

Review Article

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Smart textiles and wearable technologies – opportunities offered in the fight against pandemics in relation to current COVID-19 state

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Abstract: Recent outbreak of the COVID-19 pandemic has changed the world dramatically, posing profound challenges to our healthcare infrastructure, economic systems, social and cultural life but also to our freedom. What this pandemic made us realize so far, is that, despite the tremendous advances in medicine and pharmacy, in the initial moments, which are crucial in the containment of spreading of any pandemic, the key role is played by the non-pharmaceutical measures. These measures are the ones that bridge the time between pandemic outbreaks and the development of drugs or vaccines and are crucial for the number of human lives spared. Smart textiles and novel materials as part of the personal protective equipment (PPE) and telemedicine are crucial factors in the healthcare system. Here, we present an overview on the use of textiles in the fight against pandemics, in the past and current COVID-19, we analyze the morphology of the commonly used face masks, made of cotton and typically used polypropylene (PP). We also present the perspective that smart textiles, wearable technologies and novel materials are offering in the fight against future pandemics, mainly as part of the personal protective equipment and telemedicine.

Keywords: COVID-19; textiles; pandemics; personal protective equipment; telemedicine

1 Introduction

More than 100 years since the outbreak of the 1918 influenza pandemic, we now seem to face another one. In December 2019, pneumonia of unknown cause was detected in Wuhan, the capital of China's Hubei province. It was later disclosed that it is a new type of coronavirus which was named severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and the respiratory disease it is causing – coronavirus disease (COVID-19) [1, 2]. Since the first outbreak, it spread worldwide. The World Health Organization (WHO) declared the 2019–20 coronavirus outbreaks a Public Health Emergency of International Concern (PHEIC) on 30 January 2020 [3] and a pandemic on 11 March 2020 [4]. By mid-May 2020, only within the 6 months from Wuhan detection, there have been more than 4.36 million cases reported worldwide in more than 200 countries and territories, resulting in more than 297,000 deaths [5]. Undisputedly, the coronavirus pandemic is posing profound challenges to our healthcare infrastructure, economic systems, social and cultural life but also to our private lives and personal freedom [6–9].

The SARS-CoV-2, similarly to common viruses, is mainly transmitted through respiratory droplets [10, 11] and contact [12]. What makes it specific is the particularly high speed of its transmission which originates from the longer median incubation period (the time from infection to appearance of symptoms) and the longer serial interval (the time between successive cases) [13]. The basic principles of prevention and control of infectious diseases are the elimination of the source of infection, cutting off the transmission routes and protection of the vulnerable population [12]. An available SARS-CoV-2 vaccine would be an effective measure to protect the population at risk and that is why research institutions and enterprises are working hard on developing one [14]. Biotech companies are developing mRNA vaccine as a potential candidate against COVID-19, and have successfully obtained a SARS-CoV-2 antibody. According to the WHO draft landscape of COVID-19 candidate vaccines until September 2020, there are 38

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candidate vaccines in clinical evaluation and 149 in pre-clinical evaluation [15]. Another remaining challenge in the elimination of the source of infection and cutting off the transmission routes is the quick and reliable diagnostics which will allow fast case identification, isolation, and contact tracing [16–18]. Meanwhile, the measures of protection against COVID-19, which proved to be effective in reducing virus spread [19], are limited to physical distancing, reduced traveling, improved hygiene and wearing of personal protective equipment especially for occupational groups at risk of COVID-19 [20–24].

In recent years the results from the tremendous research in the field of material, surface, and aerosol science and engineering [25] have enriched the textile materials with properties (like improved filtration, antibacterial and antiviral activity, breathability, etc.) crucial for successful prevention of the spread of infectious diseases. This fact is placing textiles on the front line in the fight against the current pandemic and the textile industry – an important player since many textile companies are currently implementing the production of protective masks and protective clothing using their production facilities [26].

Another specification of COVID-19 is the exponential growth in the number of new cases that can easily lead to systemic healthcare failure. Therefore WHO recommends patients with mild symptoms and without cardinal chronic conditions to be cared for at home while keeping a communication link with the healthcare personnel [27]. Here the smart textile role for sensing and monitoring of body parameters as part of telemedicine could play an important role [28]. Nanotechnology and smart textiles are promising in tackling the pandemic [29].

This review article presents an overview of the use of textiles in the fight against pandemics, past and current, additionally, the morphology of the commonly used face masks, made of cotton and typically used polypropylene (PP) is analyzed. Finally, the perspective that smart textiles, wearable technologies and novel materials are offering in the future pandemics is presented, since the situation of COVID-19 is a proof that future pandemics are going to happen and that we should be prepared.

2 Role of textiles in the past pandemics

There were several influenza pandemics in the last century during which influenza viruses spread on a worldwide scale and infected a large proportion of the world population. The deadliest one, by far, is the 1918 influenza

pandemic, commonly referred to as the Spanish flu which lasted from 1918 to 1920 [30]. Older estimations say it killed 40 to 50 million people [31] while current revisions claim that between 50 million and 100 million people worldwide were killed by this disease [32]. That is why the Spanish flu pandemic has been described as “the greatest medical holocaust in history” [33]. In 1918, the virology was at its infancy so the available tools to control the spread of the flu were mainly limited to non-pharmaceutical measures such as isolation, quarantine, improved personal hygiene, disinfection, and avoiding grouping, which doesn’t differ much from the current situation with COVID-19. The healthcare workers were instructed to wear gauze masks when treating flu patients. It was also suggested to change the clothes when leaving the influenza wards. The face masks used were a half meter of gauze folded like a triangle that was worn over the mouth, nose and chin [34]. These gauze masks acted to prevent the spread of the infectious droplets from the wearer’s mouth and nose and also to protect him/her to put the contaminated hands in the nose or mouth. In some regions, the whole population was obliged to wear masks, for instance, in San Francisco. There are no consistent studies on whether the wearing of masks helped to prevent the spread of the disease. Some studies found that the mask-wearing led to “a rapid decline in the number of cases of influenza” [35], while others, like the one in the Great Lakes, did not confirm this. The obtained results showed that mask-wearing by healthcare workers did not have an effect on whether or not they would be infected. 8% of those who used the mask and 7.75% of those who did not, developed infection [36]. Despite this, the masks were used by a wide population in order to protect themselves from getting infected. At that time, the number of companies specialized in mask manufacturing was really small, one such manufacturer was the Prophylacto Manufacturing Company of Chicago, and it was really hard for them to meet this increased demand. As a response to this shortage, women all over America organized in churches and community groups used their spare time for mask making.

Other, less serious pandemics occurred in 1957 (Asian influenza) and 1968 (Hong Kong influenza). The main efforts to fight these pandemics were directed to vaccine supplying and the non-pharmaceutical measures like closing schools, restricting travel, closing borders, or recommending wearing masks, were generally not taken [37].

The masks used in these past pandemics were cloth masks made of common textiles, usually cotton. They were not subject to regulation, and there is insufficient research and substantiated evidence that they are an effective measure to prevent the spread of infectious diseases. However,

they were consistently used by healthcare professionals from the late 19th century to the mid-20th century when they were replaced by modern medical masks. Their use continues in developing countries [38].

3 Role of the textiles in the current COVID-19 pandemic

Since the coronavirus outbreak, the demand for personal protective equipment (PPE) and especially medical masks and respirators has risen to a point where fears of shortages are driving many countries to take increasingly drastic measures [39]. In absence of an available vaccine, PPE is considered an essential infection control measure. This global overwhelmed demand led WHO to issue a document that summarizes their recommendations for the rational use of PPE. According to WHO's estimations, the current global stockpile of PPE is insufficient, especially for medical masks and respirators. This is not only a result of the high number of people infected with COVID-19 but also by misleading information, panic buying and stockpiling [40]. The supply chain distribution due to the subsequent lockdowns to high risk-related practices kept the businesses unsustainable in difficult and unpredicted times [41].

Various types of masks are used worldwide by healthcare workers and the general population which are reduced mainly to cloth masks (Figure 1), medical masks, and respirators [42], see the examples in Figure 2. But only medical masks and respirators are subject to regulation. Medical masks are intended to be worn by healthcare professionals during treating and nursing patients to protect them from infecting [43, 44]. They are not designed to protect the wearer from inhaling airborne bacteria or virus particles [45]. The masks are usually pleated to allow the user to expand them and cover the area from the nose

to the chin. The masks are secured to the head with ear loops, head ties, or elastic straps. The performance of surgical masks is evaluated based on bacterial filtration efficiency, splash resistance, microbial cleanliness, breathability [46], and water repellency [47]. On the other hand, a respirator is a device that can be fitted on the wearer's face providing a seal around the mouth and nose and in such a way protects the wearer from respiratory infections. Its filtration capacity is strictly regulated [42]. Usually, the masks are made up of a multi-layered structure, see Figure 2. The layers are made from non-woven fabric made of melt-blown polymer, most commonly polypropylene (PP), but also polystyrene (PS), polycarbonate (PC), polyethylene (PE), or polyester is used. In Figure 2(a-d) we have presented the typical face masks all containing the common PP layer at the outside, similar to the one used in the vacuum cleaner dust bag (Figure 2e), which are often used to produce homemade masks. From the morphology point of view the PP fibers present in the masks and vacuum cleaner bags are similar and therefore have a similar ability in stopping spread of the infectious droplets as many commercial masks. The SEM micrographs in Figure 2(f-h) show the melt-blown PP fibers with the approximate fiber diameter of 10 μm that is present in all the imaged masks including respiratory KN95/FFP2 (Figure 2c) and FFP3V conforming to EN149:2001 standards (Figure 2d). Additionally, the surgical and respiratory masks containing the extra layer of PP with the diameter of 1 μm are presented, see Figure 2(i-j). The additional layer of smaller in diameter fibers (approximately 1 μm) is able to stop also the airborne particles enhancing the protection level of the facial masks, (Figure 2k).

The WHO in the guidance on infection prevention and control strategies when COVID-19 is suspected, recommends the use of particulate respirator at least as protective as a US National Institute for Occupational Safety and Health (NIOSH)-certified N95, European Union (EU) standard FFP2, or equivalent [48]. These respirators filter

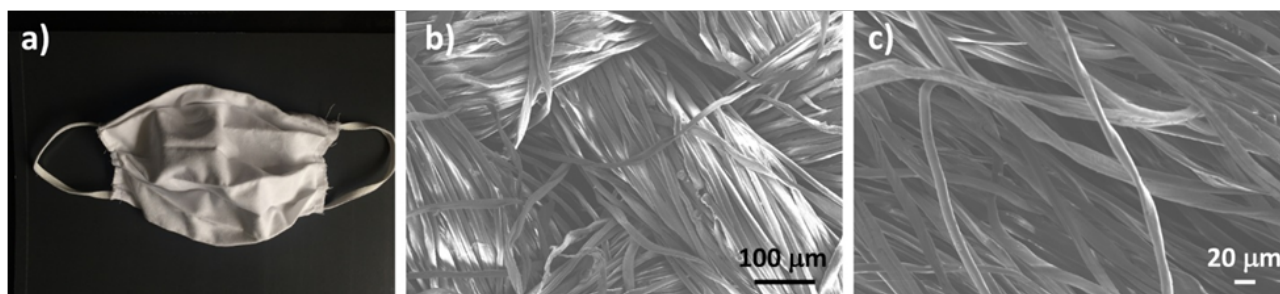


Figure 1: The homemade cloth face mask: a) the photo showing the typical shape of cotton masks; b) SEM micrographs of cotton fibers – traditional weave and c) SEM micrograph focusing on individual cotton fibers with the diameter approximately 10 μm .

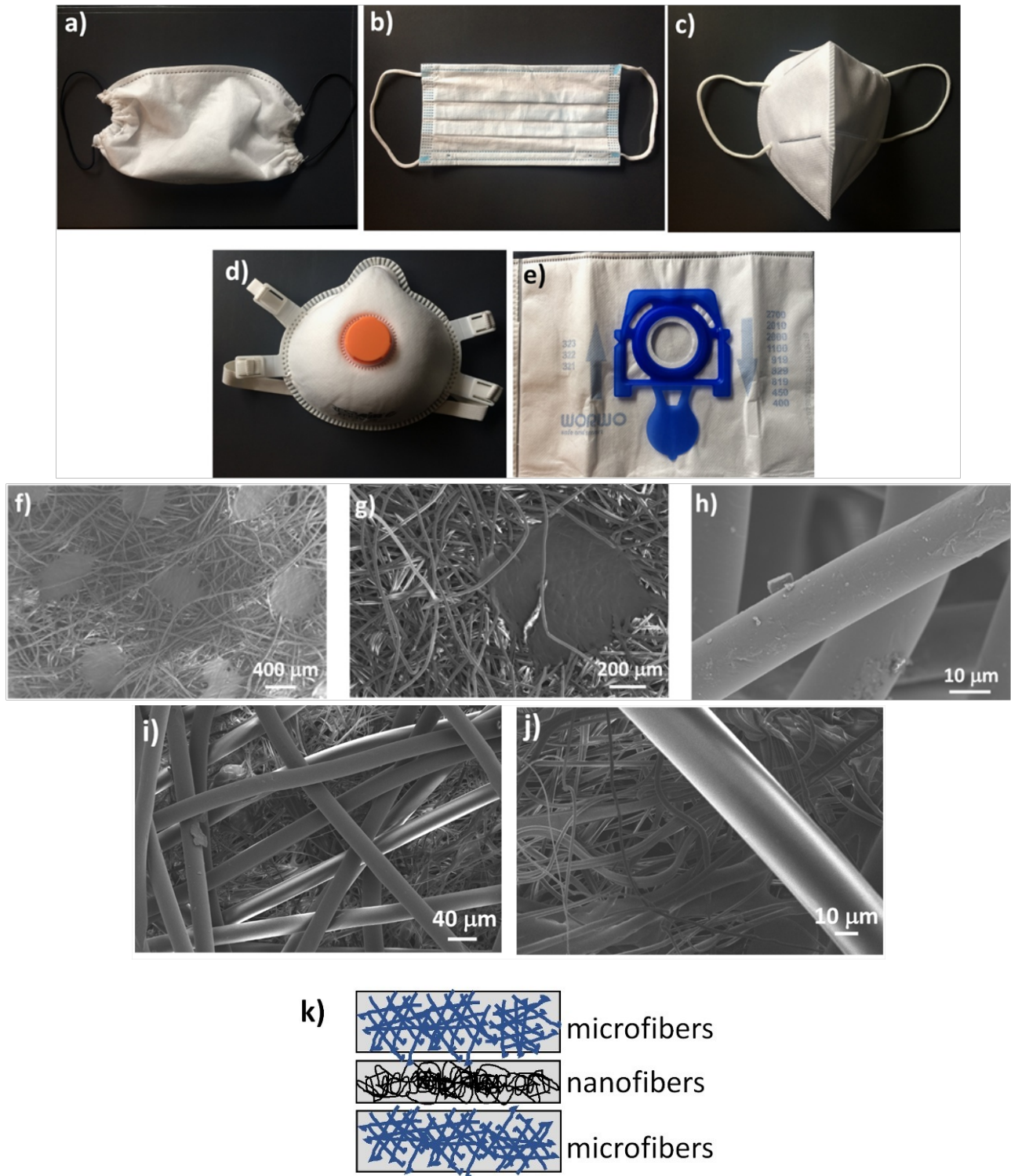


Figure 2: Typical commercial face masks from various materials: a) spundbond based on PP; b) surgery face masks, 3 layers with PP fibers and microfibers in between; c) KN95/FFP2 respiratory; d) respiratory FFP3V conforming to EN149:2001 standards; e) vacuum cleaner dust bag; (f-h) scanning electron micrographs showing the top layer of PP fibers of all the masks (a-d) and vacuum cleaner dust bag (e). (i-j) SEM micrographs indicating the inside layer of 1 μm PP fibers present in masks presented in b, c, and d; k) schematic of the typical 3 layers used in the surgical or respiratory masks.

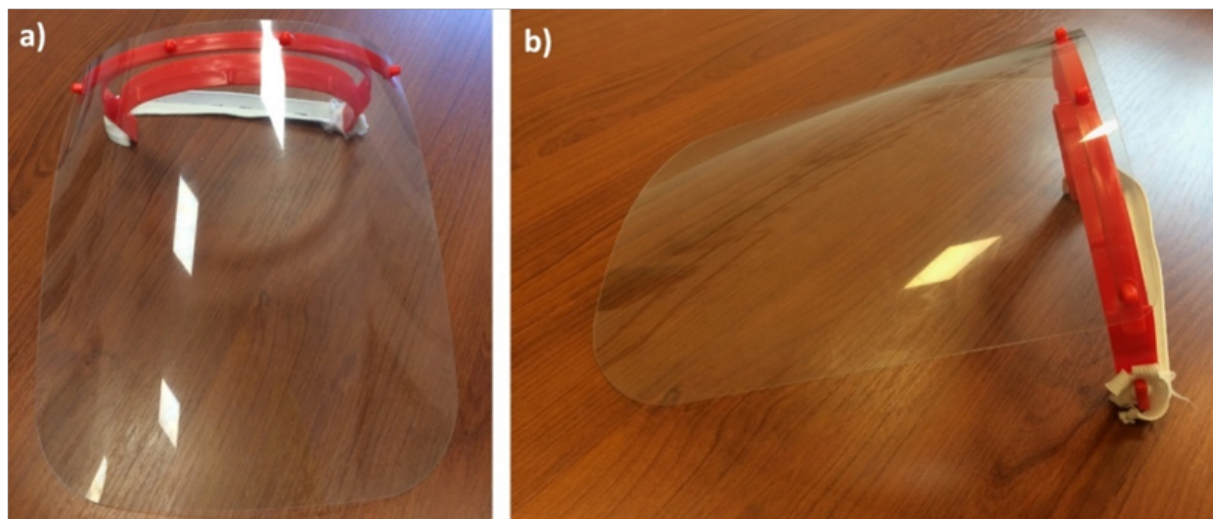


Figure 3: The example of the plastic safety face shield screen a) front and b) side view, produced by the volunteers at AGH University of Science and Technology in Krakow, Poland [62].

at least 95% for N95-respirators (42 CFR Part 84) and at least 94% for FFP2-respirators (EN 149 standard) of airborne particles. The inner filtration layer is made of fine PP mash, with fibers diameter less than a micron, obtained by melt blowing [35, 49]. When masks form a tight seal with the face, the 95% efficiency refers to particle sizes ranging from 0.1–0.3 μm [50]. The masks should preferably be used in combination with a face shield that covers the entire front and sides of the face and extends to the chin or below, see example in Figure 3. Face masks are capable of blocking virus nanoparticles, which are typically around 100 nm in diameter, but there are parts of the respiratory fluid droplets containing a variety of other components including insoluble particulates reaching the size of 5–20 μm in diameter. These droplets can be caught by regular masks and prevent person-to-person infection through droplet transmission [51, 52]. During the 2019–20 coronavirus pandemic, there has been a shortage in N95 and FFP2 masks supply due to constraints on the supply of nonwoven PP fabric as well as the cessation of exports from China, a country which controls 50% of global production of masks [49]. In this acute shortage of protective medical equipment, an interesting trend worldwide emerged – many companies, universities and tech enthusiasts armed with 3D printers produced a large number of medical visors or medical face shields (Figure 3) that were distributed for free to hospitals and clinics [53, 54]. Specifically, concerning COVID-19, special attention was paid to informing the general public about the best practice of wearing the masks [11, 51, 55], giving many instructions on how to produce the masks by themselves and how and when to wear them [56]. Among the very efficient anti-viral materials are

the electrospun nonwoven filters consisting of the fibers with a diameter below 100 nm, suitable for low cost and mass facial masks production [57, 58].

Despite the challenges with the shortages of PPE, there is another problem resulting from the prolonged use of personal protective equipment. Nurses, doctors and other healthcare workers, who have been pushed to the frontline of the outbreak, are spending more than 8 h at hospitals wearing PPE, consisted of gowns, gloves, medical mask or respirator and eye protection (goggles or face shield). This is not without consequences, many skin conditions and injuries caused by prolonged use of PPE were described like pressure injuries, contact dermatitis, itch, pressure urticaria, seborrheic dermatitis, acne, pruritus, folliculitis, maceration and erosions of the epidermis [59–61]. They are frequently reported by the healthcare workers during the COVID-19 pandemic and are generally caused by the hyper-hydration effect of PPE, friction, epidermal barrier breakdown, and contact reactions.

Another health problem related to prolonged use of PPE is the development of headaches. In very recent research, conducted among frontline healthcare personnel working in high-risk areas of a tertiary institution during the current COVID-19 outbreak in Singapore, the association of the PPE exposure and the headaches, either with the use of N95 face mask alone or in combination with protective eyewear (mainly goggles), was studied. 81.0% of the respondents reported having PPE associated headaches (described as bilateral in location) when they wore either N95 face mask, with or without protective eyewear. 91.3% of the respondents with an underlying pre-existing headache stated that the increased PPE

usage aggravated their background headaches in terms of frequency and attack duration [63]. Such side effects caused by prolonged wearing of PPE, emphasize the need for lighter, breathable and yet protective materials and also the necessity of more comprehensive testing (pre- and post-market) to meet the real working conditions.

Another important role that smart textiles could play in future pandemics is being a part of the telemedicine system. The COVID-19 pandemic brought telemedicine into a new light and is likely to accelerate its development and implementation. Telemedicine is the tool that could help the healthcare systems to overcome the problems they are currently facing mainly connected to overcrowding in hospitals and treatment of patients with chronic illnesses. Telemedicine enables a reduction in direct contacts between healthcare workers and patients and thus a decrease in human exposure to the infection [61]. Remote sensing and monitoring are the crucial aspects of telemedicine and here smart textiles offer many solutions [15, 64].

3.1 Hydrophobicity and permeability of personal protective clothing

Usually, personal protective clothing is made of materials based on impermeable textiles and coatings. Although these materials are successful in blocking contaminants and offer good protection, they are bulky and heavy and are seldom found to be breathable [65]. Thus, they offer poor comfort to the wearer in prolonged use. Currently, there is a great interest in developing protective clothing based on nonwoven micro- and nanoporous membranes. The advantages of these kinds of materials, besides their low price, are the facts that they offer excellent protection while maintaining lightweight and breathable [5, 32]. The presence of micron and nano-sized pores in the membranes enables the transport of air and water vapor and restricts entry of water and other liquid droplets [65]. Recently, it has been demonstrated that water-resistant yet breathable materials can be fabricated by using hydrophobic materials from which porous membranes with interconnected pores are obtained [66, 67]. Yung *et al.* [67] prepared a novel kind of hydrophobic fibrous membranes with good water/windproof and breathable performance via electrospinning by using polyvinylidene fluoride (PVDF) as raw polymer. They regulated the fibrous and porous structure of the membranes by tuning the N,N-dimethyl acetamide (DMAc)/acetone ratios and NaCl concentrations in the PVDF solutions. The obtained membranes exhibited simultaneously good water-

proof and breathable performance while keeping excellent mechanical properties, high strength and toughness [66, 68–71].

By controlling the pore size and overall porosity the water-resistance and permeability could be simultaneously enhanced. A reduction in pore size would lead to higher resistance to water droplets entry improving permeability. On the other side, a higher overall porosity in the material would ease the transmission of air and water vapor through the material and thus improve the breathability. Li *et al.* [72], in their study, evaluated the effect of the pore size, pore length and overall porosity on the electrospun membranes' breathability and water-resistance. They used electrospinning to prepare membranes based on polyurethane (PU) and fluorinated PU. The porosity and pore size of the membranes was tuned by controlling the relative humidity during the electrospinning process and its duration. They found out that the breathability mainly depended on the porosity and pore length. So electrospinning, apart from melt blowing [73], is another crucial process in fiber manufacturing that is already extensively used in the filtration industry [74–78] and many types of sensors [79]. Electrospinning belongs to electrohydrodynamic processes [80–82] involving the polymer solution jetting controlled with the electrostatic forces [83–86]. The advantage of nanofibers is the high surface area to volume ratio which allows filtering particles and enhancing the superhydrophobic properties [66, 87, 88]. The porosity in the electrospun membranes can be controlled by the arrangement of fibers [89] or the use of special collectors [90–93]. For mass production of nanofibers, needleless electrospinning is commonly used [94–101].

Chen *et al.* [102] presented an effective approach to mimic the self-cleaning hierarchical structure of lotus by fabricating a flexible hybrid material, PVDF microfibers decorated with inorganic ZnO nanowires covered with oleic acid. This hierarchical structure exhibited superhydrophobicity and self-cleaning properties and at the same time was permeable to air and water vapor. PVDF is known for its high piezoelectricity and ferroelectric properties [103, 104], but also exhibits high mechanical strength, high thermal stability, and biocompatibility [105–108] which make it an ideal candidate for polymer-based piezoelectric generators and therefore is used in many smart textiles technologies [109–111] also as electrospun fibers [68, 112–115]. This concept of energy harvesting in smart textiles was recently applied in a self-powered electrostatic adsorption face mask [116] with enhanced removal efficiency and filtration life for ultrafine particulates or droplets [117]. All the mentioned technologies including the electrospun membranes have been applied in the cur-

rent situation concerning COVID-19, one of the recent suggestions is Ag or Cu nanoparticles impregnation [15, 118–120].

4 Smart textiles in future pandemics

Smart textile is a “functional textile material, which interacts actively with its environment, *i.e.* it responds or adapts to changes in the environment” [121, 122]. The fast development of microelectronics and its implementation in smart textiles led to remarkable improvements and new potentials in the textile field [123–126]. Also, the changes in our lifestyles and usage of smart electronic devices in daily routines open the possibilities of acceptance of smart textiles as comfortable and reliable devices. Smart textiles find applications in all sectors from automotive [127, 128] and sports [129, 130] to buildings and interior design [131, 132], but here our focus is on their use in the fight against pandemics as part of the healthcare and medicine systems and personal protective equipment.

4.1 Smart textiles for protective clothing

Protective equipment has become an important subject during the current COVID-19 pandemic, it's even become a symbol of the fight against this globally spread virus. Nevertheless, dealing with this pandemic has also shown deficiencies related to PPE, first of all, the shortages in their supply and second the health problems they cause in healthcare workers during prolonged use. To be prepared for the next pandemic we need to apply what we have learned from the current situation. We should pay special attention to the protective equipment; develop capacities for rapid PPE production and no less importantly develop novel PPE that is cost-effective, safe, comfortable and “smart” at the same time. In terms of gowns and drapes, there are more details provided in some previous reviews [64] and studies related to environmental conditions [133] and thermo-physiological discomfort [134] of medical textiles [135].

The recent studies on the SARS-CoV-2 virus stability in different environmental conditions and on various surfaces showed that the virus can survive on cloth or standard textiles for several days, but on smooth surfaces like stainless steel or plastic even for up to a week [136, 137]. Thus, all textiles or medical equipment used in hospitals by medical personnel or patients could easily be contam-

inated by infectious carriers [135]. That is why the fabrication of inexpensive antimicrobial and antiviral materials is of great interest. For this purpose, the use of metals is widespread due to their ability to deactivate bacteria [138]. Here, in particular, silver stands out attributed to its distinctive physiochemical properties, and its demonstrated toxicity towards bacteria, fungi, virus, leishmania, malaria, and neoplastic [139]. A recent *in-vivo* study demonstrated that aqueous solution of colloidal Ag alone enabled effective sterilization of biodegradable PU based scaffolds [140]. The compressed-PU facial masks were modified with the hydrophobic coating to obtain the self-cleaning characteristic [141], to address the wetting and blocking water spatter in protective textiles used during COVID-19. In other study fibers with antimicrobial properties were obtained by electrospinning dispersed silver in polyvinylpyrrolidone (PVP) solution [138]. Their toxicity against *Escherichia coli* and *Staphylococcus aureus* was demonstrated. In a similar study [142], electrospun nanocomposites based on polyacrylonitrile (PAN) modified with silver nanoparticles were obtained from solution of dimethyl formamide (DMF). The obtained membranes possessed good antimicrobial properties and a case for using these fibers as filters to protect the personnel from bacterial contamination was presented.

The importance of PPE repellency to viruses was demonstrated in a very recent study of the level of contamination on the surface of medical masks [143]. The results showed that respiratory viruses were present on the outer surface of about 1 in 10 medical masks worn by healthcare personnel which could easily lead to self-contamination of the wearer of the mask. To provide antimicrobial and antiviral properties of the medical textiles, they have to be impermeable to body fluids like blood, urine, saliva, and sweat which are the main carriers of infectious vectors. Galante *et al.* [144], very recently, demonstrated a simple, durable and scalable coating on non-woven PP textile that was both superhydrophobic and anti-virofouling. The treatment consisted of polytetrafluoroethylene (PTFE) nanoparticles in a solvent thermally sintered to PP microfibers which created a robust, low surface energy, and multi-layer, multi-length scale rough surface. The authors demonstrated that the obtained material could effectively repel various liquids including water and fetal bovine serum and that the treatment could significantly reduce the attachment of serum protein and infectious non-enveloped virions to the surface. Moreover, the treated textiles exhibited unprecedented mechanical durability, maintaining their liquid, protein, and viral repellency even after extensive and harsh abrasion and washing. Besides washing, SARS-CoV can be inactivated by UV

light (254 nm), at pH above 12 or below 3, and above the temperature of 65°C, similar conditions can be applied for SARS-CoV-2 [145, 146]. Among metals Cu besides Ag, also showed effectiveness in the inactivation of SARS-CoV, indicating the possibility Cu ions to be used for destroying viral proteins and lipids [119, 137].

4.2 Smart textiles for monitoring and sensing as part of the telemedicine

The healthcare systems worldwide are facing a current problem – how to maintain the capacity and provide quality health care not only to those suffering from COVID-19 but also to patients with chronic and acute diseases. The health systems globally, to cope with the unique challenges imposed by COVID-19 are seeking help in telemedicine so they can provide care for the patients while keeping them in their homes [147]. One of the key features of telemedicine is that it relies extensively on remote sensing and monitoring. These sensors should enable continuous accurate monitoring of the user's physiological states in the long-term. Textiles and clothing are omnipresent in our daily life and are the layers closest to our body providing an ideal platform for the integration of electronics to monitor physiological processes through the skin. There are already wearable non-textile products on the commercial market, for instance, smartwatches and wrist bands, which are used to monitor activity and the wearer's health parameters. But, electronic devices integrated into textiles can offer several advantages, such as enhanced mobility and comfort for the user [148]. Reliability, performance, consistency over time, and comfort are the most important features that smart textiles should fulfill to enable their applications in the commercial market.

Smart textiles used for monitoring body parameters could be divided into two basic groups. One that is focused on physical sensors that react to physical changes in their environment, for example, electric fields, pressure, temperature, and movement. These can be used to detect body movements, changes in thoracic volume during breathing, but also electric signals from the body, such as electrocardiography (ECG) from the heart and electromyography (EMG) from skeletal muscles [149]. The second group is focused on biosensors that incorporate a biological recognition element into their operation (for example, enzyme, antibody, cell receptor, or organelle) and are an emerging field in the area of wearable sensors. They can monitor the composition of biofluids, such as sweat, tears, saliva, urine, or interstitial fluid (ISF) [150]. Here, we focus on smart textile sensors of body parameters that are relevant

for monitoring in a home-cared patient during a pandemic similar to COVID-19. Another challenge for telemedicine is drug delivery, which in the aerosol therapy is using nebulizers containing special meshes or filter to improve the treatment efficiency and reducing the contamination [151].

4.2.1 Perspectives of smart textiles as part of the telemedicine

The stages of treatment for most medical conditions include prevention, immediate care, rehabilitation, and long-term support. Smart textiles have a role to play in each of these stages. Integrating smart garments into our lives is a natural step. One of the probable future scenarios is that as the field of fibertronics becomes more mature, the hybrid structures will include more electronic functionality at the fiber level until we eventually end up with electronic textiles where all advanced electronic function, such as batteries, lightning, communication and computing is embedded in the textile fibers [152, 153]. Smart textiles are expected to become more streamlined and move into a wearer's daily life. They will noninvasively monitor a wide range of body parameters ultimately enabling a comprehensive medical diagnostics and performance assessment. But their acceptance by the medical community will require extensive and successful validation in human testing and improved understanding of the clinical relevancy of the provided information. Besides challenges connected to smart textiles and their fabrication, design, device operation, relevance, stability, implementation, data interpretation, etc., there are other challenges that telemedicine is facing mainly connected to encryption and security. To ensure the safety of the information gathered by a portable telemedicine system access rights and encryption algorithms have to be implemented and a stringent data protection policy developed. The data and communication have to be protected from tampering and communication have to be secured from all potential errors [154]. Having all the challenges in the head of us the optimal outcome is to emerge from the current crisis with a clearer vision of how to deploy telemedicine to achieve its benefits while avoiding or minimizing potential abuse and exploitation [147].

Smart or e-textiles start to include natural fabrics and become sensors of human body temperature, sweat, or breathing [155] or bending able to monitor human touch [156]. As the strain sensors can be incorporated in smart garment parts, it can be a part of face masks too, together with other biosensing capabilities for detecting viruses. The data collection from patients throughout the

wearable devices in the current COVID-19 pandemics could give a new look into public health surveillance and also new possibility of tacking and reacting to the patient's responses [157–160]. The skin-integrated sensors capable of reporting fever, cough, breath, hypoxemia, or loss of smell are being developed including the machine learning techniques [161]. The diagnosis together with the treatment is a crucial part of development in many integrated technologies seeking the adaptation in clinical practices during COVID-19 pandemic and vaccine development [162].

It is clear from the above that in the future, one should think of smart and intelligent PPE that not only protects but also detects, is capable of self-decontamination along with being comfortable, durable, and possibly biodegradable [163]. During the COVID-19 the waste products increase [164–166] rising many new challenges for the pulp and paper industry [167]. Biodegradable nonwovens are often based on polylactic acids (PLA) or any natural fibers being extensively developed in recent years [168–172]. Many new fabrics and designs have been tested against the blocking droplets in face masks built of a few covering multi-layers [173]. Personal protection and healthcare purposes are facing now many challenges related to the solid waste management sector during the pandemic, as the single-use plastic usage is set to bounce back due to its growth. The main concern is associated with hygiene and personal protection [174–178].

4.2.2 Monitoring breathing

Since the COVID-19 is an acute respiratory syndrome monitoring breathing is of the crucial importance of patient treatment. Respiratory rate values are used to support the assignment of patients to different categories and to make decisions on the use of supplemental oxygen [179]. The treatment of patients affected by acute respiratory insufficiency from COVID-19 is also tailored considering respiratory rate values [180].

Breathing can be monitored by measuring the changes in the thoracic volume caused by lung displacement in the process of breathing. Several technological solutions have been developed to register breathing induced thoracic strain. Textile-based strain sensors can be fabricated by using stretchable fabrics modified with inherently conductive polymers or by using polymers loaded with conductive particles like carbon-based nanofillers [52]. Knitting with conductive yarns is another approach to creating textile piezoresistive sensors [54]. Using multiple sensors gives a possibility besides breathing rate the capacity and type of breathing to be indicated. For instance,

deep breathing would cause a large change in signal amplitude. Another promising approach of respiratory monitoring is by using smart textiles based on fiber optic sensors integrated into the textile for monitoring different vital body parameters [181, 182]. For respiratory monitoring, the fibers were stitched onto a textile in a sinusoidal shape. The fibers were illuminated with a laser and light was detected with photodiodes. The curvature of the bends affected the light attenuation through the fiber. Analysis of the bending of these fibers was used to indicate the movements caused by the changes in the thoracic volume. This technology has the advantage of being compatible with MRI scanners [183]. In a more recent study, highly flexible polymeric optical fibers (POFs) that react to applied pressure were integrated into a fabric-carrier to form a wearable sensing system [184]. The wearable system enables detailed monitoring of the breathing rate and type. The sensor is usually placed at different positions of the torso. The authors confirmed the utility of such a monitoring device by a comparison of the results with the output of commercial respiratory measurements devices.

Many textile-based wearable systems are being developed for getting recordings of cardiorespiratory and motion signals by combining textile sensors for ECG and breathing frequency detection with portable electronic and signal preprocessing technologies [185]. Wearable technology during Covid-19 – combine the trackers and apps that can measure vital signs related to developing symptoms [186], but also monitoring with the assessments [187]. The availability of a large number of accurate data collected from breathing monitoring could contribute to improving the development of predictive models for the risk of hospital admission, and the development of diagnostic and prognostic models. Effective breathing monitoring would be an important contribution to managing similar scenarios like current COVID-19 that may occur in the next months or years [188].

4.2.3 Monitoring heart activity

Acute myocardial injury and chronic damage to the cardiovascular system are possible complications associated with COVID-19 [189, 190]. Cardiac involvement has been reported in patients with COVID-19, which may be reflected by electrocardiographic (ECG) changes [191]. Therefore, particular attention should be given to cardiovascular protection during treatment for COVID-19 and here monitoring of heart activity plays a crucial role.

ECG records the electrical activity of the heart from the skin's surface and ECG monitoring traditionally relies

upon adhesive electrodes coupled to the skin with gel. Many challenges arise with potential in-home use of this type of electrode but the major issue is the use of the gel. In recent years, much effort has been focused on the development of “dry” electrodes that are directly integrated into clothing [147]. An *et al.* [192] developed a new hybrid textile electrode suitable for long-term ECG monitoring. In this study, four different conductive fabrics for electrode materials and also the electrode size were investigated. The results showed that the optimal hybrid textile electrode could perform equally well as commercial wet electrodes in electrocardiograph machines. Recently, Weder *et al.* [193] reported the development of a portable ECG measuring device (ECG-belt), contemplated to pass the disadvantages of current wearable systems. The ECG-belt employed embroidered, self-humidifying electrodes with Ag/Ti coating for long-term ECG-monitoring which met all the requirements concerning cytotoxicity and signal stability. Fontana *et al.* [194] assessed the clinical applicability for overnight monitoring of this ECG-belt to screen patients for breathing-related disorders during sleep. When compared to reference gel electrodes, ECG-belt data showed acceptable quality and accuracy. Therefore, they concluded that the ECG belt is an applicable tool for continuous ECG patient monitoring. In a very recent study Arquilla *et al.* [195], developed and designed sewn electrodes that can be integrated into wearable garments for ECG monitoring. They showed that the sewn textile electrodes reliably recorded the ECG signal and did not exhibit changes in resistance during the stretch, bend, or wash testing and that they are a promising option for implementation into a garment-integrated ECG monitoring system.

4.2.4 Monitoring of blood oxygen saturation

Monitoring of blood oxygen saturation is crucial in COVID-19 patients because COVID pneumonia initially causes a form of the oxygen deprivation that is called “silent hypoxia”. This means that COVID patients do not feel chest discomfort or shortness of breath, even as their oxygen levels fall. And by the time they do, they have noticeable trouble breathing and alarmingly low oxygen levels, justifying using urgently a ventilator. Silent hypoxia progressing rapidly to respiratory failure explains cases of COVID-19 patients dying suddenly after not feeling short of breath [196–198]. This hypoxia can be detected, thus healthcare workers are advised to use pulse oximetry [199], a simple, fast, easy to use, noninvasive method for real-time monitoring of hypoxemia. It can provide an early warning system for the breathing problems and low oxygen saturation levels

associated with COVID-19 pneumonia. Pulse oximetry enables monitoring of the percentage of Hb in blood, which is saturated with oxygen. It works by measuring the absorption of light through body tissue with a high perfusion rate of blood, usually at the finger or earlobe. Hb has a different absorption spectrum depending on whether it is oxygenated (oxy-Hb) or deoxygenated (deoxy-Hb). Oxygen saturation is estimated by measuring the absorption of two different wavelengths of light through the tissue. Light-emitting diodes (LEDs) are typically used as the light source and photodiodes as light detectors. These optical components may be placed in a transmission mode configuration, on either side of the tissue, or else in reflectance mode on the same side of the tissue. Photonic textiles using organic LEDs (OLEDs) or woven polymer optical fibers (POFs) offer an alternative to conventional LEDs, to create a textile-based pulse oximetry system. Rothmaier *et al.* [200] have demonstrated such a system, using a cotton glove with woven POFs positioned at a fingertip of the glove. To improve the reliability of reflectance oximeters Liu *et al.* [201] demonstrated a novel optical fiber sensor probe for simultaneously monitoring the photoplethysmogram and contact pressure to provide reliable blood oxygen saturation monitoring. This probe combined a reflectance pulse oximeter with a fiber Bragg grating contact pressure sensor and enables more comfort of the user because it can be used in loosely fitting garments and the measurements can only be recorded when appropriate pressure is applied.

4.2.5 Monitoring the composition of body fluids

Wearable biosensors are garnering substantial interest due to their potential to provide continuous, real-time physiological information via dynamic, noninvasive measurements of biochemical markers in biofluids, such as sweat, tears, saliva, and interstitial fluid (ISF) [150]. Blood is the most reliable diagnostic medium; however, as it requires invasive techniques for sampling, it is typically sampled at specified time intervals. Therefore, other body fluids, which can be accessed more easily through non- or minimally-invasive means, must be considered for continuous analysis. Possible samples include urine, saliva, sweat, interstitial fluid (ISF), and wound exudate. Of all these body fluids, sweat is the most accessible within a garment structure.

In a recent study, a flexible poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) fiber-based sensor was proposed, which could accurately measure the amount of salt (*i.e.*, sodium chloride) ions in sweat re-

leased from the human body. The authors performed this using one single strand of hair-like conducting polymer fiber. The fabrication process involved the introduction of an aqueous PEDOT:PSS solution into a sulfuric acid coagulation bath, in which monolithic fibers, with simple geometry and tunable electrical characteristics, were produced. The authors demonstrated that the conductivity of a PEDOT:PSS fiber changed linearly according to the concentration of sodium chloride in liquid. The obtained results suggested the possibility of PEDOT:PSS fiber-based wearable sensors to be developed in skin-attachable next-generation healthcare devices, which could reproducibly determine the physiological condition of a human subject by measuring the sodium chloride concentration in sweat [130], which is important for health condition monitoring of any patient.

More related to COVID-19 is the remote monitoring of the glucose level in sweat. Type 2 diabetes (T2D) is major comorbidity of COVID-19 and although the impact of glucose control on the degree of required medical interventions and on mortality in patients with COVID-19 and T2D remains uncertain there is clinical evidence correlating improved glycemic control with better outcomes in patients with COVID-19 and pre-existing T2D [202]. Development of an enzyme-based non-invasive wearable electrochemical sensor to monitor biochemical vital signs of health such as the glucose level in sweat has attracted increasing attention recently, due to the unmet clinical needs for diabetic patients. Very recently, Zhao *et al.* [203] demonstrated an elastic gold fiber-based three-electrode electrochemical platform for wearable textile glucose biosensing. The gold fiber was functionalized with Prussian blue and glucose oxidase to obtain the working electrode and modified by Ag/AgCl to serve as the reference electrode; and the non-modified gold fiber served as the counter electrode. The as-fabricated textile glucose biosensors achieved a linear range of 0–500 μM and a sensitivity of 11.7 $\mu\text{A mM}^{-1} \text{cm}^{-2}$. Importantly, such sensing performance was maintained even under a large strain of 200%, indicating the potential applications in real-world wearable biochemical diagnostics from human sweat.

The fundamental principles of biosensor systems, the challenges in operating biosensors in specific noninvasive biofluids and the physiological relevance of monitoring key biomarkers in these fluids, and finally the prospects of wearable biosensing devices for the biomedical field have been highlighted in a recent review [150]. Regarding the COVID-19 easier diagnostics recent research suggests that saliva can be used as a viable biosample for the detection of COVID-19. Experimental studies showed that the salivary glands could be a potential target for SAR-CoV-2 in-

fection, and hence saliva could be a potential sample for SARS-CoV-2 detection [204, 205]. Researchers from RUCDR Infinite Biologics at Rutgers University have successfully validated saliva as being a viable biosample source for COVID-19 detection when compared to nasopharyngeal or oropharyngeal swabs [206]. Very recently, Murugan *et al.* [207] proposed to exploit a field-deployable/portable plasmonic fiber-optic absorbance biosensor (P-FAB) platform for one-step, wash-free detection of SARS-CoV-2 virus particles directly in saliva sample with minimal sample pre-processing. Further studies are required but salivary diagnostics may play a crucial role in the detection of COVID-19 and can offer a mass screening of the population and more importantly it can eliminate the requirement of health care professionals to collect samples and risking infections.

5 Conclusions and Perspectives

The COVID-19 outbreak caught us off guard and unprepared, despite the numerous scientific indications that a respiratory pandemic is possible and is going to happen we were not ready for such a rapid spread through the human population. Many governments are still scrambling to ‘flatten the curve’ as they attempt to maintain increasingly overburdened healthcare systems and mitigate shortages in medical supplies. What can be deduced from what has been learned so far is that, despite the tremendous advances in medicine and pharmacy, in the initial moments, which are crucial in the containment of the spreading of any pandemic, the key role is played by the non-pharmaceutical measures. By applying these measures, we give the medical and pharmaceutical sciences time to develop a cure or a vaccine, which could take anywhere from several years to over a decade but is a permanent solution in the fight against pandemics. In meantime, between pandemic outbreak and finding a cure or vaccine, we should improve the non-pharmaceutical measures applied and here the smart textiles play an important role mainly as part of the personal protective equipment (PPE) and telemedicine. Despite the great progress made so far in this field, several challenges need to be overcome. One of them is including the chemical sensors able to detect viruses from the breath, as at the moment some efforts are already made in monitoring and analysis of biomarkers in sweat [208].

Dealing with the COVID-19 pandemic has shown the deficiencies related to PPE, first of all the shortages in their supply and second the health problems they cause in

healthcare workers during prolonged use. It is necessary to work on the development of capacities for rapid PPE production and even more importantly on the development of novel PPE that is cost-effective, safe, comfortable and “smart” at the same time that not only protects, but also detects, is capable of self-decontamination, is durable and possibly biodegradable.

What we have experienced so far is that COVID-19 requires unprecedented mobilization of healthcare systems. There is only a narrow opportunity to slow transmission and prepare healthcare systems to mitigate the impact of the outbreak. In these terms, telemedicine is brought into a new light. Telemedicine platforms can help to prevent overcrowding in hospitals and decrease human exposures (among healthcare workers and patients). One of the key features of telemedicine is that it relays extensively on remote sensing and monitoring. These sensors should enable continuous accurate monitoring of user’s physiological states in the long-term while allowing enhanced mobility and comfort and here smart textiles offer many advantages. As the field of fibertronics becomes more mature smart textiles are expected to become more streamlined and move into a wearer’s daily life. They will noninvasively monitor a wide range of body parameters ultimately enabling a comprehensive medical diagnostics and performance assessment.

It is evident that to combat COVID-19 and build resilient healthcare systems to face future pandemics we need lasting investments in research and response strategies. But besides financing projects in the field of vaccine development, diagnostic and treatment, which is undisputedly important, more time and money should also be invested in the non-pharmaceutical measures, highlighting the smart textiles as part of PPE and telemedicine. These non-pharmaceutical measures are the ones that bridge the time between pandemic outbreaks and the development of drugs or vaccines and are crucial for the number of human lives spared.

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