Textile & Leather Review

ISSN: 2623-6257 (Print) 2623-6281 (Online) Journal homepage: www.textile-leather.com Journal doi: 10.31881/TLR

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How to cite: Khan MKR, Hassan MN. Solution Blow Spinning (SBS): A Promising Spinning System for Submicron/Nanofibre Production. Textile & Leather Review. 2021; 4(3):181-200. https://doi.org/10.31881/TLR.2021.04

How to link: https://doi.org/10.31881/TLR.2021.04

Published: 7 September 2021

Solution Blow Spinning (SBS): A Promising Spinning System for Submicron/Nanofibre Production

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Review
UDC 677.021.125.26
DOI: 10.31881/TLR.2021.04
Received 31 January 2021; Accepted 28 March 2021; Published Online 29 April 2021; Published 7 September 2021

ABSTRACT

Submicron/nanofibres possess great potential for application in different areas because of their amazingly high surface area-to-weight ratio. The demand for fabrication of such fibres on a huge scale is increasing with the fast improvement of nanotechnology. Traditionally, nanofibre fabrication methods have intrinsic faults, limiting their application in industry. Solution blow spinning (SBS) is a viable option for producing adaptable and conformable submicron/nanofibre mats on a variety of surfaces. The technique can be employed to produce submicron/nanofibres with only a simple commercial airbrush, a concentrated polymer solution, and a compressed gas source. It depends on the high velocity of decompressed air that allows the rapid stretching and evaporation of the solvent from a polymeric solution jet at the outlet of the concentric nozzles system. Along with recent advancements, the importance and drawbacks of the solution blow spinning system in comparison to other methods, such as electrospinning and melt blowing, are briefly discussed. Furthermore, the mechanisms of co-axial SBS spinning and micro SBS spinning system for submicron/nanofibre fabrication are also described. Drawbacks and research challenges of SBS are also addressed in this paper.

KEYWORDS

Submicron/nanofibre, Solution blow spinning (SBS), Airbrushing, Co-axial spinning

INTRODUCTION

At present, the focus of engineers and scientists is on nanomaterials because of their potential to improve material efficiency and capabilities in a variety of commercial sectors [1]. The greatest significance of the nanotechnology is its aspect ratio that is related to the enormous surface area-to-volume ratio and their quantum effects [2]. Some advantageous features offered by the nano size of the materials enhance the properties of the material [3]. Thereby, nanostructured materials are used in numerous applications, such as catalysis, electronics, separation technologies, sensors, information storage, drug delivery systems, diagnostics, energy batteries, fuel cells, solar cells and more [4]. Researchers and industries have a considerable interest in the advanced functional nanostructured materials that use one-dimensional (1-D) nanostructures for their development [5]. Due to their distinctive physical and chemical characteristics, one-dimensional (1D) nanostructured materials, such as nanofibres (NFs), nanowires (NWs), nanotubes (NTs) and nanorods (NRs), have drawn substantial interest [6]. Fibrous materials are very intriguing structures with distinctive properties among other materials. They have a high porosity, a large specific surface area and good breathability [7]. For a wide variety of research and commercial utilization, nanofibres have appeared as a promising single-dimensional nanomaterial [8]. Typically, nanofibres are known as fibres with the diameter of less than 100 nm in the fibre science literature [9].

The nanofibre technology includes synthesis, processing, manufacturing, and application of fibres with the nanoscale dimension [10]. Unlike traditional rigid porous structures, a porous structure made of nanofibres is a dynamic device where the pore size and shape can change [11]. Nanofibres have a great variety of applications since they have high applicability in the fabrication of composites with other materials [12]. Besides, nanofibre scaffolds emulate the fibrous nanostructure of native extracellular matrix (ECM) and can be used effectively for tissue engineering [13]. The offering of nanofibres to the growth of the market for nonwovens will be dependent on the advancement of modern, affordable technologies, especially those that can scale up to manage large commercial volumes [14].

In view of the future opportunities presented by nanofibres, a growing interest in nanofibre technologies has emerged in the last decade to scale up the production of nanofibres [10]. SBS has the significance to be easily scaled-up in its in-situ use for different applications [15]. However, different procedures, such as template synthesis [16], phase inversion/separation, freeze/drying synthesis [17], drawing [18], bi-component extrusion [19], electrospinning [20], melt blowing [21], force spinning [22] and so on; can be used to produce nanofibres. While electrospinning is the most common spinning method used to produce nanofibres, it has drawbacks such that it can only be used in electrically conductive systems to conduct voltages applied during the electrospinning process and involves skilled personnel [23-24]. Electrospinning has advanced from very slow single-jet spinning to multi-jet or needleless spinning systems, which has permitted an improvement in the production rate, yet the rates are still much below than what is expected for it to be economical [25]. The throughput of SBS can be several times larger than that of electrospinning [26].

In the endeavour of creating micro- and nanoscale fibres, solution blow spinning comes as a hopeful prospect in recent times. Over the decade, due to its simplicity and high efficiency, solution blow spinning (SBS) has attracted a great deal of interest. A strong knowledge of technology and engineering is the driving force behind creativity and growth in the textile industry. This suggests that a yarn producer must also be technologically competent, effective, versatile, and cost-conscious. From this viewpoint, a description of the solution blow spinning (SBS) is being pursued regarding the advantages of this spinning device for the processing of submicron/nanofibre. Along with the influencing parameters, some examples of applications and challenges of SBS system are also addressed briefly in this article. However, the basic principles of the co-axial and micro SBS systems are also briefly mentioned.

SOLUTION BLOW SPINNING (SBS)

Solution blow spinning (SBS) is a neoteric process for the preparation of high-efficiency and secure nanofibre mats, and SBS is a mature fibre-forming technique (shown in Figure 1) that provides several advantages over traditional electrospinning methods [27]. Centred on the concepts of ES and melt-blowing technologies, SBS offers the possibility to process nanofibre with a variety of diameters comparable to the ES system [28]. In 2009 Medeiros et al. first reported on the SBS spinning system.

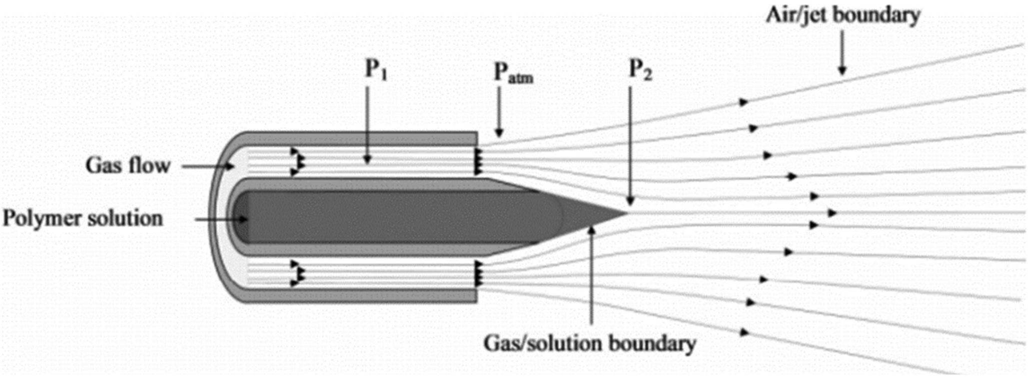

Figure 1. The nozzle geometry creates a region of low pressure around the inner nozzle (P2) compared to high pressure (P1) stream of gas that passes through the outer nozzle, which helps draw the polymer solution into a cone [Courtesy: Medeiros ES et al. Journal of Applied Polymer Science. 2009; 113(4):2322-2330. https://doi.org/10.1002/app.30275 © 2009 Wiley Periodicals, Inc.]

Basic Mechanism of the SBS System

It is similar to the dry spinning process because the solution made of a polymer dissolved in a volatile solvent needs to be dried rapidly. It also corresponds similarly to the electrospinning process as there is a stretching induced by an external force prior to the deposition [28].

Solution blowing, however, is a system for spinning submicron and nanofibres from polymer solutions where high-velocity gas flow is used as a fibre-forming driving force [29]. In SBS, a polymer is dissolved into an appropriate solvent to reduce its viscosity [24]. A basic SBS system consists of a compressed gas supply, a pressure regulator, a syringe, a pump for the syringe, a concentric nozzle spray apparatus, and a collector as shown in Figure 2 [30,31]. A needle inserted concentrically inside the air nozzle is a more common configuration. The needle size can be changed accordingly. Usually, 0.2-0.7 mm is the inner diameter of the orifice [29]. SBS uses pressurized gas to create submicron and nanofibre from polymer solution. Parallel streams of polymer solution and pressurized gas are blown through the concentric nozzle chambers during fibre production. The polymer solution is contained in the inner chamber, while the pressure gas is located in the outer chamber [30]. Gas velocity increases due to the accelerated decompression of air based on the Bernoulli principle [28]. The pressurized high-speed gas induces a decrease in pressure and then the shearing at the gas/solution interface occurs and the polymer solution is stretched towards a fixed collector when the critical air pressure is surpassed [30,32]. In other words, the solvent went into a droplet out of the inner nozzle. The solution interface of the droplet was then deformed into a conical shape by the high-speed air flow coming from the outer nozzle. The solution droplet is ejected into several fine streams immediately after the surface tension is overcome because of the forces of air flow [33]. When these jets fly over the working distance towards the collector, they are stretched by the pressure drop. If the solvent evaporates, streams of extended polymers then easily form into fibres [30,32]. Highly viscous liquid jets experience lateral distributed force when it travels at a high-speed relative to the surrounding gas, resulting in enhanced bending perturbations [34]. However, within the working distance (typically 10-20 cm but differs depending on solvent volatility) the solvent evaporates, and polymer fibres are deposited with no further drying, cooling, or washing necessary [35]. Polymer fibres can be spun with a wide surface area for various future applications such as membranes for biological and chemical sensors, drug distribution, filtration media, and tissue engineering by varying polymer architecture and processing environments in the SBS system [32]. For example, Bonan et al. performed fibre processing by using poly (lactic acid) (PLA) polymer that is the most widely used biocompatible and non-toxic polymer in general. Solutions were pumped at a rate of 120 µL/min through the inner nozzle and a pressurized gas stream was delivered at 2.4 kPa through the outer nozzle. Fibre mats were directly deposited at 200 rpm on a revolving cylindrical collector, located at a working distance of 20 cm [36]. Wojasiński carried out the SBS procedure in atmospheric conditions with a RH of 45% -50% during the processing of PLA fibre [28]. The successfully fabricated polymers by the SBS system include PLGA, PEO, PLA, polyimide, SPEEK, poly (caprolactone), poly (styrene), poly (vinyl acetate), poly (methyl methacrylate), PVDF, and poly (acrylonitrile). However, Aerospinner (SBS) for lab and industrial scale production is provided by the Areka Group [37].

Influencing Parameters of SBS

Many studies have been conducted to determine the effect of process parameters on the morphology of the fibre, such as concentration of polymer solution, air pressure, feed rate, work distance, and distance between nozzles. The nozzle diameter has to be small enough to facilitate the generation of fibres within the nanoscale range. The initial diameter of the free jet is dictated by the cross-sectional area of the inner orifice where the solution is extruded before jet experiences the stretching stage. Greater resistance is offered by a thicker jet to the stretching and bending instability which results in a thicker fibre. The most important parameters influencing fibre diameter have been found to be polymer solution concentration and air pressure. The entanglement of polymer chains is linked to the formation of fibres from the polymer solution, and it requires a specific concentration (overlap concentration) of polymer in the solution. The entanglement of polymer chains leads to the increase in viscosity that overcomes the surface tension. The lower concentration of polymers creates fibres of smaller diameters. The low concentration rate of the solution lowers the viscosity of the solution. Therefore, the solution jet is more refined by high-pressure airflow which leads to the production of thinner fibres. An increase in polymer concentration increases the difficulties in nanofibre production. In addition, the polymer-solvent system is also very critical since the viscosity of the solution and the surface tension have a direct effect on the SBS system [15,29,34,38-40]. In addition, the molecular weight of the polymer and the evaporation rate of polymer solutions influence the diameter of the fibre [32]. For instance, scaffold qualities are improved by low molecular weight polymers because of acting as plasticizers and it leads to generating longer fibres [41]. Properties such as the average fibre diameter and morphology of nanofibrous sheets derived from SBS can be adjusted [28]. SBS fabricated fibres have a diameter ranging from 100 nm to greater than 1 µm [35]. When the air pressure is increased, the fibre diameter is reduced and fibre mats become more uniform. The airflow field distribution, air velocity and morphology of the final product greatly depend on the nozzle design which is a very critical parameter in the SBS system. Although a smaller orifice can generate thinner fibres, it decreases the throughput rate [24]. For producing fibres, the air pressure higher than 30 psi is required in general. Otherwise, it will not be able to provide adequate driving force to overcome the surface tension. The air pressure working range is reported to be between 30 and 90 psi [42]. Providing extra gas pressure produces smaller and thinner fibres, which is due to the greater level of fibre stretching as well as the shearing force [29]. Fibre formation is also influenced by the working distance but has a low effect on the fibre diameter. The distance required for the fibres to dry before collection is called minimum working distance and the distance that avoids the excessive loss of the jettisoned fibres is considered as maximum working distance [42]. A higher stretching of fibre and a better dissipation of the solvent is obtained at a higher working distance [29]. The temperature ameliorates the drying and spinnability of the SBS nanofibres when a spinning line is arranged with a heating environment. For example, once the configuration of the nozzle, the feed rate, the air pressure, the solvent and the polymer concentration are being optimized, the yield can be further improved by the combination of several nozzles and the solution is injected into each nozzle at the same time [24]. The polymer blending improves the process ability and it can be utilized to adjust the polymer degradation rates [29]. More research should focus on optimizing the process parameters of the SBS system to fabricate the mats based on the characteristics of the polymer and the requirements for final products.

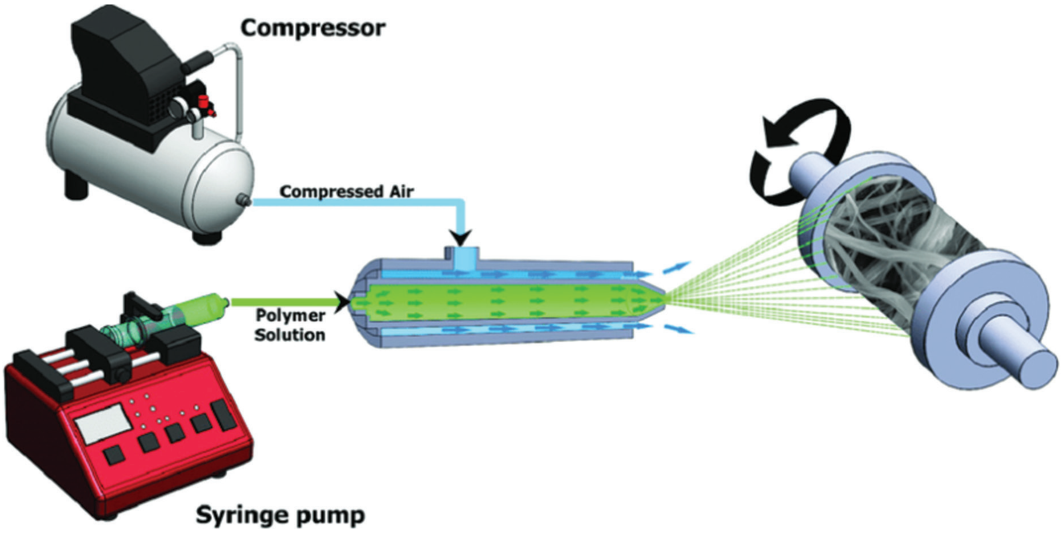

Figure 2. Schematic of solution blow spinning process [Courtesy: Atif et al. Polymers. 2020; 12(5):1140. https://doi.org/10.3390/polym12051140 © 2020 by Atif et al.]

AIRBRUSHING SYSTEM

The commercial airbrush is the most commonly used device for the SBS process [43]. Commercial airbrushes (a gravity-fed brush) have been successfully used as an alternative to the traditional SBS apparatus to produce polymer fibres based on the same principles [34]. It is often referred to as airbrushing [44] or solution spraying [45]. It is estimated that the set-up is ten times quicker and 100 times less costly than the traditional electrospinning techniques [46]. The polymer solution is sprayed at a predetermined temperature and relative humidity by using an airbrush (shown in Figure 3) atomization unit. With an internal mixing capability, the atomization nozzle used has a double action. For atomizing the polymer solution, the air pressure is applied and the distance between the tip of the nozzle and the collector plate is set typically at the range of 30-40 cm [47]. The reduced cost and instant availability are the benefits of airbrushing; there are less parameters in the airbrushing method that obstruct reproducibility [48,49]. Dias et al. found the optimum working conditions during fabricating SBS spun PVDF nanofibres as follows: the pressure at 5 bar, a working distance of 20 cm, and a polymer concentration of 20% (w/v) [49]. The porosity of the airbrushed material ranged from 77% to 95%, while the porosity of the nanofibres produced by electrospinning was 67%, and the airbrushed nanofibres were more commercially viable, easier to handle and safer [49]. Costs are decreased and deposition rates are in the order 10 times higher than electrospinning when a gravity-fed or siphon-fed airbrush is used [35]. The process is environmentally friendly and simple [46]. Cell adhesion, proliferation and differentiation are also supported by the airbrushing system [13]. It could promote the deposition of nanofibres directly onto living tissues at a higher rate, form three-dimensional biomimetic scaffolds with enhanced cell penetration and could be deposited in different chemical and structural configurations [46]. This technique has been mentioned by many researchers [13,43,50-53] as a viable and alternative nanofibre production spinning system for 3D tissue engineering scaffolds. Nevertheless, one downside of the airbrush is that this approach is unable to generate nonwovens consisting of long individual fibres. Instead, they create entangled fibres or fibre strands [52]. However, Hell AF et al. developed a semi-automatic SBS system to produce poly (ε-caprolactone) (PCL) fibrous mats for tissue engineering and compared its merits and demerits to the airbrushing system. They mentioned that the airbrushing tended to create more fibre bundles than SBS and produced more beads as well. Diameter ranges were similar, but airbrushing gave a narrower distribution than that of SBS (i.e., 132-1607 nm for airbrushing and 132-1268 nm for semi-automatic SBS) [48].

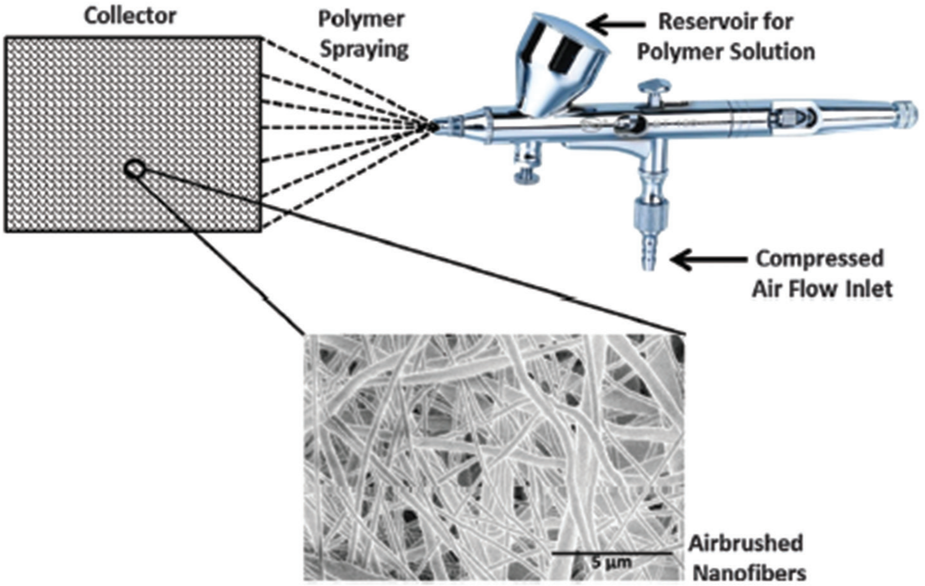

Figure 3. Schematic illustration of the Airbrush Spinning System
[Courtesy: Bhullar SK et al. Journal of Nanoscience and Nanotechnology. 2018; 18(4):2951–2955. https://doi.org/10.1166/jnn.2018.14376, Copyright © 2018 American Scientific Publishers, ref. 46]

COAXIAL SOLUTION BLOWING METHOD (CSB)

Over the last decade, core-shore nanofibres have become popular based on their special features and their biomedicine application [54,55]. Core–shell bi-component nanofibres are emerging for tissue engineering and wound healing applications as they mimic the natural extracellular matrix (ECM). They can serve as conduits for the delivery of the growth factors such as proteins, antibiotics, and other agents, while remaining bioactive [56]. A novel co-axial airbrushing technique successfully created the core-shell nanofibre mat. There are three detachable components in the coaxial solution blowing process (shown in Figure 4). The process of co-axial airbrushing can be explained as follows: The core-shell polymer drop at the tip of the needle elongates due to the stress generated and the shell polymer solution causes the core solution to be sheared through viscous drag and contact friction. This phenomenon allows the conical structure of the central polymer fluid and a compound co-axial jet forms at the tip of the cones, and further progression leads to the creation of core-shell fibres [44]. Polymer nanofibres are dragged out of the cone by the viscous forces of the moving air that overpower the surface tension forces [28]. Pressurized air confines the polymer solution to generate a fine liquid jet [57]. Fine polymer nanofibres are collected on rotating drums [28]. However, Lei Li et al. produced the three-dimensional hollow PAN nanofibre mat (CSB-HPAN) successfully using a coaxial solution blowing process [58]. Higher molecular weight PDLLA (Mw ≈ 100 000 g mol^{-1}) and lower molecular weight carboxylic acid terminated PDLLA (PDLLA-COOH, Mw ≈ 25 000 g mol^{-1}) were blended to produce nanofibre scaffolds through a co-axial air-brushing system [41]. Oliveira et al. applied a blend of PEO and PLA to produce fibres with the core of amorphous PLA and the shell of semicrystalline PEO [59]. Cellulose solution and polyethylene oxide (PEO) solution were used as the core and shell liquids, respectively, to create core–shell structures submicron-scale amorphous cellulose fibres. Cellulose fibres with diameters in the range of 160 nm and 960 nm were subsequently produced after removing the PEO shell [60]. Another attracting purpose for core-shell blowing is the resulting barrier characteristics given by the shell material. Such a structure permits controlled release and self-healing applications. Rhodamine B was integrated in a core-shell of soy protein/nylon resulting in a longer release time of the dye compared to the monolithic fibres [29].

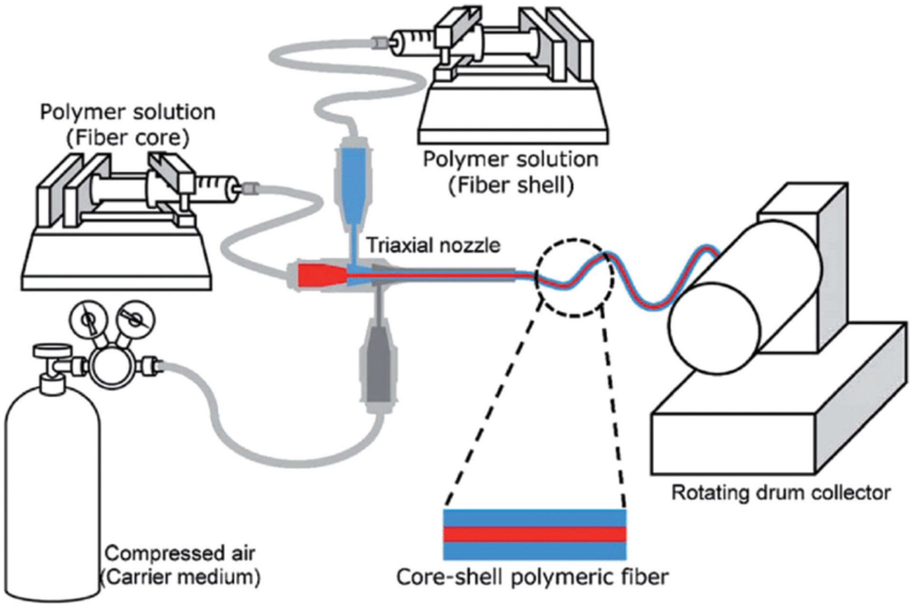

Figure 4. Schematic of the coaxial solution blowing apparatus [Courtesy: Park SC et al. RSC Advances. 2018; 8(57):32470-32480. https://doi.org/10.1039/C8RA05485A, © The Royal Society of Chemistry 2018, ref. 61]

MICRO SOLUTION BLOW SPINNING (MSBS)

The gas dynamic virtual nozzle (GDVN) principle is used by micro solution blow spinning (µSBS) to produce micron-sized fibres in a continuous and stable process from a polymer solution. Hofmann et al. described microfluidic chip featured nozzle that is comprised of two inlet ports. One was attached to pressurized air, while the other was connected to a syringe pump carrying a polymer solution. Unlike solvent blow spinning with a concentric nozzle, the inner nozzle, which provides the polymer solution, does not protrude from the compressed air outlet. In a micro-fluid system, the polymer solution from orthogonal directions is centred on a steady flow of pressurized air, such that a fine liquid jet is generated [57,62]. The combined forces of tangential shear and extensional stress, viscous stress, and surface tension here contribute to acceleration and the collision of liquid without the wall interaction. This merging fluid meniscus results in a cylindrical microjet with the diameter down to a few micrometres and below [63]. Microfluidic solution blow spinning allows for effective jet diameter control. Hofmann et al. mentioned that the fibre spinning was carried out at atmospheric conditions with the temperature at 23 °C and the relative humidity in the range of 45-55%. In principle, this efficient use of the microfluidic nozzle system for continuous fibre processing could be applied to bio-based nanofibrils, which have recently shown to be a promising material for fibre spinning technology [57,63].

ADVANTAGEOUS FEATURES OF SBS SYSTEM

Due to miniaturization and future applications in various fields, such as electronics and medicine, the market for nanostructured materials can grow exponentially. Fast output rates are therefore necessary in order to make nanomaterials commercially available [64]. SBS is considered to be maturing among the new technologies used for the development of nanofibres, primarily because of its capacity to generate the most nanofibres in the shortest possible time [30]. Special characteristics of SBS include a way of investigating the effectiveness of nonwoven fibrous materials in new applications. SBS uses processes similar to those used in industrial production systems, which facilitate its potential application to large-scale manufacturing like the electrospinning system [35,65]. For instance, gas is used to cool or vaporize solvent from fibres after extrusion through a spinneret in a melt spinning or dry spinning system, respectively. SBS uses pressurized gas to extrude the polymer solution and to induce solvent evaporation, which results in a simplified operation, consisting of a single step, for producing polymer fibres [35].

It has been researched in relation to the production of functional polymer nanofibre coatings, nonwoven textiles, and stretchable electronics because of its flexibility and ability to convey conformal fibres directly. These investigations have shown that SBS is capable of producing high-precision, effective, and durable fibrous materials [35]. It should be mentioned that the fibre mats obtained by the process of solution blowing also have three-dimensional curly and loose fibrous morphologies, which are helpful in the application of catalysis [58]. Feng Liang et al. reported on the fabrication of a three-dimensional micro-nanofibre structure with the minimum fibre diameter of 200 nm in the structure and the maximum porosity of 89.9% [33]. Solution blow spinning (SBS) has emerged as an alternative technique that can overcome the limitations of electrospinning during the production of submicron/nano sized fibres. The value of SBS is that it can be applied to both electrically conducting and insulating systems and does not need the application of an electric field and conductive collectors to initiate the fibre processing. SBS has less process requirements and variables compared to the electrospinning system during the fibre fabrication. SBS also has the ability, on planar and nonplanar substrates, to deposit conformal fibres [35]. Large scale fabrication is possible in SBS as it is in electrospinning [65].

Although melt blowing is the key commercial technique for nonwovens in the production of polymer microfibres, this process is only applicable for thermoplastic polymers and not suited for other polymers (e.g., polytetrafluoroethane) which have extremely high viscosities because of their high crystallinity and high melting points. This technique is not also suitable for biopolymers as they tend to denaturalize at high temperature [66]. In addition, fibres of the same size as the electrospun fibres cannot be generated by the melt blowing technique [67]. In contrast, SBS can effectively prevent thermal degradation of the polymer as it requires normal temperature and compressed air [65]. Melt blowing produces microfibres, whereas SBS are able to produce nanofibres as well as microfibres [67].

However, SBS technically generates fibres of the same size as the electrospun fibres with improved consumer scale potential [14]. In comparison to electrospinning, the SBS system has lower parameters and process requirements [35]. SBS has a high performance, simple function, fast planning time and high use value compared to the e-spinning technology. Furthermore, since no high-voltage electric field is needed in the spinning chamber, this device provides safe operation [37]. The thermo-degradation problems of polymers are eliminated as the solution blowing procedure applies compressed air at room temperature [66]. The higher velocity and characteristic forces of SBS are likely to support the chain orientation, contributing to the greater crystallinity of fibres compared to electrospinning [68]. One of the advantages of SBS is high spinning efficiency. According to Gao et al., the efficiency of solution blow spinning is 5-8 times higher than that of the single conventional electrospinning device. The SBS system produces fibres in the same size range as fibres produced by electrospinning, therefore, it has greater potential for being commercially scaled-up [14]. The electrical conductivity of the polymer solution has little impact on the fibre diameter in SBS and, subsequently, little reason to use extremely poisonous fluorinated solvents [35]. The diameter of the yttrium barium copper oxide (YBCO) superconducting fibres, for example, averaged 258 nm, 562 nm, and 984 nm, respectively, were produced with solution injection speeds of 60 µL/min, 80 µL/min and 100 µL/min [64]. In the case of an electrospinning technique, an injection rate of 1–6 µL/min is usually reported, whereas the injection rate for SBS lies in the range of 10–140 µL/min [69]. Besides, there is no need for a sophisticated support for a higher degree of protection, resulting in less system requirement [65]. In addition, the simple devices needed for SBS will allow researchers to explore new applications for nanofibrous and micro fibrous materials [35]. Santos et al. reported that the aqueous solutions of PVA were used to produce micro and nanofibres successfully through SBS [70]. Blending biopolymers is a mentionable advantage of solution blow spinning [67]. For instance, Liu et al. fabricated chitosan/PVA blended hydrogel nanofibre mats (HNMs) by SBS process [71].

It is very important to note that the processing of biopolymer fibres is not as easy and not as scalable as conventional polymers or thermoplastic polymers since biopolymers can be denaturalized at higher temperatures. Non-thermal methods are also the only feasible routes to produce biopolymer fibres. Researchers also use a polymer carrier to face the difficulties such as the globular shape, the absence of necessary viscoelasticity and low solubility in common solvents during biopolymer processing in electrospinning. However, it is notable that electrospinning can be problematic, and the charge distribution becomes difficult due to the regular polyelectrolytic nature. Solution blowing is a plausible solution in such a situation since the aerodynamic drag of the coaxial heavy air flow is the only driving force. This gives an excellent opportunity for the final composite to be maneuvered, especially with biopolymer blends [26]. SBS provides safe working conditions during the spinning operation [37]. Santos et al. also reported that the SBS method is suitable for producing alumina nanofibres at a low cost with reproducibility [72]. Besides, the airbrushing SBS can “paint” nanofibres on any target, while ES needs an electrically conductive target [13]. It is also worth mentioning that the airbrushing SBS has benefits over basic SBS in terms of cost and availability. The airbrushing SBS starts at $25, while solution blow spinning requires $260 for the nozzle and $690 for the syringe pump [48]. According to Areka, a single nozzle SBS system needs 300 l/min of compressed air and 1.5 kWh (approx.) of power, while electrospinning requires 200-500 Wh of power. It is also said that by using a central compressor instead of a portable one, the required level of power for the SBS system will be reduced to 0.1 kWh [37]. The energy efficiency of the compressor plays a significant role for power consumption of the SBS system since the cost of compressed air is significant. However, as the productivity of SBS is 30 times higher than that of electrospinning, the energy consumption rate per unit of production of the SBS system will be lower compared to that of electrospinning.

APPLICATIONS OF SBS SUBMICRON/ NANOFIBRE

SBS-spun submicron/nanofibres have been applied widely due to their high surface area, crystalline structures, superior kinetic characteristic, and their practicability for a ready-to-scale-up system. Many fields have been already investigated regarding SBS-spun submicron/nanofibres, such as biomaterials, tissue engineering, textiles for environment, energy harvesting textiles and composites. Biomedical fields include tissue engineering, controlled release, antimicrobial films, and food packaging where SBS-spun nanofibres have been used successfully [29]. PLA nanofibre scaffolds fabricated by means of SBS provide favourable physical and chemical properties for being applied in tissue engineering [73]. Bhullar et al. mentioned that the airbrushed Nylon-6/AgCl composite nanofibres may be used as a potential candidate for fabricating antibacterial scaffolding system suitable for tissue engineering fields [46]. The production of biometrics scaffold for tissue regeneration mimicking the geometry of the native extracellular matrix (ECM) of tissues has been reported by many researchers [48,74]. SBS system also permits for portable device and conformal fibre deposition on any substrate [35]. For example, Gao et al. developed portable SBS device to guide fibre deposition and completed liver haemostasis in a minimally invasive surgical environment [38]. The core-shell PLA/PEG nanofibres incorporated with amphotericin B (AmpB) were synthesized through SBS for a controlled release and a successful encapsulation, as well as antifungal and antileishmanial activity. According to Gonçalves et al., the approach should be regarded as a therapeutic alternative for the treatment of fungal diseases and leishmaniasis in the production of drug delivery systems [75]. SBS core−shell fibres with epoxy precursors or other self-healing monomers loaded into the core provided self-healing properties and improved fatigue strength [76,77]. SBS nanofibres have gained an increased attention in wound healing. Several researchers already investigated the performances of SBS nanofibre dressings for wound healing purposes [78]. It can reduce the pain associated with wound healing and dressing change. Medical applications are distinctively fitted for direct fibre deposition in targets and would be able to take advantage of the properties of SBS that make it especially biocompatible: low toxicity, high porosity, and compatibility with biodegradable materials [35]. For instance, Liu et al. fabricated chitosan/PVA blended hydrogel nanofibre mats (HNMs) by the SBS process and recommended CS/PVA hydrogel nanofibre mats as a perfect moist dressing [71]. Stafford et al. conducted a research to create a conductive smart wound dressing for diabetic foot ulcers through solution blow spinning system [79].

SBS spun nanofibre offer significant opportunities to solve the environmental problem. It is a promising system to address the pollutions related to oil [80]. For example, Zhang et al. produced the polystyrene (PS) fibrous sponge and polyvinylidene fluoride (PVDF)/polystyrene (PS) composite package with the ultrahigh oil adsorption capacity through the SBS system. According to Zhang et al., it is viable for a large-scale industrial production of oil sorbents and oil spill clean-up for the protection of the environment [81]. The SBS-spun nanofibrous polystyrene membranes (NPS) could separate oil from water surface in a matter of seconds [82]. A composite membrane of SBS poly (methyl methacrylate) nanofibres wrapped with reduced graphene oxide (PMMA-rGO) was fabricated to adsorb the typical dye called methylene blue (MB) [83]. Membranes for the removal of methylene blue (MB) dyes from water were successfully developed by other researchers as well [84]. Tan et al. developed composite multi-layered filter mask from nanofibre materials (i.e., cellulose diacetate (CDA), poly (acrylonitrile) (PAN), and poly- (vinylidene fluoride) (PVDF)) produced by solution blow spinning. They reported better filter performances compared to the commercial surgical masks [85]. 500 mm wide PAN nanofibre membranes were realized by SBS that allows preparation of multi-level filter materials [86]. Zhuang et al. found that the mean pore size of the SBS mat is larger than that of the electrospun mat and smaller than that of the melt-blown fabric, making them a potential candidate for filtration [87]. Heat-resistant air filters based on polyimide were fabricated by this spinning system [88]. Micronutrient delivery systems comprised of Zn-loaded poly (butylene adipate-co-terephthalate) (PBAT) nanofibres were fabricated by SBS and results demonstrated that the SBS-spun nanofibres slowly released Zn to the soil in a controlled fashion [89]. SBS has developed a new type of modified Nafion membrane with sulfonated poly (ether ketone) (SPEEK) nanofibres for being utilized as a proton exchange membrane fuel cells [90].

Furthermore, PVDF nanofibre membranes (NFMs) produced by SBS were successfully used as self-powered nanogenerators [27]. Dong et al. developed β-phase-preferential SBS fabrics for wearable TENGs and a textile interactive interface application [91]. Moreover, $CaFe_2O_4$ nanofibres were successfully synthesized via solution blow spinning (SBS) for photocatalytic applications [92]. Production of ceramic nanofibres such as TiO_2 nanofibres was performed through the SBS system followed by calcination [15].

Polystyrene nanofibrous (PSNF) mats containing the bromothymol blue (BTB) indicator for sensing the pH of wine was made by this spinning principle [93]. Conductive nonwoven fabric has successfully been developed and applied in smart textronics to detect various biosignals [94]. Huang et al. built highly flexible, 2D and 3D conductive electrodes using silver nanofibres (AgNFs) made by a modified blow spinning method [95]. SBS spun fibres sprayed as continuous mats on the surface or woven into textiles can be used in displays, thermochromic temperature sensors, chemical sensors or biological sensors. They allow for a huge potential in wearable textiles [96].

The fabrication of cellulose-based nanofibres remains a global challenge, particularly in terms of using alternative cellulosic materials. However, cellulose-based nanofibre membrane can be successfully fabricated through the assistance of an easy-to-spin polymer precursor (e.g., PAN) by using solution blow spinning (SBS) [97]. Zein fibres were successfully produced through (SBS) by using acetic acid as the solvent [98]. Food-grade gelatine nanofibres from pork skin gelatines (PGs) and fish skin gelatine are prepared by the SBS system [99]. Renewable polymers [100], such as starch, chitosan, cellulose [98], alginate, fibrinogen, fibrin, gelatine, and collagen need to be explored more and more because of their excellent performances in cell adhesion, proliferation [101], migration, differentiation, and characteristics analogous to those of ECM. However, many research works are supposed to be conducted to materialize fully the possibilities of the SBS spinning system for application in different fields.

LIMITATIONS AND CHALLENGES OF SBS

SBS nanofibre nonwovens have some drawbacks, such as larger fibre diameter and more beaded fibres [102]. The reproducibility and alignment of nanofibres remain as one of the challenges of SBS [66]. Fibre morphology is weak for the solution blow spinning method, whereas the electrospinning process provides the optimized morphology of the resulting nanofibrous material in terms of porosity and fibre orientation [28]. However, a number of improvements to the SBS system are being made to address the shortcomings of this spinning system. For instance, Zheng et al. have devised a new cylindrical-electrode-assisted blowing solution (CSBS) technique to produce high-grade, ultra-fine nanofibres by combining air stretching and electrostatic forces. PEO nanofibre mats were successfully produced by using CSBS with satisfactory quality. The standard deviation in the diameter of the CSBS fibres decreased by 21% and the average fibre diameter decreased by 6.17% compared to the traditional SBS. In other words, the CSBS fibres had a greater uniformity and a higher fineness [70,102]. Moreover, the microfluidic spinning system is also considered as a modification of the solution blow spinning system. Well-aligned BaTiO3 membrane was obtained by modifying a fibre collection device for the SBS system [103]. Cryogenic solution blow spinning is another type of modification developed for producing 3D macroporous scaffold [104]. An aqueous solution blow spinning (ASBS) method is designed for the fabrication of seawater-stable polyamidoxime/alginate nanofibres on a large scale in order to extract uranium from seawater [105]. However, there are still huge scopes of work needed in order to enable the incorporation of different types of modifications in the basic SBS setup for producing better quality nanofibrous mats along with the optimization of process parameters. Obtaining consistent fineness as similar as the fineness of the electrospun nanofibres and maintaining a smaller number of fibre beads should be recognized as significant challenges for the solution blow spinning system.

Creation of a full range of SBS equipment to adapt to the commercial-scale production is still in its research stage. Owing to the short development period, SBS stays in the laboratory experimental stage [65]. However, it is one of the most industrially viable spinning systems for mass production of submicron/nanofibres without the need for major changes in business practices. Already, Kolbasov investigated the industrial approach of a multi-orifice SBS to generate soy protein-PEO nanofibrous nonwovens [106]. SBS has still a long way to go, particularly in the context of basic theory and material application research, which requires a considerable amount of planning. The mass processing of fibres may lead to a significant amount of solvent evaporation, increasing production costs and polluting the environment. Therefore, these issues need to be considered as challenges for the SBS system. SBS technology will advance with further product innovation [65]. The portable SBS technology also should be used in the field of rapid wound dressings, with a wide range of applications. It is desired that more sophisticated structures made from SBS nanofibre assemblies (e.g., nanofibre yarns from different polymers) be produced for novel applications. SBS-spun nano yarn may allow for obtaining complicated fibrous structures for diverse applications, including apparels. Additionally, research studies should focus on ameliorating the properties of the products made of the SBS-spun nanofibres as well as functionalizing the fabricated materials. Flame retardancy, thermal and electrical conductivity, magnetic properties, anisotropic properties, and improved mechanical stability can all be studied by using the SBS-spun nanofibres. For example, recently Liu et al. incorporated a natural preservative (cinnamaldehyde) into fish skin gelatine (FSG) nanofibres fabricated by SBS, resulting in the increased level of antimicrobial activity. Tandon et al. integrated hydroxyapatite particles during the fabrication of stimuli responsive piezoelectric PVDF SBS-spun fibrous membranes in order to increase the bioactivity of tissue engineering scaffolds [107 -108]. Airbrushed Nylon-6/AgCl composite nanofibres have been fabricated in order to increase the anti-bacterial functionality that could be used for tissue engineering and regenerative medicine [46]. Dias et al. expected from their research that the Nickel nano particles incorporating the SBS-spun PVDF fibres can be utilized in magnetic sensors, flexible magnets, spintronic instruments, and the removal of impurities from oil, water, and blood [109]. In addition, further studies may be carried out to investigate the effects of hybrid nanofibre mats which may be produced by incorporating different polymers and tailoring the structure for specific and mass applications. It is also expected to look for the options for a greener solvent for solution blow spinning process. For instance, Parize et al. applied dimethyl carbonate (DMC) as a greener solvent for the PLA fibre production through SBS [34]. SBS will be crucial to the scientific community in the future as a means of finding new types of polymers and solvents that are not suitable for electrospinning, as well as a tool for producing translatable fibrous materials quickly [35].

Polymer/layered silicate (PLS) nano composites may be a possible research area for solution blow spinning. The conjugated nanofibre such as Janus fibre also needs to be explored through solution blow spinning system. However, it is required to study the structure-property relationship, theoretical modelling, and commercialization of the process. The prime issue of solution blow spinning still waiting to be resolved is commercialization. In a nutshell, solution blow spinning system presents a huge research opportunity for researchers interested in it.

CONCLUSION

Solution blowing is a revolutionary method for spinning submicron/nanofibres from polymer solutions by using high-speed gas flow as a fibre-forming driving force at higher output rates, from different polymers and in an economical manner. This technique has been developed in order to overcome the constraints of traditional electrospinning and melt blowing techniques. Various types of improvements have already been made to this spinning system (e.g., CSB, CSBS, μSBS etc.). Airbrushing is commonly used as a promising tool in the production of nanofibre polymers based on the same technique as SBS. However, SBS is expected to grow significantly due to many advantages of nanofibres and their use in a wide range of industrial fields, including the atmosphere, electricity, electronics, biotechnology, pharmaceutics, and so on. More specifically, the SBS system is gaining its popularity in bio-medical applications due to its capability to produce nanofibrous mats without electricity. In the literature, nanofibres made by SBS are being reported on at a growing pace. Still, there are lot of areas in which the researchers can study the spinning process and SBS-spun nanofibres. Although some significant issues in this spinning system must be addressed, continued research activities will undoubtedly allow advancements in the SBS technology in the near future, allowing solution blow spinning (SBS) processes and products to reach commercialization.

Author Contributions

All authors have contributed to the final mauscript. All authors provided critical feedback and helped to shape the final manuscript.

Conceptualization – Khan MKR conceived and planned the study; methodology – Hassan MN developed the framework; Figures- Hassan MN collected the figures; writing-original draft preparation – Khan MKR wrote the manuscript; writing-review and editing – Khan MKR. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

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