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REVIEW PAPER

Electrospinning in personal protective equipment for healthcare work

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Abstract

Protection in many service areas is mandatory for good performance in daily activities of workers, especially health areas. Personal protective equipment (PPE) is used to protect patients and health workers from contamination by harmful pathogens and body fluids during clinical attendance. The pandemic scenario caused by SARS-CoV-2 has shown that the world is not prepared to face global disease outbreaks, especially when it comes to the PPE of healthcare workers. In the last years, the world has faced a deficiency in the development of advanced technologies to produce high-quality PPE to attend to the exponential increasing demand. Electrospinning is a technology that can be used to produce high-quality PPE by improving the protective action of clothing. In the face of this concern, this manuscript presents as focus the potential of electrospinning to be applied in protective clothing. PPE mostly used by healthcare workers are also presented. The physicochemical characteristics and production processes of medical textiles for PPE are addressed. Furthermore, an overview of the electrospinning technique is shown. It is important to highlight most research about electrospinning applied to PPE for health areas presents gaps and challenges; thus, future projections are also addressed in this manuscript.

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Introduction

The safety concern of workers from various areas around the world and the search for suitable protective clothing are growing. Personal protective equipment (PPE) must be chosen according to the risk to be exposed [1]. Health workers are at constant risk of contamination due to exposure to different pathogens that are present in the medical routine. Thus, direct contact with body fluids and cross-contamination protectors (such as masks, overalls, aprons, gloves, caps and laboratory coats) are usually recommended PPE for healthcare professionals [2].

On the whole, medical textiles of the nonwoven and melt-blown are the most used for the manufacture of PPEs because they are light and have fibrous interlacing [2]. However, one of the disadvantages of the use of non-woven tissues is the thermal discomfort caused by the low heat transfer with the medium, providing a high thermal load to the user [3, 4]. A current approach to the manufacture of nonwovens with protective power and thermal comfort is electrospinning [2].

Electrospinning (3D-printing) stands out for its great versatility, low cost and breathability. One branch of research in nanotechnology is that which can produce fibers on a nanometric scale through electrostatic forces [5, 6]. Electrospun membranes (EM) can be nailed to various segments, such as agriculture, sensors, medicine, textiles, electrical components and others [7]. In the health area, the largest applications are for drug delivery, theragnostic formulations, diagnosis and imaging and also tissue engineering [8].

The use of EM for protective clothing has advantages of high porosity, lightness and high surface area when compared to commercial textiles. Important points remain in the applicability as reinforcement, directly to other fabrics and materials already produced [9]. Direct electrospinning in garments already made can be molded according to the thickness and desired location, in addition to being able to be used for finishing and sealing [10]. Also, compounds can be used in solution to be electro-challenged to provide unique characteristics, such as repellents, antimicrobial and biocompatible protective clothing [11].

This review will initially present the main PPE used by health workers. Furthermore, an overview of the electrospinning technique is summarized. Subsequently, papers which address the applicability of electrospinning for PPE in the health area are presented, such as laboratory coats, gloves and respirators. At the end, directions for the development of research with the proposed theme are discussed, especially for better ergonomic and protective performances.

Personal protective equipment for healthcare personnel

Use of personal protective equipment (PPE) is widespread of world as strategy for transmission diminution of the pathogens among patients and healthcare workers (HCWs) [12]. Protection is considered primary for the HCWs in the patient care and contact with infectious diseases [13]. In addition to microorganisms, PPE is also indicated to prevent contact with body fluids (e.g., blood, urine, vomiting and others), medicaments and fecal material [14].

During the confrontation with epidemics and pandemics, PPE had great prominence in the protection of HCWs when there were no drugs, medications or vaccines available [1]. During SARS CoV-2 pandemic, the use of PPE was highlighted as essential for reducing transmission and protection of health workers who had direct contact with infected patients [15]. PPE was also essential in the Ebola epidemic to reduce transmission and infectiousness [16].

The type of PPE can be divided: respirators, body protection, facial protection, hand protection and others [12]. The uniforms are not considered in PPE, but they must play a protective role and be fully hygienic [14]. The types of PPE in protection of HCWs are shown in Fig. 1.

The term respirators for the PPE of the HCWs are used, indicating the utilization of the filter media facial. Face masks and respirators are utilized for the protection of the possible pathogens disperses in air in droplets and particles, also body fluids contaminated exposed in face [17]. Are classified conform to the performance of the retention of particles and type of protection, and, for the protection adequate, mask and respirator must cover the mouth and nose correctly [18].

Facial masks, also called medical masks, are most common for the population and at more affordable cost. They are generally used to contain respiratory viruses, with a protective performance ranging from 80 to 99%, high breathability, fluid penetration resistance and inflammability [19]. They have, as desirable characteristics, the easy-use, confirmed barrier against pathogens on a sub-micron scale, besides being disposable [12, 18]. The difference between face masks and respirators is given by adjusting the face of users and the level of protection. Respirators are usually precast with a more effective seal, with filtration efficiency of 95–99% particles below 100 nm and indicated to high-risk pathogens [12, 18, 20].

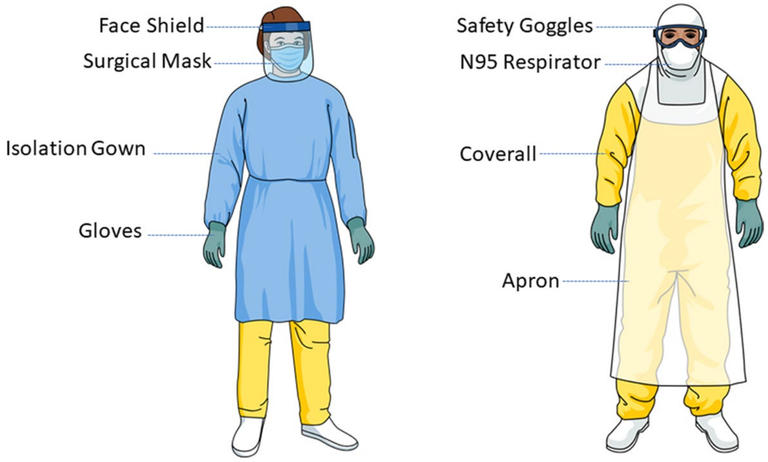

Fig. 1 Protective clothing in healthcare work

Medical gowns or coveralls, as well as respirators, released by the United States Food and Drug Administration (FDA) are approved as an essential PEE the body protection of HCWs. They are components with high use in medical routine, being the second most used PPE after gloves [13]. According to the world's center for disease controls, aprons should protect arms, chest and other exposed parts of HCWs in patient care. They are used to prevent contact with pathogen-contaminated fluids and increase the sterile field of HCWs [21, 22]. They must have some performance characteristics, such as comfort, freedom of movement to the user, flexibility, air permeability, breathability, pathogen protection barrier, liquid repellent, thermal comfort and among others [22].

Hands are the most well-known disease transmission vectors, and high-quality hygiene is important for the patient and hospital workers. Cleaning skin does not remove pathogens in large quantity [23]. Gloves are fundamental for the protection of the hands of HCWs and are considered the PPE most used in clinical practice [24]. They are classified according to the use and "sterile surgical gloves" and non-sterile gloves for the common procedure. Most disposable single-use gloves are used by HCWs, thus requirements such as tear resistance, hand ergonomics, validity of up to 3 years, biocompatibility and protection against pathogens, chemicals and fluids [25].

Medical textiles in PPE for HCWS

Medical textiles (MTs) are considered textile structures produced for any medical application, being implantable or not. They should be designed in a non-toxic, biocompatible, hypoallergenic and non-carcinogenic process. According to their applicability, unique characteristics can be obtained; some of them are air permeability, flexibility, strength, biological inactivity and in some cases, chemically resistant, physically, and mechanically sterilization [26, 27].

MT can be classified as (non)implantable, extracorporeal and medical/hygiene assistance. Non-implantable materials are those used outside the body, such as dressings, bandages, gauze and others. Implantable are biocompatible, biodegradable and non-toxic materials used within the human body, such as sutures and implants. Extracorporeal can be MT used to perform functions of artificial organs, blood purification and others. MT for healthcare is the most numerous and occupies more space in the market; in addition to the PPE already mentioned, they are also applied to bedding and other hygiene items [28].

The structure of MT for PPE is composed mainly of polymer fibers, as they provide a large surface area and make it impossible to spread pathogens [2]. These fibers may come from naturally occurring or synthetic polymers. Natural polymers are cellulose, chitosan, chitin and others. On the other side, synthetic polymers can be polyamides, polyandries, polyurethanes, polyethylene and the world most widely used polypropylene [26]. Cotton, wool and seed stand out as animal materials used for PPE [2].

MT fibers can be produced with a structure of fabrics, knits or nonwovens; among these nonwovens are widely used. Nonwovens have the advantage due to the low

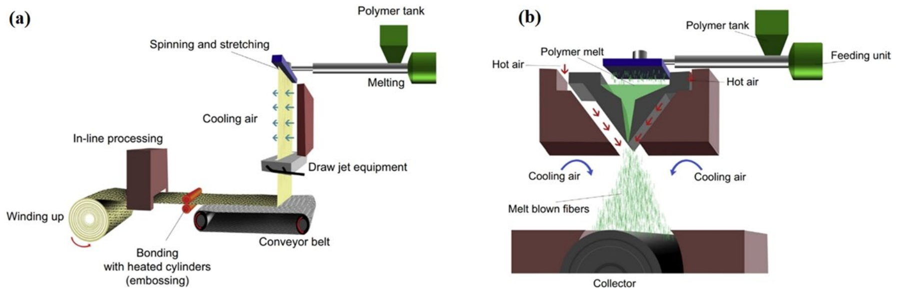

Fig. 2 Process nonwovens: **a** spunbonding and **b** melt-blown. Reproduced with permission from [30] Copyright © 2019 Elsevier Ltd

Table 1 Description of the manufacturing process of nonwovens

Process	Manufacturing
Spunbond/spunlaid	The molten polymer passes through an extruder forming the filaments. These filaments are cooled and solidified by an air jet. Then, the fibers are stretched to reduce the diameter and collected for further treatment and folding processes [31]
Melt-blown	Polymer is heated and extruded into small filaments. Fast-flowing air jet coming out of the tip of the canister is used for solidification and stretching of filaments into fibers, that are collected on a mobile substrate [31]
Composite fabrics	Union of spun-bond and melt-blown techniques forming spun-bond-melt-blown-spun-bond (SMS) fabrics [2]
Electrospinning	Described in the next section

production cost, flexibility, versatility in applications and easily incineration after use [29]. Manufacture processes of nonwovens can be spunbond/spunlaid (Fig. 2a), melt blown (Fig. 2b), composite fabrics, electrospinning and others. Its process is shown in Table 1.

Electrospinning

Electrospinning is a fiber production method based on the utilization of electrostatic force to draw charged threads of polymer solutions [32]. Thus, the electrospinning process is enterally physical. Nowadays, the utilization of electrospinning achieved widespread popularity either in research laboratories or in chemical industries, where the main focus is the production of nanoscale fiber continuously.

The chronological history of the electrospinning technique begins long before the formation of fibers directly, going through scientific variants until it reached the current high visibility scenario. In 1600, William Gilbert was responsible for observing the influence of an electric field over a drop of water. In 1900, Cooley and Morton were responsible for registering the first patent of electrospinning, later in 1934 and 1944, Anton Formhals obtained 22 more patents on the spraying of liquids by electrostatic forces. In 1938, N.D. Rozenblum and I.V. Petryanov-Sokolov developed an EM for filtration systems [33]. The mathematical description of the technique was described by Sir Geoffrey Ingram Taylor, between 1964 and 1969, detailing the theoretical basis of the processes that occur at the tip of the capillary with the application of a constant electric field [34]. The conical shape of the drop at the tip of the capillary was named Taylor's cone in honor of the researcher. Later, in 1990, the term electrospinning was popularized in the scientific community by Reneker's group, who was responsible for electrospinning various organic polymers [7]. The number of electrospinning publications has significantly increased since 1995, becoming a reference in nanotechnology.

Electrospinning is a simple and promising technique, being possible to be performed in any laboratory, requiring a high-voltage source, an infusion pump, a syringe and a metallic collector [35]. Figure 3 presents a schematic model of the electrospinning apparatus.

Initially, the fiber formation process takes place with the influence of an electrostatic field when the drop of the polymeric solution is deformed. Such deformation occurs because the coulomb repulsion force becomes greater than the surface tension, which is broken, and what was previously spherical becomes a conical shape, at the tip of the capillary, which is then designated as Taylor's cone. After that, the cone is launched at the collector at constant acceleration, favoring the formation of the fibers with fine diameters. In this way, the solvent is evaporated, so that only polymeric fibers are deposited and accumulated in the collector, forming the polymeric mesh [37, 38].

The potential of electrospinning can be deeply explored; it is necessary to apply strict control over the electrospun fibers. Many parameters can influence the fibers morphology and diameter. Such parameters can be grouped into three classifications, named processing, solution and environmental [39, 40]. Some of the processing parameters are electrical voltage, solution flow rate, collector type and the distance between the capillary and collector. For the start of the jet, a minimum voltage of 6.0 kV must be applied and then adjusted, taking into account the influence that tension makes on the arrangement of molecules in the fiber [34]. Very high voltages tend to accelerate the jet a lot, and with this, more solutions will be ejected from the tip of the capillary. In this way, they tend to form a small and unstable Taylor cone, causing the formation of beads [41]. The flow rate is responsible for giving

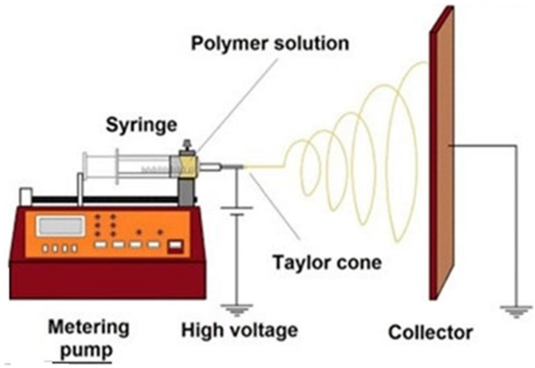

Fig. 3 Schematic representation of an electrospinning apparatus. Reproduced with permission from [36] Copyright © 2019 Elsevier Ltd

characteristics to the diameter, porosity and geometry of the electrospun nanofibers since it is connected to the formation of a stable Taylor cone [42]. Smaller flows can provide less solution ejected from capillary and, consequently, less time for optimal polarization [36]. Collectors must be a material that provides conductivity, creating the potential difference required in electrospinning. Rotary collectors with a certain speed have as advantage an extended time for drying and alignment of fibers [36]. The distance from the collector and the tip of the capillary is one of the least expressive factors of the processing conditions.

The distance should be sufficient for the solidification of the fibers and evaporation of the solvent [41]. The physic-chemical solution features are predominant factors for electrospinning, being directly related to the morphology of the fibers. Some properties of the solutions can be highlighted: type of solvent, concentration, conductivity and surface tension. The solvent is a predominant factor for the formation of fibers without imperfections, since it must completely dissolve the polymer and have moderate volatility [43]. Very volatile solvents can cause capillary clogging, preventing the solution from leaving. However, solvents with low volatility can provide an ineffective drying of the nanofibers when they are deposited in the collector [41, 44]. The elongation of the uniaxial jet is related to the concentration of the polymeric solution. At low concentrations, the surface tension of Newtonian fluids tends to reduce, and the electric field is not able to keep the entanglement of the polymer chains together, resulting in fragmentation before reaching the collector. On the other hand, concentrations above a critical value might cause problems in the flow rate and clogging of the capillary, forming irregular fibers [45]. Conductivity is closely related to the formation of the Taylor cone. Small conductivity values, and the ones above a critical value, do not provide a drop with load and, therefore, the Taylor cone formation does not occur. Conductivities within the critical value generate surface load on the drop, forming the Taylor cone and consequently a smaller diameter in the fiber [46]. Another parameter attached to the Taylor cone is the surface tension. Higher surface stresses require larger coulombic forces for stretch initiation, as well as a smaller jet flow [42].

Recurrent interactions around the electrospinning system affect the polymer solution itself and may influence the morphology of the fibers. Thus, environmental factors should also be considered. Temperature can influence the evaporation rate of the solvent and the viscosity of the solution. On the whole, an increase in temperature generates greater mobility in polymer chains, allowing electrostatic forces to further stretch the solution, forming fibers with smaller diameters [42]. Moisture is interrelated with solvent evaporation. High humidity provides a condensation of water on the surface of the fiber and, in turn, it can hinder the evaporation of the solvent [39]. However, very low humidity with solutions of very volatile solvents causes very fast evaporation of the needle tip, causing clogging.

The use of polymeric matrices in electrospinning is found in a wide range of technological applications, showing great results and future ambitions [47]. Recent studies show some possibilities for the application of electrospinning, in the use of filters for air purification [48, 49], in the electrochemistry field [50, 51], catalysis [52, 53], tissue engineering [54, 55], biomedicine [56, 57], and in manufacture of protective clothing [58, 59].

Electrospinning protective clothing

Since World War II protective clothing (PC) has had great notoriety for the primary function of protecting the military from chemicals and biological warfare agents [60]. Currently, there is a high demand for such protective clothing for health agents or any emergency team against chemical and/or biological threats to which they might be exposed [60, 61]. The protection of this clothing is given by the total barrier of the contaminant, preventing its permeation to deeper layers and contact with respiratory routes [62]. In addition to the examples cited, PCs are also applied in sportswear, smart fabrics, face masks, ballistic protection and against nuclear war agents [63, 64]. For producing cheap and versatile materials, with thermal comfort and easy functionalization, the electrospinning technique can be used as an advanced system to produce chemical and biological protection scaffolding for PC [60, 63]. Gibson et al. [65] published a pioneer work in which the author joins the electrospinning with PC technology by producing polyurethane EM under foams of the same polymer. The authors indicated that the material was light and could be easily applied to PC because they have high breathability along with elasticity and filtration efficiency. When compared to the pure foam, which allowed the particles to penetrate, the small layer of deposited nanofibers managed to block the penetration and the arrival of the elements to the foam.

Many efforts today are made to develop EM for detoxification, degradation and separation of harmful substances with high efficiency in adsorption and lightness, bringing comfort to the user [66]. Table 2 shows some applications of EM on PC.

Purwar et al. [73] increased the biological protection of sericin and poly(vinyl alcohol) (PVA) EMs by adding 0.75% Cloisite® 30B, which is a nanoclay. The presence of the nanoclay promoted modifications of mechanical and antimicrobial resistances for the filtration of bioaerosols (e.g., viruses, fungi, and bacteria). Furthermore, the breathability tests of suspended particles showed the EM with 0.75% Cloisite® 30B is capable of retaining particulate matter with a concentration of 0.725 mg m^{-3} s^{-1}. The authors indicate efficient filtering of particulate matter from the size of 1.0 µm to 10 µ, acting as a barrier to undesirable substances. Choi et al. [74] studied the use of polyurethane nanofibers associated with inhibitory agents for the manufacture of protective clothing. The EM had a decontamination rate of 69% for a toxic sulfur compound. Han et al. [75] demonstrated that a blend of PVP and polycaprolactone (PCL) that encapsulated an antimicrobial agent has a destructive activity of bacteria. The EM showed a 99.99% bacterial death rate and a potentially beneficial one for application in protective tissue and food packaging.

Electrospinning in PPE for healthcare work

The success of electrospun polymeric matrices is due to the high filtration when compared to other materials. Ultrafine fibers with a large surface area and fine porosity can be more efficient in permeating undue agents [76]. Khan et al. [70] evaluated the electrospinning of PVA together with ZnO nanoparticles for use in

Table 2 Examples of protective clothing based on electrospun matrixes

Polymer	Functionalization	Application	Activity
Polyacrylonitrile (PAN)	Ethylenediamine, diethylenetriamine, triethylenetetramine and ethanolamine	Self-detoxifying [67]	Detoxifying efficiency diisopropyl fluorophosphate (DFP) utilized chemical warfare
Organo-soluble polyamide/Kevlar	Organo-soluble polyamide synthesized	Heat and flame [68]	High thermal stability; Fire resistance; Improvement in air permeability
Poly(ethylene oxide)	Fluorescent chemosensor—phos-3	Gas sensing [69]	Rapid screening of phosgene in suspected gas; Quick response ($\ll$1 s) to phosgene; High sensitivity (25 ppb) and high selectivity;
Polyvinyl alcohol	Zinc oxide (ZnO)	PPE (surgical gowns, gloves and masks) [70]	Photo-catalysis efficiency; Protection against ultraviolet (UV) rays; Antibacterial efficiency
Poly(methyl methacrylate)	ZnO nanorods and Ag nanoparticles	Self-cleaning [71]	Antibacterial, Antiviral (corona and influenza viruses) Degradation of organic pollutants; Quantitative analysis of trace pollutants
Poly(vinylidene fluoride)	2-Hydroxy-4-methoxy benzophenone (UV9) and hydrophobic nanotitanium dioxide	Waterproof and (UV) resistance [72]	Moisture breathability; Tensile strength; Waterproof performance; Ultraviolet protection factor

surgical gowns for the formulation of a self-cleaning material with UV protection. The authors observed an interaction between the nanoparticles and the polymer with an interesting photocatalytic efficiency. Antibacterial efficiency against *Staphylococcus aureus* (*S. aureus*) and *Escherichia coli* (*E. coli*) with increasing ZnO concentration. The authors indicate that the material produced has multifunctional power and is indicated for medical use against bacteria, stains and UV protection.

Salam et al. [77] studied the electrospinning of PAN functionalized with ZnO and HeiQ Viroblock. HeiQ Viroblock is known as a formulation composed of silver particles and liposomal vesicles. The authors obtained an antibacterial reduction greater than 90% against *S. aureus* and 88% against *P. aeruginosa*. When the electrospinning material was applied to avian Influenza virus, there was a viral reduction of approximately 37% in three hours. The material is indicated for use in face masks, surgical gowns and health PPE against enveloped viruses and bacteria. The EMs are also used as an improvement in commercial mask filters. Alshabanah et al. [78] electrospun zinc oxide (ZnO) and copper oxide (CuO) nanoparticles using PVA as a polymer to evaluate effects against covid-19 and multidrug-resistant bacteria. In in vitro test against The Spike S protein of SARS-CoV-2, they obtained better inhibition results with ZnO when compared to CuO. For multiresistant strains, *Methicillin resistant S. aureus* (*MRSA*), *Methicillin resistant S. epidermidis* (*MRSE*), *P. aeruginosa*, and *Klebsiella pneumonia* (*K. pneumoniae*) EM containing ZnO also obtained more satisfactory results. The authors indicate the use of MS in PPE as aprons, and masks and also for hygienic hospital sheets.

The use of electrospinning for improvement and improvement in gloves is still little explored. Vongsetskul et al. [79] used nitrile gloves as a base, electrospun trimethylated chitosan (TMC)-loaded PVA. Due to the antimicrobial properties provided by TCM, it was able to inhibit Gram-negative bacteria (*E. coli*, *P. aeruginosa* and *Acinetobacter baumannii* (*A. baumannii*)) and yeasts *Candida albicans* (*C. albicans*). The same effect was not observed for pure nitrile gloves and those with electrospun PVA matrix. The authors also observed greater roughness, something considered beneficial in practical terms.

Because of the pandemic scenario experienced, research to reinforce filtering media such as masks and respirators has grown significantly, with emphasis on the use of electrospinning to produce improved protection for users. Additionally, it was possible to notice an aerosol capture of 90%, indicating its great applicability as a SARS-CoV-2 filter; the material can also be used for other viruses and types of pollution which might bring serious diseases. Still, in the case of masks for the medical area, electrospinning can provide an even greater reinforcement, as shown in Fig. 4.

Leung and Sun [83] evaluated electrospun polyvinylidene fluoride (PVDF) membranes as a 50–500 nm sodium chloride aerosol filter, size range chosen to simulate SARS-CoV-2 (average 100 nm). The authors noted that the smaller the fiber diameter, the better the retention efficiency of this particulate aerosol, due to the large surface area. He et al. [84] combined the power of electrospinning with 3D printing for filter formulation to produce masks. Initially, the printing of polylactic acid (PLA) media was performed and later the manufacture of nanofibers of the same polymer. The filtration efficiency study showed that the material has a higher holding power than surgical masks (55%) and performance close to the well-known KN95 (Chinese

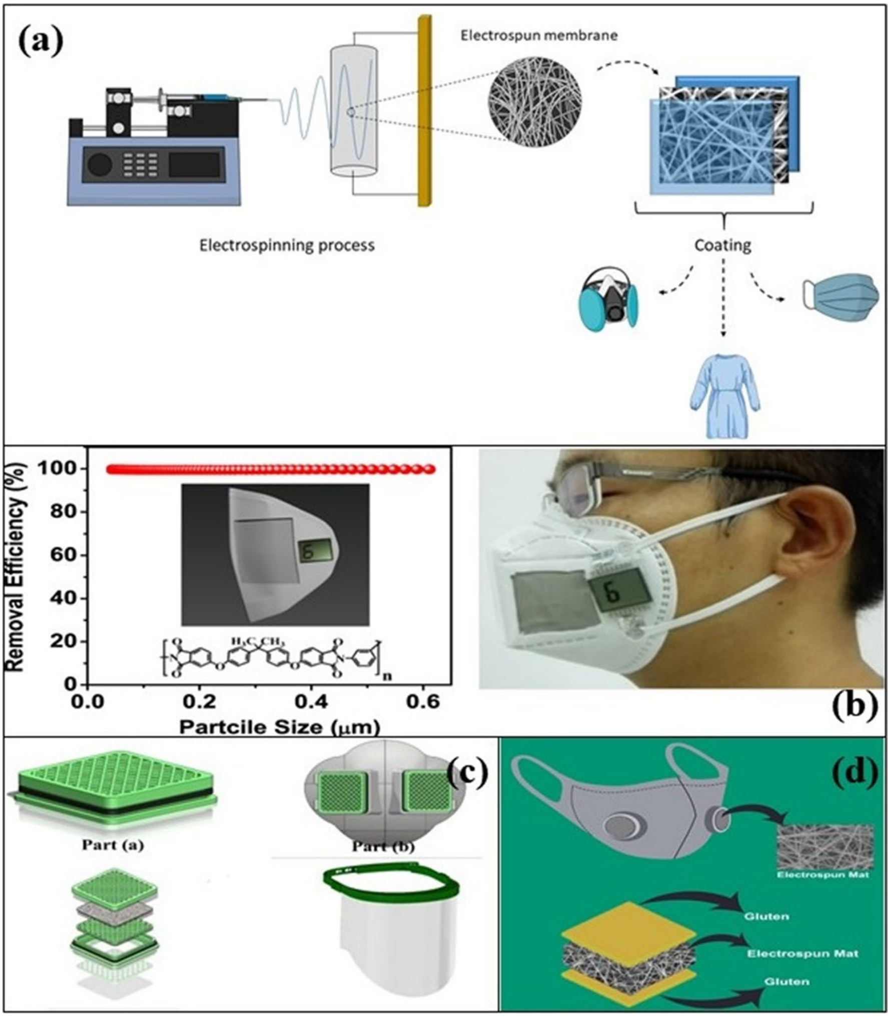

Fig. 4 **a** Schematic representation of EM for use as scaffolds in masks, medical clothes, and filters for breathers. **b** Smart face mask from EM. Reproduced with permission from [80] Copyright © 2017 Nano Energy. **c** Representation respirator face mask using EM as a filter. Reproduced with permission from [81] Copyright © 2020 Journal of Infection and Public Health. **d** Face mask coating electrospun matrix. Reproduced with permission from [82]. Copyright © 2020 Science of The Total Environment

retention standard) and N95 (American retention standard) masks. Furthermore, the authors point out that the transparent look of the material can be used to mitigate social traumas caused by the pandemic.

Due to its versatility to meet needs and obtain commercially available fibers, electrospinning allows modifications to improve its chemical, mechanical, and antimicrobial features [85]. Thus, the interest in this branch of science daily grows, especially in a way to find new membranes with better antibacterial and antiviral properties [86]. Besides the pure polymer, the most diverse drugs or medicinal plants can be inserted into the polymeric solution to provide unique properties. As example of additives can be highlighted nanoparticles [87], plants extract [88], and organic compounds [89] formulate functionalized masks (Fig. 5).

Ahmed et al. [81] developed a new prototype of a mask (Fig. 4c) with respiratory filter using electrolyte matrix of PLA and CA with the insertion of copper oxide nanoparticles (CuO) e and graphene oxide (GO). For the authors EM would be able to make a barrier to SARS-CoV-2 viruses transported by air, CuO and GO would be responsible for inhibiting and inactivating harmful particles trapped in the filters. The filters could be discarded and changed and the prototype washed and sterilized, providing a lifetime mask. The authors also highlight the cost–benefit and low market value of the material, being accessible to the general population. Khanzada et al. [91] studied PVA electrospinning with Aloe Vera (AV) as an attractive alternative to antimicrobial products. The material besides fibrous characteristics also obtained a slow AV release performance, which is paramount to protective clothing. Furthermore, antimicrobial activity was attested against *S. aureus* and *E. coli*. The authors indicate the use of the material in surgical gowns, gloves and clothing for health in general.

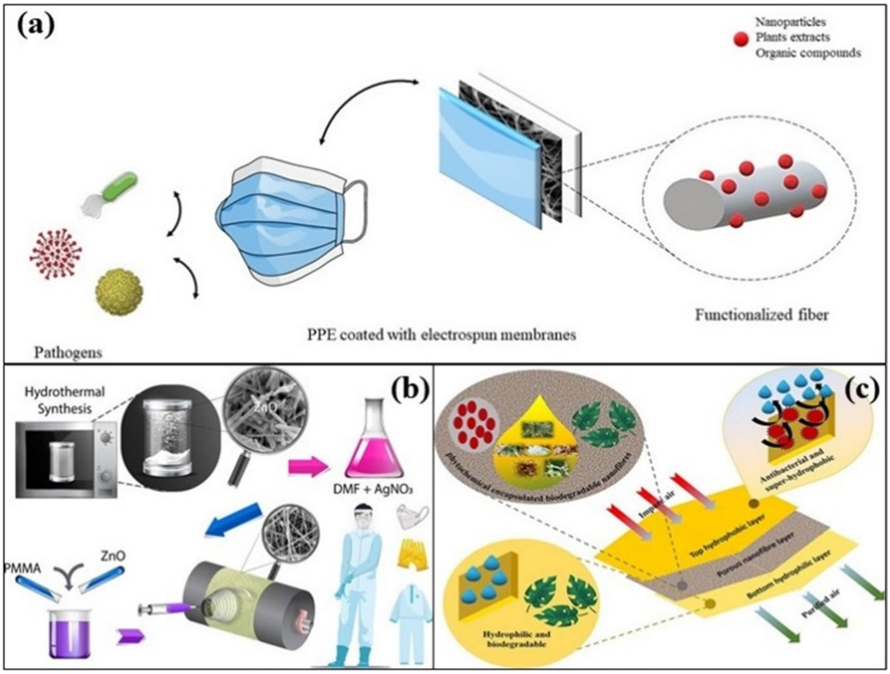

Fig. 5 **a** Representation of functionalized masks, **b** functionalized nanofibers for the PPE. Reproduced with permission from [71] Copyright © 2021 American Chemical Society. **c** Face mask 3-layered phytochemicals functionalized. Reproduced with permission from [90] Copyright © 2021 Chemical Engineering Journal

Buluş et al. [92] studied the production of EM of PLA with activated carbon (AC) for the formulation of filter material for prolonged use by health professionals. The AC was probably chosen because it is a material that presents high values of specific surface areas, acting as a great capturer of airborne composts. The study reveals that the best AC dosage in the material is 8% by weight, showing bacterial filtration efficiency above 98%. The authors highlight that the composite has characteristics for application in PPE and filtration systems, especially for SARS-CoV-2. Chowdhury et al. [93] used in their study the EM of PVA and functionalized with licorice extract to the propagation of SARS-CoV-2 at early stage. The produced material had desirable porosity and excellent airflow rates, ensuring optimal breathability. Due to the production of triterpenes, acid 18-β glycyrrhizin and glycyrrhizin that have great results against Respiratory Syncytial Virus (RSV) [94], Human Immunodeficiency Virus (HIV) [95], and SARS-CoV [96]. The authors believe in the potential of the material but denote that still needs more comprehensive studies.

Patil et al. [90] evaluated the insertion of electrospun PLA nanofibers functionalized with phytochemicals (*Azadirachta indica* and *Eucalyptus citriodora*) between layers of cotton to produce biodegradable masks with disinfection characteristics. When compared to conventional facial masks, the produced material has greater air permeability and efficiency of bacterial filtration. Computational studies of phytochemicals indicate the activity of inhibiting pathogens with a protein structure similar to SARS-CoV-2. A promising biodegradation effect was verified using artificial cow manure, reducing post-pandemic environmental impacts. Motivated to develop multifunctional materials for pandemics, Koragoz et al. [71] investigated the potential of EM of poly(methyl methacrylate) (PMMA) functionalized with ZnO nanorods and Ag nanoparticles for PPE. In addition to nanoscale fiber formation, the authors observed antibacterial activity against *S. aureus* and *E. coli* and antiviral activity against parainfluenza virus-3 (BPIV3) and bovine coronavirus (BCoV). Still, the material has photocatalytic features of organic pollutants, which can promote the self-cleaning of the system. The authors believe in the potential of the material for passive and active protection.

Fadil et al. [97] evaluated the air permeability with the addition of EM in commercial face masks. The insertion of layers of nanofibers increases air permeability, vapor transmission and flexural rigidity without causing discomfort to the user. These factors added together provide greater filtration capacity. The insertion of nanofibers is indicated to improve commercial masks.

During the SARS-CoV-2 pandemic outbreak, some companies (Table 3) bet on the use of electrospinning as an additional reinforcement in masks and developed products that can be purchased by the general population.

Korea Advanced Institute of Science and Technology (KAIST) [98] has a patented project for the production of masks coated with EM with aligned fibers. The great advantage of this material compared to ordinary masks is the power of reuse even after 20 consecutive washes. The material can block 80% of particles with diameters up to 600 nm. On the other hand, the 4C Air start-up (a start-up in Silicon Valley that uses nanotechnology to create air filters with new functionality) [99] highlights the sale of KN95 masks coated with EM, without mentioning the used polymer. The company indicates high filtration efficiency (> 95%) of 03-micron

Table 3 PPE developed in industrial climbing

Industry	Product	Retention efficiency
Institute of Science and Technology	Mask	80%
4C Air	KN95 masks	> 95%
PROVEIL®	Biodegradable mask	Bacterial filtration 98% Aerosols 93%
Inovenso	NOFILTER® 95/99 INOFILTER V	96% 99%

particles and low breathing resistance, also highlighting the ergometer's comfort for daily use. The Bioinicia company [100], an engineering company dedicated to the development and manufacture of nano- and microstructured materials by electro-hydro dynamic processes, is betting on the PROVEIL®, a biodegradable mask coated with an EM capable of providing a useful life of up to 6 h, disinfection with 70% alcohol without losing both properties, bacterial filtration of 98% and aerosols 93%.

Another company that is also betting on the use of EM as reinforcement is Inovenso [101], which highlights the use of two products: INOFILTER® 95/99 and INOFILTER V. The former are masks produced from polyethylene terephthalate (PET) and polyvinylidene fluoride (PDVF) nanofibers with the purpose to capture bacteria and viruses, whose filtering efficiency lays between 96 and 99%, with low-pressure drop which provides high breathability, whereas the later promises the same applications with the additional resistance against liquids or bodily fluids.

Future projections and conclusions

In the course of the clinical routine, it is very common to use one or more PPE by HCWs for complete characterization of protection, which can bring thermal discomfort and also ergonomic damage. During Ebola endemic and SARS-CoV-2 pandemic, PPE was used for long periods and in very large demand, which led to many complaints of discomfort on the part of doctors and nurses. A study conducted by Boon et al. [102] with physicians and nurses who responded to Cases of Ebola, indicated that the greatest complaints regarding PPE were: blurry glasses, breathing difficulties due to masks/respirators, lack of ventilation and weight of clothing. In a study by Yildiz et al. [103] with HCWs in coping with SARs-CoV-2, the discomfort caused behind the ears, close to the eyes and nose (pain, redness and wounds) by masks/respirators and dehydration caused by the heating of costumes/masks were the most frequently reported complaints.

In many cases, the layers used in the manufacture of PPE have reduced pores and with resistance to penetration of liquids, do not allow the permeability of the steam and cause a thermal charge to the user [104]. In this context, the EM by having lightness, high permeability and breathability together with a protective character can provide breathability and comfort to PPE to be employed [105].

Bhuiyan et al. [4] evaluated the insertion of EM in non-woven viscose layers. The authors obtained a lightweight, flexible material, resistant to penetration of liquids, thermal transmittance and improved moisture vapor and high evaporative cooling index. The results show that the material provides thermal comfort due to a lower perspiration accumulation. Zhang et al.[106] electrospun hydrophobic siliceous polyurethane membranes with the addition of stearic acid and obtained a material with excellent impermeability. Thermal tests indicated that electrolyte membranes have a temperature regulation with latent heat of up to 40 J/g. The Authors suggest the use of this material for medical, military, intelligence and other clothing.

The SARs-CoV-2 pandemic has demonstrated the need for the formulation of tissues with more effective antiviral power. Advances in material sciences in antimicrobial finishing and/or surface modification methods can be used to improve the antiviral properties of PPE [26]. Functionalized materials with different graphenes (GPs), such as graphene oxide (GO), reduced graphene oxide (rGO) and in its pure form [107, 108]. Reina et al. [109], in a systematic review, praised the use of GPs for their antimicrobial, immunological and photothermal characteristics; they can be applied to reduce the life of the virus on surfaces, selective biodetection, interference in viral replication and others. In the work, the authors highlighted the use of GPs in polymeric materials for the formulation of coated antiviral surfaces. The antibacterial activity of graphenes along with electrospinning is already reported. Yang et al. [110] in their work reported PVA electrospinning together with chitosan functionalized with GO. The authors observed that, in addition to changes in thermal and chemical properties, the insertion of GO provides antibacterial activity against E. coli and *S. aureus* being a promising material for dressings. Furthermore, to further increase the properties of GPs, the insertion of metal nanoparticles is reported. For instance, Zhang et al. [111] electrospun silk fibroin/gelatin together with GO with silver nanoparticles (GO-AgNPs). The inhibition study of *E. coli* colonies showed a new efficient approach with satisfactory results.

The consumption of single-use PPEs has made a significant leap with the advance of SARs-CoV-2 around the world, resulting in an increase in ocean pollution [112]. This constant growth leads to eminent concerns about a new environmental risk, the inappropriate disposal of contaminated PPEs (Fig. 6). Ocean Asia [113] in 2020 already estimated the insertion of 1.56 billion facial masks in oceans alone and called for the formulation of scientific innovations for the production of sustainable alternatives. Thus, electrospinning of biodegradable polymers presents itself as an environmentally friendly solution. Lv et al. [114], in a systematic review, address the so-called green electrospinning, highlighting the use of natural or biosynthetic polymers for application in air filters with great retention efficiency. The electrospinning of polymers such as gelatin, cellulose, soy protein, chitosan and other hybrid mixtures has their potential for filtration known in the literature and can be widely explored [115]. Kadam et al. [116] proposed gelatin (a natural polymer) electrospinning together with β-cyclodextrin for applicability in air filtration medium. The material obtained a filtration efficiency of $<95\%$ for aerosols of 0.3–5 μm. Furthermore, the material showed high retention capacity when adsorption of volatile compounds and solid particulate matter was evaluated. The authors pointed up the use

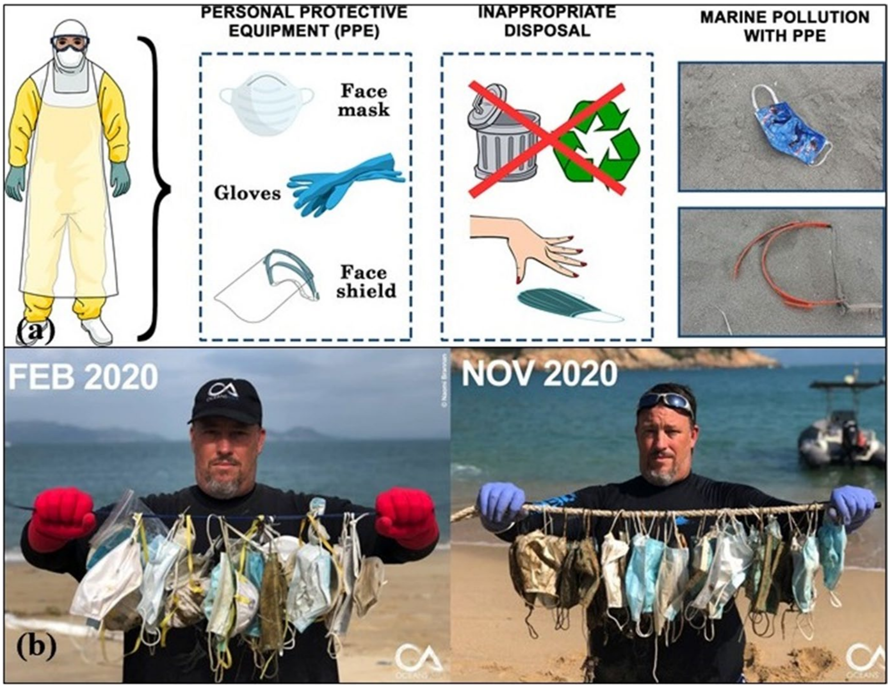

Fig. 6 **a** Pollution of the marine environment by PPE. Reproduced with permission from [117] Copyright © 2021 Marine Pollution Bulletin. **b** Pollution face masks on beach (credit by image Ocean Asia)

of the material because it has sustainable characteristics and provides the capture of viruses in respiratory filters.

The reuse of PPEs is a current idea and, in the future, may come as an ecologically sustainable bias [112]. Further research should be based on improvements in polymers and chemical additives used in PPEs processing. A therapeutic area that can be explored with electrospinning is the photodynamic inactivation of microorganisms (PDI). PDI is based on the use of a photosensitive drug, light, and molecular oxygen to inhibit viruses, bacteria, and fungi in a fast, low cost and effective way at the right dosage [118]. Studies approach the effectiveness of photosensitizers (e.g., methylene blue, curcumin, rose bengal, and others) as accelerating agents for inhibiting microorganisms even in the blood flow [119]. Several studies that include PDT/PDI have already been reported with great success when applied as dressings for disinfection, and it is also possible to use in oncological areas. Thus, medical PPE with functionalized fibers and photosensitive drugs (Fig. 7) can be a viable strategy for double reinforcement, initially as a biological barrier, and later for disinfection, which can prolong the useful life of these materials.

Another way to produce sustainable PPEs is to use quantum dots (QDs) or carbon quantum dots (CQDs). QDs and CDQs are the new line of zero-dimensional nanomaterials that can be produced by various syntheses with different semiconductor elements which provide low-cost, non-toxic, biocompatible, favorable dispersion in water and generation of reactive species. Reactive species generated by the

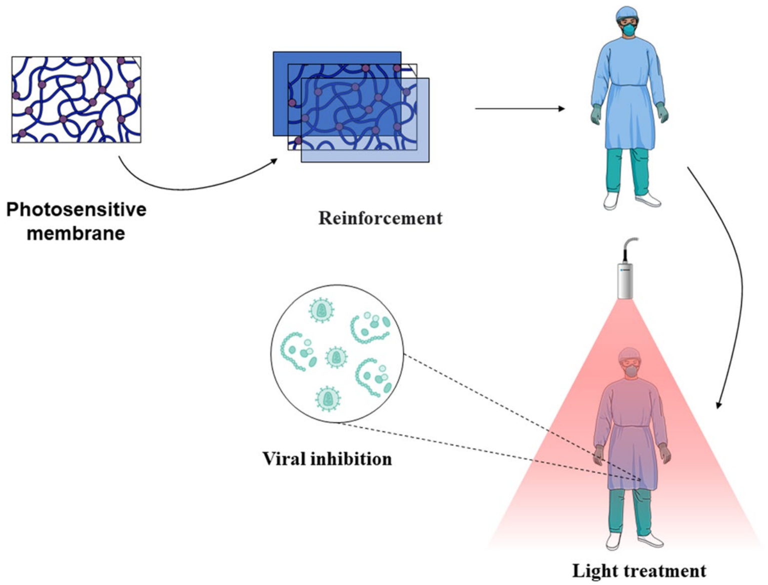

Fig. 7 Projections for the use of fibers and photosensitizers as a biological barrier

absorption of light at specific wavelengths can provide a PDI effect with advantages superior to ordinary photosensitizers because they do not have the presence of heavy metals and are less toxic to the environment [120]. Bronzato et al. [121] synthesized cobalt oxide QDs (Co_3O_4) and soaked in 100% cotton fabrics to verify the virucide characteristic against human coronavirus 229E (HCoV-229E). The results indicated a reduction in viral load by 20 times; the authors indicate the use of QDs for the formulation of self-cleaning PPEs. Nie et al. [120] electrospun PAN and CQDs to formulate an antibacterial material. With lighting, they observed the formation of reactive species and characteristics of low cytotoxicity and biocompatibility. Studies against *E. coli*, *P. aeruginosa* and *Bacillus subtilis* had a very effective and modest PDI for *S. aureus*. Ghosal et al. [122] electrospun PCL membranes with the addition hydrophobic carbon quantum dots (hCQDs) for antimicrobial activity. The authors attested to the formation of reactive species with the illumination of the material and a PDI effect against *S. aureus, Listeria monocytogenes, E. coli* and *K. pneumoniae.*

In another aspect, QDs and CDQs can be used in photothermal therapy (PTT) that is based on the incidence of near-infrared light (NIR) for conversion into heat, generating an increase in temperature of up to 10 °C to the tissue and without the formation of reactive species. Tian et al. [123] electrospun PVA membranes with gold nanoparticles and CDQs (Au@CDs) synthesized for PTT effect and observed a high inactivation of *E. coli* and *S. aureus* by membranes irradiated with NIR, superior to the solution.

Curcumin (Cur) can also be employed in EM to increase PPE service life. Cur is a natural compound obtained from Curcuma long rhizome l. widely used as a condiment [124]. Furthermore, its anti-inflammatory, antibacterial, pro-apoptotic, anticancer and other properties have been documented [125]. Curcumin electrospinning is well reported for drug delivery systems [126], wound healing [127] and cancer treatment [128]. The photodynamic property of curcumin with absorption in the UV–Vis region in a range of 408–434 nm and phototoxic effect on micromolar amounts in PDI studies can be highlighted [129]. Raza et al. [124] in a review of antimicrobial compounds for PPE also believe in the potential of using Cur for gowns application.

The estimate of HCWs for 2030 is more than 80 million people and the search for improvements to PPE in this sector is extremely important [2]. Electrospinning shows great applicability and satisfactory results to produce sustainable, comfortable PPE and as a barrier to harmful pathogens. Its use on an industrial scale can produce, in a short time, from scaffolds to masks and medical clothes. The insertion of compounds to EM can provide an antibacterial effect, prolonging the life of PPE and protecting to the user. Despite satisfactory results already found, there is still a need for more comprehensive research approach of MS in the gowns and gloves segments. It is expected that this work will serve as an aid for further research in the follow-up of electrospinning applied to PPE.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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