electrospinning and centrifugal spinning lead to nanofibers with still relatively high dispersion of nanofiber diameters. This is for some applications highly undesired–such as for the filtration, where a precise control of the pore diameter is required for classification of filter efficiencies and particles classes (Barhate and Ramakrishna, 2007). Nanofibers also usually possess mean diameters close to 1 mm, which is also a subject of improvement (lowering). In addition, there are also some defects among nanofibers, such as beads or droplets, which have negative impact on the nanofiber homogeneity (Teyeb et al., 2025; Morina et al., 2023). To achieve a more consistent nanofiber diameters (and pores) and homogeneity there is still large room in the control and optimization of the processes, in particular on the side of spinnerets, nozzles and for electrospinning also the control of the electrostatic field of related aspects. Modern tools, such as high-speed cameras for operando process´ monitoring (Uematsu et al., 2018; Valipouri et al., 2015), different types of sensors and also machine-learning and AI protocols could be put together, to obtain a precise control of the process and their standardization and optimization to the particular needs of the final nanofiber-based product. Some pioneering repots on machine-learning electrospinning processes recently appeared in the literature that show a promise (Shabani et al., 2025; Subeshan et al., 2024; López-Flores et al., 2024; Javier et al., 2024).

Overall, there is a large room for exploiting such technologies and there is a very high likelihood that these challenges could be overcome, which would be very beneficial for the society that needs nanofibers in different forms. Last, but not least, a very promising alternative seems to be also the electro-centrifugal spinning, which combines benefits of both techniques, as described above (Khamforoush and Asgari, 2015; Xu et al., 2023).

Production rates

The production rates of both spinning techniques are also not yet at the satisfactory level, even though for the centrifugal spinning, as tabulated in Table 1, relatively high production rates were reported in the batch processing (Xu et al., 2023; Erickson et al., 2015). Unfortunately, the room for improvement in this particular aspect is somewhat limited. To maintain a process in a continuous operation (24/7) or at least semi-continuous operation is still rather a dream for the nanofiber producers, but it could at least partially compensate the lower production rates. Most processes, that are operated by companies making nanofibers, still work in a batch regime, and would need to move forward. However, the interplay between solution preparation and dosing, spinning, nanofiber collection and quality control needs to be set and modern tools (again machine learning, AI) could be certainly helpful in that.

Moreover, water-based processes tend to have rather lower production rate, compared to organic-solvent driven processes. The water vapour pressure is significantly lower compared to readily evaporating organic solvents during the process, and also some remaining humidity can be kept in the nanofibers which would need post-drying (Mahalingam et al., 2015; Mit-Uppatham et al., 2004; Golecki et al., 2014; Szewczyk and Stachewicz, 2020).

Design of spinnerets vs. rheological properties of the spinning solutions need to be in the best possible interplay, which can be difficult to find purely experimentally, as there is a large number of variables. However, all necessary details and aspects on the nanofiber formation, in particular in the very early stages of their spinning, are still not known and could be further investigated by high-tech sensors and cameras.

Also the optimization of air flow needs to be optimized and in a quite narrow range of conditions–too fast flow means losses in spinning chambers (due to turbulences) and low rates mean that nanofibers do not arrive in given spot completely dried (Naseri Joda et al., 2024).

One possible approach to tackle lower production rates would be to involve complex spinning configurations using multiple nozzles or spinnerets, which would significantly aid the pilot to industrial upscale of the spinning technologies (Valipouri, 2017; Luo et al., 2012).

To solve all these challenges is a complex task, that requires expertise in process modelling, computational models, air flow dynamics, etc. Companies usually do not have resource and time to do this. So it would be really great, if academia can help with these challenging tasks. To gain insights into these issues would be very big thing and a big move for the whole nanofiber industry.

Conservativeness and skepticism in the use of nanofibers

Safety concerns in past (given the asbestos fibers) and also the general attitude of companies not to change things, unless necessary, puts also some barrier in the implementation of nanofibers. While some groups and individuals are highly optimistic about nanofibers, some are pessimistic–primarily because they are not convinced about the nanofiber potential and are worried about the safety concerns.

Recent toxicological studies show that inorganic nanofibers are not in any aspect "worse" or more "dangerous" than nanoparticles of the same chemical compounds (Bacova et al., 2022; Smela et al., 2022). The lower risk associated with nanofibers is mainly due to their larger size, compared to nanoparticles, which makes nanoparticles potentially more hazardous. In fact, in many ways, nanofibers are less problematic, as they cannot penetrate the skin and get into our respiratory system with large difficulties or not at all. Another potential problem is inhalation. Research shows that ceramic fibers are generally no more harmful to lung cells than nanoparticles of the same material (Bacova et al., 2022). Therefore, any handling and applications of nanofibers appear to be safer than those of nanoparticles.

Although biopolymeric nanomaterials appear safe because they can degrade and do not accumulate in the body, their breakdown into monomers and subsequent interactions with the human organism are still poorly understood. This represents a significant challenge for future research.

Last, but not least, the skepticism of nanofiber use in products could be dispersed or at least significantly lowered by champion performance of fibers in specific application. The already achieved performances in filtration are of the champion class, but more such cases in other applications would be welcome.

Table 2 below provides an executive summary of the main limitations and challenges in various aspects of fibers synthesis, upscale and applications. It also summarizes and proposes relevant steps to be undertaken to address these limitations and challenges.

Conclusion

This article demonstrates that there are numerous remaining challenges in the nanofiber production and exploitation, which need to be overcome toward further improvements and industrial exploitability of these materials and their producibility at reasonable costs. These challenges need to be addressed, and they can only be addressed if the academia and industry talk together and work together on these topics and prioritize them.

Necessary improvements include increasing overall productivity of the spinning processes, optimization of polymer/solvent systems, through recovery of solvents, all bearing potential to reduce nanofibers production costs. A large room is also in the post-modification of nanofibers, which could further expand and justify their subsequent use in various application.

Researchers should not fear to push boundaries, as this is essential for advancing knowledge and achieving improvements. Nanofibers still have much to offer and they remain one of the most essential nanomaterials available.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

LH: Data curation, Validation, Writing – review and editing. MR: Conceptualization, Methodology, Visualization, Writing – review and editing. JM: Conceptualization, Funding acquisition, Resources, Supervision, Visualization, Writing – original draft.

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