Sustainable Personal Protective Clothing for Healthcare Applications: A Review

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Abstract

Personal protective equipment (PPE) is critical to protect healthcare workers (HCWs) from highly infectious diseases such as the Covid-19. However, hospitals have been at risk of running out of the safe and effective PPE including personal protective clothing needed to treat patients with Covid-19, due to unprecedented global demand. In addition, there are only limited manufacturing facilities of such clothing available worldwide, due to a lack of available knowledge about relevant technologies, ineffective supply chains and stringent regulatory requirements. Therefore, there remains a clear unmet need for coordinating the actions and efforts from scientists, engineers, manufacturers, suppliers and regulatory bodies to develop and produce safe and effective protective clothing using the technologies that are locally available around the world. In this review, we discuss currently used personal protective equipment, their quality and the associated regulatory standards. We survey the current state-of-the-art anti-microbial functional finishes on fabrics to protect the wearer against viruses and bacteria, and provide an overview of protective medical fabric manufacturing techniques, their supply chains and the environmental impacts of current single-use synthetic fibre-based protective clothing. Finally, we discuss future research directions, which include increasing efficiency, safety and availability of personal protective clothing worldwide without conferring environmental problems.

Keywords: protective clothing, sustainability, personal protective equipment (PPE), anti-microbial, covid-19, anti-viral, medical textiles, single-use PPE and environmental impact

In pandemics of highly infectious diseases such as Covid-19,[1] the risk of healthcare workers (HCWs) being infected is much greater than the general population, as they are in direct contact with patients. Personal protective equipment (PPE) is considered to be a critical component that can be used to protect HCWs from droplets from coughs, sneezes and aerosol generating procedures, in addition to other contaminated body fluids and surfaces from infected patients.[2] PPE may include aprons, gowns or coveralls, masks or respirators and goggles.[3] The supplies of safe and effective protective clothing needed to treat Covid-19 patients have been severely depleted due to the unprecedented global demand. In addition, in some cases, the standard of PPE has not been of the required quality for medical uses, thus adding to delay and waste. A recent survey by *Nursing Times* showed that ~73% of National Health Services (NHS) nurses were without long-sleeved disposable gowns, eye protection and FFP3 respirators. In addition, ~63% did not have fluid-repellent face masks due to the current crisis.[4] Furthermore, PPE needs to be 'donned' and 'doffed' correctly, and it may be uncomfortable to wear. Although there have been many advisory publications from various organizations and regulatory bodies such as the World Health Organization (WHO), the NHS in the UK, and the Centre for Disease Control and Prevention (CDC) in the USA about the specification and use of PPE, there remains the unmet need for safer and more effective PPE for HCWs around the world, and a clear understanding and knowledge about the regulatory standards for such equipment.

Medical textiles are used in the manufacturing of personal protective clothing for healthcare or medical applications, specifically to mitigate the risks from exposure to hazardous substances including body fluids, and to minimize the risk of cross-infections.[5] There are several different types of medical clothing products, including coveralls, footwear covers, full body suits, gloves, independent sleeves, scrubs, surgical gowns, surgical masks and scrub hats. Medical textiles are also used in the manufacture of drapes and bedding textiles for healthcare settings as well as wound dressings, bandages and other products. Medical protective clothing, usually

made of synthetic fibres due to better liquid barrier properties, could be manufactured using nonwoven, weaving or knitting technologies. Among them, nonwoven fabrics are the most popular for such clothing as they facilitate relatively fast and cheap manufacturing, high levels of sterility and infection control. As such, they are commonly used in the manufacture of disposable medical textiles including surgical caps, surgical gowns and surgical masks.[6] Such nonwoven fabrics are typically made from polypropylene, and usually have a spunbond-meltblown-spunbond (SMS) construction.[7] In contrast, woven fabrics typically made from cotton or polyester/cotton blends are commonly used in the manufacture of scrubs. Providing HCWs with protection from contaminated body fluids and other hazardous substances from infected patients is important, and specialist finishes can be applied to disposable or reusable medical textiles in order to impart protective effects. Fluid repellent finishes, for example, can be used to create a barrier which prevents adsorbed fluids from penetrating contact fabrics.[8] A further challenge for HCWs is exposure to biological fluids that can transmit diseases caused by a variety of deadly pathogens including coronavirus (such as the coronavirus which causes Covid-19), Hepatitis B Virus (HBV), Hepatitis C Virus (HCV), Ebola Virus, and Human Immunodeficiency Virus (HIV). Anti-microbial finishes can be highly effective against such pathogens in preventing infections either by killing or inhibiting viruses and bacteria, and could be applied onto protective medical clothing *via* various highly scalable and cost-effective fabrication techniques.[7, 9]

While there have been many advances in high performance and functional protective clothing thus far, there remains a lack of comprehensive reviews that provide guidelines on the use of PPE, specifications and regulatory standards for PPE, a summary of fabrication techniques for medical protective clothing, and anti-microbial finishes of such clothing, and their environmental impacts and economic landscape. In this comprehensive review, we describe the mechanisms of viral infection, followed by a summary of the types of PPE used within

healthcare environment. We then discuss natural and synthetic anti-microbial agents, and their mechanisms to kill or inhibit pathogens. The review also discusses the various manufacturing techniques and anti-microbial coating techniques used, followed by the regulatory standards and required properties for producing protective clothing for healthcare applications. We then review the global market size and supply chain for such clothing and discuss the environmental impacts of single-use and reusable protective medical clothing. Finally, we present our views on current trends, future research directions and recommendations for potential solutions with current or future crises with PPE, due to epidemics and pandemics such as Covid-19.

Mechanism and Transmission of Viruses

Viruses are small (~10-200 nm) infectious agents, Figure 1a, which are typically 100 times smaller than the average bacterium and can be most easily observed using an electron microscope, Figure 1b. Viruses are dependent on the "host cells" of other living organisms to survive, thrive and reproduce, and cannot function or replicate on their own outside of a host cell. A virus particle occurs as "packets" of DNA or RNA genetic material encompassed in a protein coating and is termed as a virion. The virion is usually composed of DNA or RNA genomic material, that contains the genetic instructions for reproducing the virus, and a protein coating called capsid, which surrounds and protects DNA or RNA, Figure 1a.[10] Some viruses also have an outer lipid-based envelope and are known as enveloped viruses (H1N1, coronaviruses *etc*.).[11] The coronavirus which causes Covid-19 has such fatty envelope, which can be destroyed by the application of soap-like materials. Other viruses without such an envelope are called naked viruses *(e.g.* Rotavirus). The diameter of the coronavirus is typically between 60 nm to 140 nm and has spike-like surface projections creating a "crown-like appearance" under the electron microscope, Figure 1a.[12, 13]

A virus can spread *via* aerosols generated by coughing and sneezing in air, by vectors such as insects like mosquitoes, or by the transmission of body fluids such as saliva, blood or semen.[14] Once a virus infects a cell, it starts to replicate and reproduce virions rapidly, Figure 1c. As a result, the host cell produces more viral material than it does its own genetic material, and the virus could kill the host cell if left unchecked.[15] The human body has some natural defenses against viruses, and uses its immune system to produce antibodies that bind to the viruses and render them incapable of replicating. The immune system also releases T-cells, which work to kill viruses. In addition, several vaccines have been developed to produce an artificial immune system to the specific viral infections. However, some viruses, including those that cause Acquired Immune Deficiency Syndrome (AIDS), Human Papillomavirus (HPV) infection, and viral hepatitis are less susceptible to natural immune responses and result in chronic infections. Covid-19 is another highly infectious viral disease caused by the recently discovered coronavirus. Coronaviruses are a large family of viruses which may cause illness in animals or humans. In humans, several coronaviruses are known to cause respiratory infections. The severity of these infections can range from mild, as in the case of the common cold but some are more severe as in the cases of Middle East Respiratory Syndrome (MERS) and Severe Acute Respiratory Syndrome (SARS). The most recently discovered Coronavirus is Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-COV-2), which was identified in Wuhan, China, in December 2019 and is responsible for the Covid-19 disease.[1]

The main mechanisms for viral adsorption on surfaces are physical adsorption and electrostatic interactions, Figure 1d. The amount of virus adsorbed on a surface is the linear functional of the square root of time. Therefore, the more time virus stays on a surface the more opportunity to be strongly adsorbed onto a surface and become available to attack the population. One strategy to reduce viral infection is to decrease the amount of time the virus interacts with a material, while another strategy is to impart materials with surface properties which are

unfavorable for viruses. There are several factors which influence the movement of viruses or pathogens through fabrics, including the shape and dimensions of the microbe, the properties of carriers, and physicochemical nature of the fabric.[2, 16] There are several pathogens that can be found in healthcare environments including fungi, bacteria and viruses. Such pathogens vary in cell dimensions and morphology, mobility, and sensitivity to environmental extremes. In general, fungal microbes are larger than bacterial microbes (~1–5 μm), which in turn, are larger than viral microbes (*e.g.* the size of the HIV virus is ~13 nm). Pathogens can be carried by any persons present in healthcare settings, and they can be transported by a variety of carriers including respiratory droplets expelled by coughing or sneezing, body fluids, shed skin cells, lint and dust.[17, 18] Overall, pathogens are transmitted most easily through liquids such as respiratory droplets and body fluids, but they can also be transmitted without the presence of liquids.[16]

The transmission of liquid through textile materials could be described by two interchangeable but fundamentally different terminologies: penetration and permeation. Penetration involves the flow of gas, vapor or liquid through a porous material, while permeation involves the diffusion of gas or vapor through a porous material. Penetration and permeation usually take place due to a pressure gradient and concentration gradient across the barrier, respectively. Pathogens are larger in size than gas and vapor molecules and are considered to penetrate, and not permeate through materials.[2] The coronavirus which causes Covid-19 have been found to be transmitted *via* aerosols.[19]

Personal Protective Equipment for HCWs

About 80 million people will be working in the healthcare industry worldwide by 2030.[20] HCWs are at constant risk of exposure to pathogens and acquiring infections while treating

patients with infectious diseases, Figure 2.[2] In the last century, millions of people died from these highly infectious viruses, Figure 2a. This century has already seen breakouts of several deadly viruses including SARS, Swine Flu, MERS and the recent Covid-19 pandemic, Figure 2b. The CDC states that such pathogens could be transmitted to human body using three primarily routes: direct or indirect contact with an infected person which is the most usual; airborne transmission; and respiratory droplet transmission though coughing, sneezing or talking.[21] Personal Protective Equipment (PPE) for HCWs could prevent or reduce such contact and droplet exposures by creating a barrier between the human body and the pathogens. The Occupational Safety & Health Administration (OSHA) in the USA defines PPE as "specialized clothing or equipment worn by an employee for protection against infectious materials". OSHA issued regulations that require the use of PPE in healthcare environments to protect healthcare personnel from any exposure to potential infectious diseases. As per the regulation, employers are required to supply PPE of the correct specifications to their staff. Furthermore, in the case of reusable PPE, employers must arrange the appropriate cleaning, repair and storage of products. Additionally, employers must ensure that any "end of life" PPE is disposed of correctly.[22]

Factors Affecting the Selection of PPE

The most common types of PPE within a healthcare environment are gloves, gowns or aprons, masks or respirators, goggles and face shields, Figure 3a-e. In order to select PPE, three important points need to be considered: the types and amounts of body fluids to which the wearer might be exposed and the ways in which these fluids might be transported; the durability and appropriateness of the PPE for the task; and the fit of the PPE for individual users.[3] Gloves are the most commonly used PPE to protect hands and are manufactured from natural and synthetic rubbers for sterile and non-sterile usage and it is essential they comfortable, fit and do not tear or damage easily. Gowns are also widely used for PPE in order to protect skin and

other clothing, and should fully cover the torso, fit comfortably over the body, and have long sleeves that fit snuggly at the wrist. All or parts of face (nose, mouth and eyes) are protected by using a combination of PPE types such as masks or respirators, googles and face shields. Masks should fully cover the nose and mouth, and prevent fluid penetration; whereas goggles should fit softly over and around the eyes or personal prescription lenses. In some cases, face shields are used to substitute masks or googles, where skin protection is required in addition to mouth, nose, and eye protection. The face shield should cover the forehead, extend below the chin, and wrap around the sides of the face. HCWs are protected from hazardous or infectious aerosols, such as the coronavirus which causes Covid-19, and *Mycobacterium tuberculosis*, by using respirators that filter the air before it is inhaled. The most widely used healthcare respirators are the N95, N99, or N100 particulate respirators, which have a sub-micron filter capable of excluding particles that are less than 5 microns in diameter, Table 1. However, a higher level of respiratory protection, such as that provided by a powered air-purifying respirator (PAPR), is required when high-risk aerosol generating procedures such as bronchoscopies are being performed.[3]

How to Put on ('don'), Use and Remove ('doff') PPE Safely

The type of PPE used will vary based on the level of protections required and will consider factors such as the level of patient contact, exposure to droplets or airborne infections and isolation precautions.[23, 24] The process for donning, using and doffing PPE should respond and adjust to the specific type of PPE being worn and be carried out as per the guidance from CDC, Figure 3d-e.[3, 25] Proper hygiene should also be performed as per international recommendation before putting any PPE.[26] The first item of PPE to be donned is the gown, followed by the mask or respirator. The mask or respirator should be properly adjusted to fit the face of the user. After the mask or respirator, it is recommended that the goggles or face-shield is put on, followed by gloves as the last step. While using the PPE, it is important for users to follow safe

working practice and avoid contamination by keeping hands away from the face and not touching or adjusting PPE. Gloves should be removed if they are torn, and recommended hand hygiene should be performed before putting on a new pair of gloves. Touching surfaces and other items with contaminated gloves should be avoided in order prevent the possible spread of pathogens.[3] During the removal of PPE, self-contamination should be avoided by removing the most contaminated gloves first. The face shield or goggles are then removed, followed by the gown and then the mask or respirator.[3, 25]

Medical Gowns and Drapes

Gowns are items of protective apparel designed to ensure the protection of the wearer from the spread of infection should they come into contact with potentially infectious liquids and solid materials, Figure 3a. Gowns can also prevent the transfer of the pathogens to vulnerable patients with weakened immune systems.[27] The American National Standards Institute/Association of the Advancement of Medical Instrumentation (ANSI/AAMI) introduced standard PB70:2003, "Liquid barrier performance and classification of protective apparel and drapes intended for use in health care facilities" for gowns and other protective apparel intended for use in health care facilities in 2004. The standard describes the barrier protection levels of such apparel, and specifies test methods and performance levels necessary to verify and validate that the gown provides the necessary defined levels of protection (Section 6). Many descriptions have been used to characterize medical gowns, however the most commonly used types are surgical gowns, surgical isolation gowns and non-surgical gowns. As regulated by the US Food and Drug Administration (FDA), both surgical and surgical isolation gowns are categorized as a Class II medical device that requires a *510 (k)* pre-market notification; whereas non-surgical gowns are Class I devices, and do not require a *510 (k)* pre-market review. Surgical isolation gowns and non-surgical gowns have much larger zones of protection than surgical gowns. Non-surgical gowns are used in low or minimal risk patient

isolation situation and should never be used during surgical and invasive procedures or when there is a medium to high risk of contamination. Unlike non-surgical gowns, surgical isolation gowns could be used in medium to high risk contamination environments, whereas surgical gowns are suitable for any risk level (Levels 1-4).

Mask or Respirators

Surgical masks or respirators are used to prevent airborne particles and liquids from contaminating the face of the wearer. Medical masks are composed of a three-layer nonwoven SMS (spunbond-meltblown-spunbond) fabric laminate, Figure 2b. The inner spun-bond nonwoven fabric layer absorbs moisture released by the wearer and the outer layer is a waterproof nonwoven fabric, which is mainly used to create a barrier between the external liquids and the users. The middle melt-blown nonwoven fabric of polypropylene is the filter layer which provides protection from airborne particles. The filtering mechanism of medical masks is dominated by Brownian diffusion entrapment, inertial collision, gravity sedimentation and electrostatic adsorption. The first four physical processes are delivered by the melt-blown nonwoven polypropylene fabric and achieves ~35% filtration. However further electrostatic treatment on this layer can significantly improve the capture of aerosols or airborne particles through ionic interaction.

Table 1. Comparison of FFP2, KN95, and N95 and Other Filtering Facepiece Respirator Classes[28]

Certification/ Class (Standard)	N95 (NIOSH -42C FR84)	FFP2 (EN 149-2001)	KN95 (GB2626-20 06)	P2 (AS/NZ 1716:2012)	Korea 1st Class (KMOEL - 2017-64)	DS2 (Japan JMHLW-Notification 214, 2018)
Filter Performance (must be ≥ X% efficient)	≥ 95%	≥ 94%	≥ 95%	≥ 94%	≥ 94%	≥ 95%
Test agent	NaCl	NaCl and paraffin oil	NaCl	NaCl	NaCl and paraffin oil	NaCl
Flow rate	85 L/min	95 L/min	85 L/min	95 L/min	95 L/min	85 L/min
Total inward leakage (TIL) – tested on human subjects each performing exercises	N/A	≤ 8% leakage (arithmetic mean)	≤ 8% leakage (arithmetic mean)	≤ 8% leakage (individual and arithmetic mean)	≤ 8% leakage (arithmetic mean)	Inward Leakage measured and included in User Instructions
Inhalation resistance – max pressure drop	≤ 343 Pa	≤ 70 Pa (at 30 L/min) ≤ 240 Pa (at 95 L/min) ≤ 500 Pa (clogging)	≤ 350 Pa	≤ 70 Pa (at 30 L/min) ≤ 240 Pa (at 95 L/min)	≤ 70 Pa (at 30 L/min) ≤ 240 Pa (at 95 L/min)	≤ 70 Pa (w/valve) ≤ 50 Pa (no valve)
Flow rate	85 L/min	Varied – see above	85 L/min	Varied – see above	Varied – see above	40 L/min
Exhalation resistance - max pressure drop	≤ 245 Pa	≤ 300 Pa	≤ 250 Pa	≤ 120 Pa	≤ 300 Pa	≤ 70 Pa (w/valve) ≤ 50 Pa (no valve)
Flow rate	85 L/min	160 L/min	85 L/min	85 L/min	160 L/min	40 L/min
Exhalation valve leakage requirement	Leak rate ≤ 30 mL/min	N/A	Depressurization to 0 Pa ≥ 20 sec	Leak rate ≤ 30 mL/min	visual inspection after 300 L /min for 30 sec	Depressurization n to 0 Pa ≥ 15 sec
Force applied	-245 Pa	N/A	-1180 Pa	-250 Pa	N/A	-1,470 Pa
CO_2 clearance requirement	N/A	≤ 1%	≤ 1%	≤ 1%	≤ 1%	≤ 1%

While a surgical mask may be effective in blocking splashes and large-particle droplets, it does not provide protection against very small air borne particles, airborne viruses or other nanoscale contaminants. However, an N95/FFP2 respirator provides barrier protection against at least

95% of very small (0.3 micron) test particles, while still allowing respiration through the microscopically porous shell, Table 1. N95 respirators do not usually require *510(k)* pre-market notification in US market, and are categorized as Class II medical devices. Unlike the loose fit surgical mask, N95 respirators have extra filtration layers (Figure 3c) and are designed to achieve a very close facial fit and very efficient filtration of airborne particles. However, the risks of illness, being infected by viruses, or death are still not eliminated even with a properly fitted N95 respirator. It is worth noting, however, that a weakness of most fabric masks is that they seldom form a perfect seal against the face. As such, a mask which allows air to be drawn in through gaps caused by a poor facial seal will be ineffective, regardless of how efficient fabric filtration is. Nevertheless, in the light of the recent Covid-19 pandemic, several governments and world organizations including WHO and CDC recommended the use cloth face covering, especially in areas of significant community transmissions. [29, 30] In addition, combinations of various commonly available fabrics used in fabric masks can potentially provide significant protection against the transmission of aerosol particles.[31, 32]

Anti-Microbial Agents and Finishes

HCWs treating patients with highly infectious diseases require high level (level-4) protection against pathogens. The recent Covid-19 pandemic has highlighted the urgent need for effective anti-viral fabrics for both medical and day-to-day apparel applications that could protect the wearer from potentially infectious pathogens. As per the Association for the Advancement of Medical Instrumentation (AAMI) PB70:2012 standard,[9] protective medical clothing must be able to prevent virus and fluid penetration for up to an hour, and pass three tests: water impact, pressurizing the materials and barrier against simulated blood containing a virus. Water repellent or barrier finishes based on fluorocarbons have been a popular choice for hospital gowns to provide resistance against water and liquid.[33] However, once wet they no longer

provide an effective barrier against pathogen ingress. Additionally, some pathogens may even penetrate when no visible liquid penetration is present. In addition to repellent finishes, anti-microbial finishes have recently been widely used in medial gowns to control, destroy or suppress the growth of pathogens (Figure 4a) and their negative effects of odor, staining and deterioration.[34] There are four major pathways targeted by anti-microbial agents to inhibit or destroy pathogens, which are cell wall synthesis, protein synthesis, nucleic acid synthesis and metabolic process, Figure 4b.

Natural fibres such as cotton or wool suffer degradation, unpleasant odors, and potential health risks from microbial growth, due to their high surface area and moisture regain capability.[35, 36] In addition, various textile materials such as those made from cotton, poly/cotton and polypropylene provide favorable environments for bacteria or fungal growth, allowing such pathogens to survive for 1-90 days on textile materials in a hospital environment.[37] Furthermore, the polio and vaccinia viruses were found to survive on wool fabrics for up to 20 and 14 weeks, respectively, and for shorter duration on cotton fabrics.[38] Therefore, the use of anti-microbial textiles in healthcare facilities could diminish microbial infections compared with the use of textiles without anti-microbial finishes.[39] A polyurethane-based anti-microbial material, *N,N*-dodecyl, methyl-polyurethane (Quat-12-PU) when coated on surfaces or electro-spun into fibre, was able to kill airborne Gram-positive *Staphylococcus aureus* and Gram-negative *Escherichia coli* bacteria, as well as inactivate the Influenza virus.[40] In another study *N*-Halamines coated nonwoven fabrics completely inactivated Avian Influenza (AI) viruses and disrupted their RNA, and were found to be very effective in reducing airborne pathogens in the poultry production environment.[41] In addition, several other studies have examined the use of anti-microbial finishes on textiles to inhibit the growth of viruses and found to be highly effective against bacteria and viruses such as Influenza viruses,[42, 43] cytomegalovirus (CMV),[44] and adenovirus type 5 and poliovirus type 1.[45]

An anti-microbial agent is defined as any substance of natural, semi-synthetic or synthetic origin that kills (biocidal) or inhibits (biostatic) the growth of pathogens but causes little or no damage to the host. The term "anti-microbials" include all agents that act against all types of pathogens including bacteria (anti-bacterial), viruses (anti-viral), fungi (anti-fungal) and protozoa (anti-protozoal). In textiles applications such as clothing, anti-microbial agents need to be effective in providing protection from a wide variety of pathogens.[46] In addition, such agents have to be durable to washing, dry-cleaning and ironing, simple and easy to apply on textiles, and should not compromise appearance and hand quality of textiles.[47] Most importantly, the anti-microbial agent should be safe to wear next to the skin, and should not interfere with the skin's natural flora.

Mechanism of Anti-Microbial Activity

The anti-microbial effect on textiles is achieved *via* either cell growth inhibition (called "biostatic") or killing of the pathogens (called "biocidal"). Most of the anti-microbial agents used in commercial textiles provide a biocidal effect *via* damage or inhibition of cell wall synthesis, inhibition of cell membrane function, inhibition of protein synthesis, inhibition of nucleic acid synthesis (DNA and RNA) and inhibition of other metabolic processes such as the disruption of the folic acid pathway, Figure 4b.[48-50] In addition, the vast majority of the anti-microbial products work by leaching when in contact with moisture, as they migrate from textiles surface to the external environments, to attack the pathogen.[46, 47] However, the challenge with such anti-microbials effect is that it may also kill the 'good' natural bacterial flora associated with the skin, and may be less durable due to exposure to the external environment. Another set of anti-microbial agents are those that covalently bond with the textile and provide greater durability, but still function by rupturing the cell wall membrane of pathogens to which they come into contact.

An anti-viral effect on a surface could be achieved *via* either destroying and inactivating viruses (called "virucidal") or inhibiting the cell entry and/or virus replication (called "virustatic"). Therefore, virucidal agents (such as chlorine-based bleach and Lysol) attack and inactivate viruses outside of host cells by damaging their protein shell capsid, destroying the genetic materials such as RNA and DNA or damaging the virion structure.[51] For example, metal nanoparticles are proven to exhibit virucidal activity against a wide variety of viruses by interacting with the viral surface glycoproteins directly, as well as gaining entry into an infected cell to destroy its genome (DNA or RNA) and stop its replication process. Moreover, metal particles are active against the "naked" viruses, as such particles can interact with virus particles in a well-defined spatial arrangement.[52] However, it is easier to attack and inactivate enveloped viruses in comparison to naked viruses, as they can be neutralized *via* various chemical and physical methods. Several studies report binding and/or destroying anionic viruses *via* cationic surfaces or materials (polymers, metals),[53] hetero-coagulation with positively charged aerosols,[54] photocatalytic effect,[55] Methylene blue photochemical treatment,[56] nanoparticles,[52] aqueous and gaseous ozone,[57] anti-fouling surfaces [58] and self-cleaning surfaces.[59]

Self-cleaning and anti-fouling are important properties for anti-microbial textiles. Contamination of fibres by destroying and inactivating viruses and bacteria leads to a decrease in anti-microbial activity. Stimuli responsive polyelectrolyte multilayers attached to fibres provide cationic and anionic sites to neutral fibres,[60] and control bacterial adhesion.[61] When compared to uncoated fabric, a high degree of surface charge density leads to a reduction in adhesion of *Staphylococcus aureus* by 50%. Self-cleaning and anti-fouling mechanisms are based on both electrostatic repulsion of contaminants and the change in mechanical properties of polymer nano-coatings in response to biological contaminants and products of their living cycle[62] and degradation.[63] Uncharged polymer chains are in the collapsed inactive state but in

the presence of biological contaminants, functional groups of the polymers become charged and an active gel-like nanocoating. Such reversible phase transitions in polycationic/polyanionic multilayers provide textiles with both anti-microbial and self-cleaning properties. For instance, Gram-positive *Lactococcus Lactis* produce lactic acid which decreases the local pH to 4. However, when the pH reaches 4, the polymer became charged, the length of the charged chains increases, and the adsorbed bacteria are mechanically detached from the surface.[62]

Synthetic Anti-Microbial Agents.

Quaternary Ammonium Compounds (QACs), a class of cationic surface-active agents (Figure 4c),[64] are commonly used in textile manufacturing as biocides. They are also used as detergents, softening agents or antistatic agents at different stages of textile processing such as pre-treatment, dyeing and finishing.[65] Conventionally, QACs ($R_4N^+X^-$) refer to the subgroup of linear alkyl ammonium compounds, which is composed of a hydrophobic alkyl chain (C12-C18) and a hydrophilic counterpart.[66] Such positively charged cationic agents are usually attached to anionic fibres (cotton, polyester, nylon and wool) *via* ionic interaction.[64, 67] The anti-microbial effect on textiles with QACs is obtained by the interaction between positively charged surfaces and negatively charged cell membranes of the microbes, resulting in the damage of the cell membranes, the denaturation of proteins and the inhibition of DNA replication.[67, 68] QACs are effective against a broad spectrum of pathogens such as gram-positive and gram-negative bacteria, fungi and certain viruses.[64, 69] However, they suffer from poor durability due to the fast leaching from textiles.[50]

Triclosan (2,4,4′-trichloro-2′hydroxydiphenyl ether) ($C_{12}H_7Cl_3O_2$), an odorless synthetic chlorinated bisphenol (Figure 4d), which does not ionize in solutions unlike other cationic biocides and thus improves its resistance to laundering. Triclosan is also effective against gram-positive and gram-negative bacteria, and to some virus and fungi,[67, 70-72] by blocking lipid

biosynthesis of phospholipids, lipopolysaccharides or lipoproteins, and affecting the integrity of cell membranes.[67, 70] Triclosan has been used in hospitals and personal care products such as anti-microbial soap, tooth-paste and deodorants for decades.[73] It is suitable to be applied to polyester, nylon, polypropylene, cellulose acetate and acrylic fibres.[50] However, a number of leading retailers and governments in Europe have banned triclosan, because it could potentially cause skin irritation, as well as being non-biodegradable and toxic to aquatic and other organisms.[74]

Metal Oxide or Salts Compounds, mostly based on silver, but also on copper, zinc and cobalt have commonly been used as anti-microbial agents, due to their ability to bind to O, N or S donor ligands present in the pathogen cells, inducing oxidative stress and damaging cellular proteins, lipids and DNA.[75, 76] Among them, silver nanoparticles (Figure 4e) have been widely exploited in textiles, mainly in the form of salts, due to their broad spectrum of actions on pathogens.[77] Recently, metal nanoparticles have received significant interest because of their relatively higher surface area, higher solubility and faster release of the metal ions, resulting in a strong anti-microbial effect.[78, 79] The size of ZnO nanoparticles was found to be inversely proportional to its antibacterial activity.[78] The limitation of metal nanoparticles is their cost, technical and environmental challenges, and requirement of additional plasma, UV or acidic pre-treatment.[80]

Polyhexamethylene Biguanide (PHMB) ($(C_8H_{17}N_5)_n$) is a polycationic amine, which causes the disruption of cell membranes and lethal leakage of cytoplasmic materials by interacting with microbial cell membranes *via* electrostatic and hydrophobic interactions.[67, 81, 82] The anti-microbial activity increases with the increased level of polymerisation.[83]

Regenerable N-Halamines are heterocyclic organic compounds, which contains one or more nitrogen and a halogen (N–X) covalent bonds, where X is usually chlorine (N–Cl) but could

also be bromine or iodine, Figure 4f. Such covalent bonds could be formed *via* the chlorination of an amine (RR′−NX), amide (−C(O)−NX−R) or imide (−C(O)−NX−C(O)−) group in dilute sodium hypochlorite. The order of stability is as follows: imide < amide < amine and in terms of biocidal action effectiveness is: imide > amide > amine. [64, 67, 84] *N*-Halamines provide biocidal actions against a wide variety of bacteria, fungi and viruses, which is achieved *via* the electrophilic substitution of Cl with H in the presence of water. The free Cl anions then bind with the acceptor regions of pathogen to prevent the enzymatic and metabolic processes of their cells, thus causing the destruction of pathogen.[85] The imide *N*-Halamines work better for the rapid destruction of pathogens, however amine *N*-Halamines are the better choice for durable and sustainable anti-microbial properties on textiles.[84, 86] The advantage of *N*-Halamines are lower cost, long term stability and action against a broad spectrum of pathogen. In addition, their anti-microbial effect could be recharged by using a bleaching solution during laundering. Such bleaching solutions usually contain sodium hypochlorite, sodium hypobromite, trichloroisocyanuric acid or sodium dichlorocyanurate, which donates Cl or Br to improve anti-microbial effect with *N*-Halamines.[87] However, the disadvantage of *N*-Halamines anti-microbial finish on fabric is the presence of a substantial amount of adsorbed Cl or even other halogens on fibre surface that can discolor fabric and produce unpleasant odor.

Conjugated Polymers such as Polypyrrole (PPy) are conductive polymers (Figure 4g) that are produced *via* chemical oxidative polymerization from water solutions of the monomer, and applied *in-situ* onto textile fibres, yarns and fabrics in the oxidation bath during polymerization process. Monomers and oligomers of conjugated polymers are very toxic.[88] The presence of such low-molecular weight compounds in fibres after polymerization can significantly restrict the application of conjugated polymers for textiles that can be in contact with skin. Compared to other conjugated polymers such as polyaniline, PPy is more biocompatible and less cytotoxic.[89] The anti-microbial properties of PPy is because of the presence of positive charge

distributed along the backbone chains, and is very effective against both Gram-negative and Gram-positive bacteria.[90] In addition, PPy's non-leaching behaviour provides better safety for both outside environments and the wearer of the garment. The report on the anti-microbial activity of PPy suggests that the addition of the anti-microbial agent $CuCl_2$ to PPy increases the biocidal efficiency by up to 93, 98 and 100% against *S. aureus, E. coli and Candida albicans*, respectively.[91] In addition, PPy has also been investigated for anti-microbial applications in combination with silver,[92, 93] using silver nitrate as an oxidant[92] or silver coated fabric.[94] The presence of silver in PPy/silver composites increases the anti-microbial activity of coated fabrics by increasing the inhibition zone. The major obstacles to using of PPy and other conductive polymers are the presence of toxic monomers and the low processability of polymers. The both problems can be solved by incorporation of conjugated polymers as nanoparticles.[95]

Graphene Materials (GMs) such as graphene, graphene oxide (GO), reduced GO (rGO), and graphene quantum dots (GQDs) have shown promise as a new class of broad-spectrum anti-microbial agents.[96] Additionally, graphene-based materials have successfully been applied on textiles,[97-100] and their scalable production methods have been reported.[101-103] GO, a derivative of graphene, is a two-dimensional one-atom-thick sheet composed of sp^2-hybridized carbon atoms, Figure 4h.[104] In 2010, the study on the anti-bacterial activity of graphene materials (GO and rGO) against *E. coli* bacterial growth was reported. Since then, several studies[104-107] have reported anti-bacterial activity of such materials, which is mainly due to the combined mechanisms of bacterial membrane perturbation caused by sharp edges, and oxidative stress induction. In addition, the presence of abundant oxygen containing functional groups such as hydroxyl, epoxy, and carboxyl groups on the graphene oxide surface enhance its hydrophilicity and biocompatibility, and facilitates its surface modification with other molecules or polymers significantly.[104-106] However, there is currently no consensus in terms of the intrinsic anti-

bacterial properties of "bare" GO.[108, 109] Previous studies report that GO possesses strong,[105, 110] very weak[111] or no[112] anti-microbial activity, or even facilitates bacterial proliferation.[113] Nevertheless, the anti-microbial activity of graphene materials has been investigated as nanocomposites with other anti-microbial agents such as metal nanoparticles (mainly silver),[114, 115] metal oxides (*e.g.* Cu_2O),[116] photocatalysts (*e.g.* TiO_2),[116, 117] quaternary ammonium salts (QAS) [118-121] and polymers (*e.g.* polypyrrole).[122] In such nanocomposites, graphene-based materials are claimed to enhance the anti-bacterial performance mainly, due to their large surface and sharp edges. Only a few studies reported the broad-spectrum anti-viral activity of GO and GO-AgNPs composites against viruses such as pseudorabies virus (PRV, a DNA virus) and porcine epidemic diarrhoea virus (PEDV, an RNA virus)[123] respiratory syncytial virus (RSV)[124, 125] and Novel duck reovirus (NDRV).[126]

Natural Anti-Microbial Agents

Recently, many eco-friendly natural anti-microbial agents such as peroxy acids, chitosan and its derivatives or specific dyes have drawn significant interests for textiles applications, due to growing environmental concerns with synthetic anti-microbial agents, as well as increased awareness about consumer safety. For example, materials extracted from different parts of plants such as bark, leaves, roots and flowers containing tannin, flavonoids (Figure 4i) and quinonoids but also alkaloids, saponins, terpenoids and phenolic compounds, with strong anti-microbial properties have been studied and were found to be very effective anti-microbial agents.[127-131] In addition, essential oils have been investigated as efficient anti-microbial agents.[130, 132] Moreover, natural dyes, extracted from bark, leaves, roots, fruits, seeds and flowers, or from pathogens such as fungi, algae and bacteria, could offer low-cost and environmentally friendly colors with inherent anti-microbial properties from different coloring materials such as tannin, flavonoids and quinonoids.[133] Furthermore, natural anti-microbial peptides that are present in every living organism could be ideal candidates for anti-microbial

textile applications.[134] The use of natural high molecular weight anti-microbial compounds can overcome the issues of loss of anti-microbial activity after washing and chemical treatment, leaching out from the fabrics and contamination of the environment and users' skin as well as high costs.[90]

Chitosan (2-amino-2-deoxy-(1->4)-b-D-glucopyranan), a biodegradable, biocompatible, non-toxic, non-carcinogenic and environmentally friendly anti-microbial agent, is derived from the deacetylation of chitin. It is the second most abundant biopolymer in the world after cellulose, which consists of 20–30% of the exoskeleton of crustaceans (Figure 4j).[141] It offers a strong anti-microbial activity against a wide variety of pathogens, including fungi, algae and some bacteria. The interaction between the positively charged chitosan side groups and the negatively charged microbial cell membranes occurs through either electrostatic interaction, binding with the microbial DNA or through the excellent metal-binding capacity of chitosan due to its amine groups.[47, 138] Chitosan could be incorporated into textiles with dyes and pigments due to the presence reactive amine groups[139] and also with binder,[140] which enables flexible application methods and a durable anti-microbial effect. However, chitosan suffers from some disadvantages for textile applications such as sensitivity to temperature, pH activity dependence and imparting a poor handle to the fabric. In addition, thermal curing following padding or exhaustion is the most common application of chitosan on textiles, and involves high temperature with associated energy consumption costs and possible fabric degradation. To mitigate such problems, UV-curing has been proposed as a fast and eco-friendly process, which is carried out at room temperature, with lower cost than the traditional thermal process.[142-145] The stimuli responsive properties of chitosan are used for the design of self-cleaning, anti-fouling and self-healing[146] nano-coatings as well as the formation of polymer nanocarriers for release of anti-microbial compounds on demand for biomedical textiles.[147]

Table 2 Summary of Anti-Microbial Agents

Agents	Possible Mechanism	Type of pathogens	Application Techniques on textiles	Fibre Types	References/Limitations
QAC	Damage cell membranes; Denature proteins; Inhibit DNA production, avoiding multiplication	Gram-positive and Gram-negative bacteria, fungi and certain viruses.[64, 69]	Electrospinning, [68, 69] Exhaust, padding	cotton, polyester, nylon and wool	[68, 69, 135, 136 50] poor durability due to the fast leaching from textiles.
Triclosan	Blocks lipid biosynthesis, affecting the integrity of cell membranes[67, 70]	Gram-negative and Gram-positive bacteria, some antifungal and antiviral properties[67, 70-72]	Exhaust,[70] melt-mixing (spinning),[73]padding[64]	polyester, nylon, polypropylene, cellulose acetate and acrylic	[67, 70-72] photochemical conversion of Triclosan to 2,8-dichlorodibenzo-*p*-dioxin in aqueous solutions is another great concern, due to its toxicity
Metals and metallic salts	Generate reactive oxygen species, damaging cellular proteins, lipids and DNA[75, 76]	A broad spectrum of action against bacteria	Exhaust, padding, melt-mixing[47]	Cotton Wool Polyester Nylon	cost, technical and environmental challenges, and requirement of additional plasma, UV or acidic pre-treatment.[80]
PHMB	Interacts with membrane phospholipids to disrupt and cause the lethal leakage of cytoplasmic materials[67, 81, 82]	-	Exhaust and padding[50]	Cotton Polyester Nylon	-
N-Halamines	Precludes the cell enzymatic and metabolic processes, causing the consequent pathogen destruction[64, 84]	A broad spectrum of bacteria, fungi and viruses	Polymerization, electro-generation or chemical grafting [86]	Cotton Polyester Nylon Wool	unpleasant odor or even discoloration of fabrics[84]
Conjugated polymers (PPy)	Attack on the cell by charged N and CL ions of PPy[91]	Gram-negative and Gram-positive bacteria	*In-situ* polymerization, coating	Cotton, polyester	insoluble in water
Graphene Derivatives	Bacterial membrane perturbation caused by sharp edges and oxidative stress induction.	Bacteria and viruses	Coating [137]	Cotton, Polyester, poly-cotton, Nylon	no consensus in terms of the intrinsic antibacterial properties of bare graphene oxide
Chitosan	Electrostatic interactions or the binding with microbial DNA or the excellent metal-binding capacity of chitosan due to the amine groups[47, 138]	a wide spectrum of pathogens, including fungi, algae and some bacteria	dyeing/printing[1 39] pad-dry-cure[140]	Cotton, silk, wool, Viscose, synthetic fabrics	as temperature and pH activity dependence and poor handling.

Personal Protective Textiles

Medical textiles are typically soft goods used for healthcare and hygiene applications, and have been critical components in the protective healthcare sector.[148] Such textiles are broadly categorized into: implantable (sutures, vascular grafts, artificial ligaments, *etc.*); non-implantable (wound dressings, bandages and pressure garments); extracorporeal devices (artificial kidneys, artificial lungs, liver *etc.*); and protective, hygienic and healthcare products (surgeons' and operating theatre wear, operating drapes and medical staff uniforms).[5, 149] Surgical textiles, which fall within the class of healthcare and hygiene products, have been in unprecedent demand in recent months due to the Covid-19 pandemic. Since the first Covid-19 case was reported in China, surgical textiles such as gowns, gloves and masks have been used extensively in healthcare environments for the protection of HCWs, and to stop the spreading of the highly infectious coronavirus Covid-19. Therefore, in this section we discuss the nature of current surgical textiles, the associated performance standards, fibre and polymer types, and the fabric structures, manufacturing techniques and functional finishes used for such textiles.

Fibre and Fabric Types

The properties of an item of protective clothing is defined by the physical and chemical properties of its smallest component, the fibres. The fibres, with their high surface area and relatively shorter length, prevent transmission of particles. Microfibers, in particular, are generally preferred for manufacturing barrier materials which provide higher levels of protection. However, less absorbent or hygroscopic fibres wick liquid along the fibre surface, enhancing the capillary movement of liquid which contains pathogens. Thus, less absorbent synthetic fibres (such as polypropylene and polyester), which neither absorb liquid nor admit bacteria to be trapped inside their structure, provide better liquid barrier properties than those of natural origin (such as cotton, wool, silk, *etc.*), and are commonly used for protective clothing. Furthermore, the capillary absorption of fibrous assembly is governed by following

factors:[150] the characteristics of the fluid (surface tension, viscosity and density); fibre surface energy and surface morphology; fluid's interaction with the fibre surface (interfacial tension and contact angle); and pore characteristics (size, volume, geometry and orientation). In addition, the level of twist in textile yarns can also influence the barrier properties of fabrics.

Medical gowns can either be "disposable/single-use" or "reusable/multi-use". Reusable gowns, washed after each use, are usually tightly woven fabrics with a plain weave structure that are chemically finished *via* a pad-dry-cure process to improve liquid barrier properties. They are washed after each use, and used typically for more than 50 washing and drying cycles, which is monitored *via* a suitable tracking system.[2] Such gowns are typically made of 100% cotton, 100% polyester, or a polyester/cotton blend. Historically, loosely woven cotton muslin fabrics with high air permeability and breathability were very popular as medical textiles, however they were eliminated from the market due to their poor resistance to liquid penetration.[7] Cotton/polyester blend fabrics also faced the same problem, even with a 180-thread-count, where the blend fabrics met wearer comfort requirements but failed to resist microbial penetration.[75] Woven polyester (T280) fabrics provided better water-repellency and increased protection against strike-through liquids and pathogens, but the thermal comfort could be a problem.[151] A recent study of the North America market,[152] reported that the majority of modern reusable surgical gowns are composed of woven polyethylene terephthalate (PET) fabric in the non-critical zones and knitted PET fabric in the critical zones. A barrier fabric is used to reinforce the knitted PET in the critical zones, where 70% of the barrier fabric is based on expanded polytetrafluorethylene (PTFE) and the remaining 30% is based on breathable polyurethane (PU) barrier membranes.

Single-use or disposable nonwoven medical gowns and drapes are becoming the primary choice for healthcare professionals,[153] due to their ability to provide excellent protection against fluids and pathogens[154] as well as maintaining breathability and comfort. Single-use or

disposable gowns are usually composed of nonwoven fabrics and polyethylene films with a weight range of ~30–45 g/m^2.[153] Disposable gowns are typically based on synthetic fibre (such as polypropylene, polyester and polyethylene) nonwoven fabrics, which could be engineered to achieve desired properties by using particular fibre types, bonding processes, and fabric finishes (chemical or physical). There have also been recent approaches, such as electro-spinning, which is a well-established technique to manufacture nonwovens made from polymer fibres with diameters in the rage of 100-600 nm, to produce protective clothing with improved comfort without compromising the protective performance. We discuss various manufacturing and finishing (functional) process in details for medical protective clothing in the following section.

There is a considerable variation between reusable and disposable protective medical textiles in terms of design and performance. They both have pros and cons in terms of protection, maintenance, comfort, cost, and environmental impact.[155] Several studies[7, 152, 155, 156] have evaluated and compared the performance of both reusable and disposable medical gowns and in most cases, report that the impermeable materials are effective in reducing transfer of pathogens, however the thermal comfort of the wearer is adversely affected.[154] Moreover, the disposable surgical gowns made of SMS polypropylene laminate offer higher fluid resistance than the gowns made of a polyester-cellulosic blend, and only allow passage of methicillin-resistant *S aureus* at pressures >1 psi.[157] Reusable items of protective clothing are subjected to abrasion and damage over time, and also undergo further mechanical stress during laundering processes. Indeed, several studies[7, 154, 156, 158] have highlighted that laundering processes cause fabric to break down and, in turn, reduce a fabric's ability to prevent the penetration of pathogens through its surface. Nevertheless, gowns with reinforced layers demonstrate better durability to laundering. Furthermore, both disposable and reusable protective clothing have an environmental impact, which is discussed later in this review.

Manufacturing Process

The fabrics used for protective medical clothing are usually of woven, knitted or nonwoven structure. Woven fabrics are manufactured *via* a weaving process, where fabrics are formed by interlacing or interweaving of warp (lengthwise or vertical) and weft (widthwise or horizontal) yarns, Figure 5a.[159] Woven fabrics can be customized to have specific strength, thickness, extensibility, porosity, and durability by varying their weave construction, the thread spacing or the raw materials (fibre) structure. Such fabrics are usually strong and durable; however, they are less extensible than knitted fabrics, are porous and have poor barrier properties. After weaving, knitting is the second most popular technique for manufacturing fabrics, and it involves inter-looping one yarn or a group of yarns, Figure 5b. Compared with weaving, knitting is a faster and more economical method of converting yarn into fabrics. Additionally, knitted fabrics are more stretchable and have potential for very high extensibility, up to 100%, and offer improved comfort and a better fit in most types of apparel.[160] However, knitted fabrics also provide poor barrier properties due to their highly porous structure. Nevertheless, the barrier properties of both woven and knitted fabrics can be improved by engineering a dense fabric structure and using hygroscopic synthetic fibres.

The most popular fabrics for medical applications are nonwoven fabrics (Figure 5c-e), which are defined by ISO 9092:1988 as 'a manufactured sheet, web or batt of directionally or randomly orientated fibres, bonded by friction, and/or cohesion and/or adhesion, excluding paper and products which are woven, knitted, tufted, stitch-bonded incorporating binding yarns or filaments, or felted by wet-milling, and may be additionally needled.' Single-use disposable medical textiles are usually made of nonwoven fabrics alone or in combination with other materials (for example plastic) in order to increase fluid repellent property. Nonwoven fabrics are manufactured *via* bonding or interlocking fibres or filaments of various size and shape by mechanical, thermal, chemical, or solvent treatment, to provide integrity and strength to the

fabrics rather than the interlocking geometries associated with woven and knitted materials. In the manufacture of nonwoven fabrics, both staple and filament fibres can be used separately or in blends of different sizes and types, which are selected on the basis of the desired properties and performance of end products.[160, 161] Fibres are arranged randomly in a nonwoven fabric structure, which successfully reduces liquid transmission by providing a filtering media and reducing the capillary formation.[162] The most commonly used nonwoven fabrics for surgical gowns and drapes are: spun-lace, spunbond–meltblown–spunbond (SMS) and wet-laid.[7] Synthetic fibres (such as polypropylene, polyester and polyethylene) are typically used for single-use items. To improve the barrier resistance, absorbency and non-slippage performance of both single-use and reusable products, additional materials in the forms of coatings, reinforcements, laminates or plastic-films are often added to obtain a composite material.[7]

Nonwoven fabrics are manufactured in two stages: web formation and bonding. First, the fibres or filaments are laid on a forming or conveying surface *via* drylaid, wetlaid or spunlaid techniques. Such web forming techniques are originate from traditional carding, suspending fibres in liquid and polymer extrusion techniques used traditionally in the textiles, paper and plastic industries, respectively. The laid fibres are then arranged in the desired orientation using mechanical or fluid means. Secondly, the webs are then bonded together by mechanical, chemical, and thermal methods to form nonwoven fabrics. In the dry-laid process, staple fibres are converted into web or batt structure with uniform weight per unit area *via* carding, garneting and air-laying. Meanwhile, wet-laid nonwovens are obtained by the swelling and dispersion of fibres in water, web formation, and drying and bonding of the web. The spun-laid process, which is most commonly used for protective medical textiles, involves the extrusion of the filaments from the raw polymer material, drawing the filaments, and laying them into a batt. It is a continuous polymer-to-fabric operation. There are several methods that can be used to produce spun-laid nonwoven fabrics including spun-bond, melt-blown, aperture films, and the

many-layered combinations.[160, 163] The development of spun-bond technology was a major manufacturing breakthrough, which was followed by the development of melt-blown technology which enabled the production of finer micro-fibres.[164] The meltblown process provides advantages of better filament distribution, better filtration *via* smaller pores between the fibres, softer feel, and also the possibility of manufacturing lighter weight fabrics. Generally, high and broad molecular weight thermoplastic polymers such as polypropylene, polyester and polyamide are processed by a melt-extrusion process in all commercially available spunlaid machines.[160]

In the **spun-bond process**, melt fibre spinning is combined with web formation by placing the bonding device in line with spinning, Figure 5d. Briefly, thermoplastic polymer pellets or powder granules are fed from a hopper into an extrusion chamber where the polymer is heated to a molten state with other additives. The molten polymer is then passed through the heated screw and extruded from the extruder through a gear pump, which precisely controls the flow rate of polymer mixture, into a die block or spinpack. The spinpack, which contains a spinneret with thousands of micro-diameter holes, maintains uniform temperature and polymer distribution. The molten polymer flows through spinneret holes, jets into a quenching chamber and is converted into fibres which are solidified by cooling air. In the attenuator, fibres are stretched by high-speed air flux to reduce their diameter while travelling from the spinneret to a collecting belt. The flight velocity of the fibres slows down as they are collected onto a conveyer belt *via* a vacuum system which sucks the air flux and facilitates a nonwoven web formation on the collector belt. The untreated nonwoven fabric is then progressed to the bonding line by a conveyer belt, where its is bonded *via* a mechanical, chemical, or thermal process before wound onto a take-up roller.[165, 166] Spun-bond fabrics provide good thermal properties, high tear strength and good permeability. Therefore, they are widely used in

hygiene-related, medical, construction and agricultural applications, as well as in other end-uses in daily life.[167]

The **melt-blown process**, is similar to the spun-bond process in that the thermoplastic polymers are extruded through a spinning die, to form filament fibres, Figure 5e. The main difference between the spun-bond and melt-blown processes is the way in which the air is introduced to cool and/or attenuate the fibres as they come out of the spinneret. In the spun-bond process, the quenching airflow is horizontal to the vertical fibres emerging from the spinneret; whereas in the melt-blown process the heated air with high velocity is injected near the die tips which will which will converge with the filaments to attenuate them to very fine diameters. The attenuated filaments are quenched with cool air and collected on a moving collector screen to form a fine fibrous and self-bonding web.[168] Since the air action is more dynamic in melt-blown manufacture, much finer fibres are obtained, which results in softer and weaker nonwoven fabrics. The attenuated filaments are generally 1–4 μm in diameter and form a very uniform web at low grammage. The melt-blown process is unique, as it is used almost exclusively to produce microfibers rather than traditional coarser textiles fibres. The fine fibre network and large fibre surface area of such fabrics result in enhanced filtration efficiency, excellent barrier properties and good wicking action. Melt-blown fabrics have been widely used for applications in filtration (*e.g.* surgical mask and respiratory filtration), insulation, and liquid and oil absorption.[163]

Composite nonwoven fabrics are also very attractive for medical applications. They offer the opportunity to combine strong and durable spun-bond materials with the relatively weaker melt-blown materials with better wicking and barrier properties, and finer and higher surface area fibres. Therefore, by combining the two fabric types, a spunbond-meltblown composite can create a single product with enhanced performance. The most commonly used nonwoven composite laminates are spunbond-meltblown-spunbond (SMS), spunbond-meltblown-

meltblown-spunbond (SMMS), or spunbond-spunbond-meltblown-meltblown-spunbond (SSMMS) in weights ranging from 10 to 25 g/m^2 comprising 1–5 g/m^2 melt-blown (MB) microfibers. The use of polypropylene (PP)/polyethylene (PE) biocomponent materials in the preparation of MB webs enhances the production and properties of the composite fabrics. Excellent levels of protection with softness and comfort have been achieved in SMS products with weight ranging from 10 to 70 g/m^2.[153] Tri-layer anti-viral and antibacterial nonwoven composite fabrics with an additional anti-microbial finish on outer layer have shown level 4 protection for surgical application, according to the barrier protection classification of AAMI.[169, 170] To improve the barrier resistance, absorbency and non-slippage performance of both single-use and reusable products, additional materials in the form of coatings, reinforcements, laminates or plastic-film are often added.[7] However, such membranes or reinforcements may impair comfort in applications such as medical gowns due to less heat transfer and more sweating.

Newer techniques such as **electro-spinning** have been evaluted for use in the manufacture of gown materials to improve comfort without sacrificing the protective performance. Electrospinning is one of the most simple and effective methods of fabricating ultrafine fibers with diameters ranging from a few nanometers to several micrometers.[171] Electrospinning uses an electrostatic field and extrusion technology (Figure 5c) to generate ultrafine fibers in a very short period of time with minimum initial investment, training, and supervision. Initially, electrospinning received only a small amount of attention due to issues associated with low productivity and fibre non-uniformity. However, such issues have been resolved with the advancement of needleless electrospinning, near-field electrospinning and electrospinning with rotating strings of electrodes.[172] Table 3 summaries recent progress on filtration preformance using electro-spun membrane. As emerging nonwoven filters, elerospun fibers have

successfully been applied for PM1.0 and PM2.5 level filtration and now used for personal proection against Covid-19.

Table 3. Comparison of Filtration Performance

Filtration type	Material	Test agent	Flow rate	Collection efficiency (%)	Pressure drop (Pa)	Quality factor (Pa^{-1})	References
Fibrous filtration	PS[1]/PAN[2]/ PA[3]-6	NaCl	32 L/min	99.992	118	0.0799	[173]
Fibrous filtration	PVDF[4]-NIP[5]s	NaCl	16.6 cm/s	98.33	97	0.042	[174]
Fibrous filtration	PAN/PVDF	NaCl	0.3~0.5 m/s	99.99	86	0.1071	[175]
Fibrous filtration	PAN	KCl	5 cm/s	96,6	172	0.0196	[176]
Fibrous filtration	Nylon-6	Incense smoke	1 m/s	99.6	349	0.0158	[177]
Fibrous filtration	PAN	Incense smoke	0.21 m/s	96.12	133	0.024	[178]
Electrostatic filtration	Al coated Polyester	KCl	10 cm/s	99.99	4.9	2.2	[179]
Fibrous filtration	PVDF/ SDBS[6]	NaCl	32 L/min	99.985	66.7	0.132	[180]
Fibrous filtration	ZIF[7]-8/PAN	Cigarette smoke	0.05 L/min	88.33	20	0.1074	[181]
Fibrous filtration	Cellulose-PVP[8]	NaCl	5.3 cm/s	86.4	17	0.117	[182]

[1] Polysulfone

[2] Polyacrylonitrile

[3] Polyamide

[4] Polyvinylidene fluoride

[5] Negative ions powder

[6] Sodium dodecyl benzenesulfonate

[7] Zeolitic imidazolate framework

[8] Polyvinylpyrrolidone

Anti-Microbial Finish Techniques

Anti-microbial finishes can be applied to textiles by embedding an anti-microbial reagent into the polymer bulk during the fibre processing (Figure 5f) or by applying a surface coating or modification as a chemical or physical finishing treatment (Figure 5g-h). Among these methods, the application at the textile finishing stage is a more common and popular choice *via* traditional pad-dry-cure (Figure 5g) or exhaust (Figure 5h) techniques. The "pad-dry-cure" technique is the most commonly used method for applying functional or soft finishes onto textiles such as water repellent, anti-microbial, wrinkle free, moisture management *etc.* onto textiles. In this technique, the fabric is passed through a padding bath containing the finishing agent (such as anti-microbial agent), and the mangle nip rollers squeeze any excess solution from the fabric surface, thus producing a uniform treatment. The fabric is subsequently dried and cured using a stenter at recommended temperatures, Figure 5g. Such a technique provides very high production speed (~150 m/min)[101, 103] and is applicable to a wide range of fabrics of different structures (woven, knit and nonwoven) and fibre compositions (cotton, polyester, polypropylene and nylon). The "pad-dry-cure" technique is readily scalable, and could be used for large-scale industrial production of protective clothing with anti-microbial and fluid-repellent properties. Another popular method for the application of functional finishes onto textiles is "exhaustion" techniques, which is most commonly used to dye yarn, knit and woven fabrics and garments. The principle of such processing is the migration of dyes or finishing agent from the solution into the fibre or fabric until the dye or finishing agent has fully exhausted onto the fibrous materials, Figure 5h. Like the "pad-dry-cure" technique, the "exhaust" finishing technique is also highly scalable,[102] and could be used finish tonnes (~1000 kg) of textiles in a short period, providing an even distribution and good wash fastness of finishing agents. To improve the durability of anti-microbial finishes to the fabrics, cross-linkers[183, 184] are used to introduce intermolecular covalent bridges between the polymer chains

and the antibacterial molecule by chemical,[185] radiation[186] or physical methods.[187] In addition, surface modification methods, such as oxygen plasma treatment, ultrasound technology, UV radiation, surface bridging and enzyme treatment, have all been investigated for improving the durability of anti-microbial finishes on natural fibre-based products.[188]

The other popular approach is to incorporate the anti-microbial agents into the polymer matrix of the textile fibres before or during spinning or during the web formation process. Such agents can be mixed (commonly by melt-mixing) with polymer granules prior to production, or added to the reservoir chamber during the extrusion or electro-spinning process, Figure 5f.[67, 189, 190] Several studies[191-193] report electro-spinning of nanofibers based on polymers and nanoparticles with anti-microbial properties, that provide several advantages such as higher surface area to volume ratio, adjustable porosity and the ability to customize nanofiber composition. Additionally, the approach of mixing anti-microbial agents into thermoplastic polymers for fibre spinning or web formation processes has received substantial interests due to their durability and scalability it offers. Furthermore, such method has no negative effect on the mechanical properties of the fibrous end product. However, it requires a higher extrusion temperature and the anti-microbial agents are usually trapped in the polymer matrix, which restricts their ability to diffuse through the matrix to perform their biocidal or biostatic function. Thus, such an approach would potentially provide a lower anti-microbial effect and be limited to anti-microbial agents that are stable at higher temperature such as metallic particles.[189, 194, 195] There are also natural fibres with intrinsic anti-microbial properties based on chitosan and cellulose fibres, however their anti-microbial effect is generally less effective.[50]

Table 3. Typical Standards for PPE

PPE Types		Category	Standards	Key Requirements
Surgical Medical Face Mask		Category II: Medium risk	BS EN 14683:2019 (UK/EU) ASTM F2100 (US)	• Mask must be marked as Type IIR • Splash resistance pressure ≥ 1200mm Hg • Bacterial filtration efficiency (BFE) ≥ 98%, simulated with particles size of 3.0 μm • Single-use and anti-fogging
Respirator Masks		Category II: Medium risk	BS EN 149:2001+A1:2009 (FFP2/FFP3- UK/EU NIOSH-42C FR84 (N95 – US)	• Protect the wearer from airborne particles and from liquid contaminating the face • Blocks at least ≥94% (FFP2) or ≥95% (N95/KN95) of very small (0.3 μm) test particles; • Single-use and close fitting • Filtering specific amounts of viruses or bacteria, reducing the amount of and/or killing viruses, bacteria, or fungi, or affecting allergenicity, or • contains coating technologies unrelated to filtration (to reduce and or kill pathogens)
EU/UK Standard	Sterile Gowns	Category II: Medium risk	BS EN 13795:2019 (performance) BS EN11810:2015 (fire resistance)	• Hydrostatic pressure: >20cm H_2O (Standard Lite), >50cm H_2O (Standard) and >1000cm H_2O (Standard High-performance gown) • Single-use, latex free and antistatic
	Nonsterile /Isolation gown	Category II: Medium risk	BS EN 13795:2019 (performance) BS EN11810:2015 (fire resistance)	• Hydrostatic pressure: >20cm – 28.4cm H_2O (Fluid resistant isolation gown - low exposure to fluid), >57.3cm H_2O (Fluid resistant isolation gown -medium exposure to fluid), >91cm H_2O (Impervious isolation gown -high exposure to fluid) • Must be single-use, latex free, lint free, fire resistant and antistatic • Knitted cuffs and welded seams
	Coveralls/ Protective suits	Category III: High risk	BS EN 14126:2003 (all including 5 test methods) BS EN 943-1:2019 (1a, 1b, 1c and 2B coverall) BS EN 14605:2005+A1:2009 (type 3B and 4B coveralls) BS EN ISO 13982-1:2004+A1:2010 (type 5B coveralls)	• Single-use, latex free and antistatic • BS EN 943-2:2019 (1a, 1b, 1c and 2B coverall): • Protective clothing against liquid and gaseous chemicals, aerosols and solid • particles. Performance requirements for ventilated and nonventilated "gas-tight" (Type 1) and "non-gas-tight" (Type 2) chemical protective suits. • BS EN 14605:2005+A1:2009 or any equivalent standard • Protective clothing against liquid chemicals. Performance • requirements for clothing with liquid-tight (Type 3) or spray-tight (Type 4) • connections • BS EN ISO 13982-1:2004+A1:2010 or any equivalent standard Protective clothing for use against solid particulates. Performance requirements for chemical protective clothing providing protection to the full body against airborne solid particulates (type 5 clothing)
USA	Surgical gowns, other protective apparel, surgical drapes and drape accessories	Level 1 Minimal Risk	ANSI/AAMI PB 70:12 AATCC 42	• Impact Penetration (water) ≤4.5 g • Application: basic care, standard hospital medical unit
		Level 2 Low risk	ANSI/AAMI PB 70:12 AATCC 42 & 127	• Impact Penetration (water) ≤1.0 g • Hydrostatic Pressure ≥20 cm • Application: Blood draw from a vein, Suturing, Intensive care unit, Pathology lab
		Level 3 Medium Risk	ANSI/AAMI PB 70:12 AATCC 42 & 127	• Impact Penetration (water) ≤1.0 g • Hydrostatic Pressure ≥50 cm • Applications: Arterial blood draw, Inserting an IV, Emergency Room, Trauma

		Level 4 High Risk	ANSI/AAMI PB 70:12 ASTM F1670 & F1671 Phi-X174	• Synthetic Blood (for surgical drapes) and • Viral Penetration Test (for surgical and isolation gowns): no penetration at 2 psi • Applications: Pathogen resistance, Infectious diseases (non-airborne), Large amounts of fluid exposure over long periods
Eye protection (shields/safety glasses			BS EN 166:2002 (UK/EU) ANSI/ISEA Z87.1-2010 (US)	• Must be optically clear; • Must be resistant to fogging; and • Adjustable head band
Gloves		Category I & III: Low & High risk	EU standard directive 93/42/EEC, EN 455 EU standard directive 89/686/EEC Category III, EN 374 ANSI/ISEA 105-2011 ASTM D6319-10 (US)	• Sterile or nonsterile; Single or reusable. • Nitrile • Non-sterile • Powder-free • Outer gloves should preferably reach mid-forearm (minimum 280 mm total length) • Different sizes

Standards and Requirements for Protective Medical Clothing

The protective clothing products used in healthcare environments are considered as medical devices, and are therefore subject to stringent regulations. Such clothing is required to meet or be equivalent to certain standards originated under the auspices of the International Standards Organization (ISO), European Committee for Standardization (CEN) or under various US standards organizations (*e.g.* ANSI/AAMI, ASTM). The selection and use of personal protective clothing depend on the hazards and the risks that a wearer is exposed to. Therefore, a first critical step is to identify and assess the physical and health hazards (*i.e.* risk and hazard assessment) in the workplace. The standards will then enable the selection of the appropriate protective clothing or PPE based on the risk and hazard assessment. There are mainly three types of standards: test methods, product or performance specifications, and technical reports or guidance documents.[196] Test methods usually describe a testing method simulating the real-life exposure of protective clothing and what would be observed. The product or performance specification standards set the pass or fail criteria for protective clothing by defining the levels of performance that must be met for different properties related to hazards or risks. The guidance documents provide useful information about the selection, correct use and maintenance of protective clothing.

Regulatory Standards

For EU and UK markets, PPE must conform to European Commission (EC) regulations 2016/425, which covers the design, manufacture and marketing of personal protective equipment. CE marking must be clearly evident on the product and/or packaging. CE marking is defined as a certification mark, which indicates that a product conforms with health, safety, and environmental protection standards for products sold within the European Economic Area. In addition, any products containing phthalates should be packaged in such a way that this information is clearly indicated in accordance with medical devices regulation 2017/745. Furthermore, the products and packaging should be latex free with a minimum 3-year shelf life from the date of manufacture, and instructions for use and disposal/recycling instructions for use and disposal/recycling. As per EU 2016/425, PPE is generally categorized into three types on the basis of the risks and hazards a wearer is subject to: Category I (minimal risk), Category II (PPE not covered within category I or III) and Category III (high risks that may cause very serious consequences such as death or irreversible damage to health).[197] In the US, all PPE is regulated by FDA, and should meet applicable voluntary consensus standards for protection. Pre-market Notification or *510(k)* clearance is required for some PPE before it can be legally sold in the US. In such cases, PPE is reviewed by the FDA to make sure it meets specific criteria for performance, labelling, and intended use to demonstrate substantial equivalence by conforming to consensus standards for barrier performance and resistance to tears and snags. In addition, voluntary consensus standards may also be used to demonstrate sterility (when applicable), biocompatibility, fluid resistance, and flammability.

Functional/Barrier Properties Against Pathogens

Pathogens are transported by carriers such as body fluids, sloughed skin cells, lint, dust, and respiratory droplets. Therefore, protective clothing with functional properties such as

protection against liquids and pathogens are extremely important for healthcare applications.[198] In order to determine the ant-viral activity of textile materials, ISO 18184:2019 has been developed and provides a quantitative test method to assess the anti-viral performance of such products against specific viruses including SARS-CoV2 (NL63).[199] Recently, several commercial products claimed that their products were effective against coronavirus (kills such viruses) after testing their anti-viral performance against human coronavirus (NL63) as per ISO 18184:2019. In addition, several standard test methods have been developed to investigate the functional performance of protective clothing against liquids and pathogens by simulating real life conditions.[200] Such test methods include the water impact penetration test, the hydrostatic pressure test, resistance to liquid penetration,[201] and protection against pathogen.[202] The EN 13795 European Standard for surgical gowns and drapes specifies the performance requirements, manufacturing standards and testing methods for both reusable and single-use surgical drapes, gowns and clean-air products. In this standard, the barrier performance of the protective clothing against liquid and pathogens is tested by liquid penetration resistance test (EN IS0 811:2018), wet microbial penetration resistance test (EN ISO 22610:2006) and dry microbial penetration resistance test (EN ISO 22612:2015).[203] In the US, American National Standards Institute (ANSI) and the Association of the Advancement of Medical Instrumentation (AAMI): ANSI/AAMI PB70:2003 identifies four levels (Level 1 to 4: Minimal to high risk) of protection based on barrier performance against liquids and pathogen. Such levels of protection are assessed by the spray impact penetration test, the hydrostatic head test, and synthetic blood (for surgical drapes) and viral penetration test (for surgical and isolation gowns). Table 2 shows the characteristics to be evaluated and performance requirements for surgical gowns as per BS EN 13795-1:2019. As per the standard if the manufacturer does not categorize product areas, all areas of the protective clothing should meet the requirements for critical product areas.

Table 4. Characteristics to be Evaluated and Performance Requirements for Surgical gowns (BS EN 13795-1:2019)[203]

Characteristic	Test method	Unit	Requirement			
			Standard Performance		High Performance	
			Critical Product Area	Less Critical Product Area	Critical Product Area	Less Critical Product Area
Microbial Penetration — Dry	EN ISO 22612	CFU	Not required	≤ 300	Not required	≤ 300
Microbial Penetration — Wet	EN ISO 22610	I_B	≥ 2,8	Not required	6,0	Not required
Liquid Penetration	EN ISO 811	cm H_2O	≥ 20	≥ 10	≥ 100	≥ 10
Cleanliness Microbial / Bioburden	EN ISO 11737-1	CFU/ 100 cm^2	≤ 300	≤ 300	≤ 300	≤ 300
Particle Release	EN ISO 9073-10	$\log_{10}$ (lint count)	≤ 4,0	≤ 4,0	≤ 4,0	≤ 4,0
Bursting Strength — Dry	EN ISO 13938-1	kPa	≥ 40	≥ 40	≥ 40	≥ 40
Bursting Strength — Wet	EN ISO 13938-1	kPa	≥ 40	Not required	≥ 40	Not required
Tensile Strength — Dry	EN 29073-3	N	≥ 20	≥ 20	≥ 20	≥ 20
Tensile Strength — Wet	EN 29073-3	N	≥ 20	Not required	≥ 20	Not required

Physical Properties

The protective garment should be durable enough to last the intended lifecycle. The critical physical and mechanical properties need to be considered while selecting protective clothing, which include tensile and burst strength, dimensional stability and lint generation. Such properties are assessed by tensile test (EN 29073-3 or ASTM D5034, ASTM D1682), burst test (EN ISO 13938-1) and lint generation test (EN ISO 9073-10). In addition, the seam strength (ASTM D751) and the barrier properties of seams/closures are critical to provide the overall barrier protection by fluid-resistant or impermeable garments. Several seaming techniques with barrier properties are used in the construction of protective clothing. Examples of durable and effective seams include serged or sewn, bound, taped, double taped, and ultrasonic welded seams. Furthermore, HCW should also know the appropriate size of their protective garments as it may catch or snag on objects if they are too large. PPE that fits well and is comfortable to wear will encourage employee use of PPE. The American national standard ANSI/ISEA 101-2014 provides a sizing chart and a set of exercises in which a user can validate whether that garment is the "proper" size.[198] All reusable protective clothing and linen should be laundered

at 71°C for a minimum of 3 minutes or 65°C for at least 10 minutes as per BS EN 14065:2016 standard and still provide the specified protection after washings.[204]

Comfort

Surgeons are less likely to tolerate poor thermal comfort and fit while wearing personal protective clothing. A balance between the heat loss and gain of a human body is needed to enable thermal comfort. Such thermal comfort with a medical gown depends on the surgical environment, length of procedure and amount of exposure.[148] The temperature and relative humidity of an operating room are usually ~15.6-25.6 °C and 30-60%, respectively. However, the operating room temperature could increase during the procedure due to the radiant heat from the overhead lighting. In addition, doctors and nurses' own body heat released in a high-stress environment under strong lighting add to the feeling of discomfort,[205] which may contribute to increased mistakes, impaired performance, and less efficient work.[7] Therefore, protective medical clothing should provide an isothermal environment for HCWs during use. To improve barrier resistance, absorbency and non-slippage performance of both single-use and reusable protective clothing, additional materials in the form of coatings, reinforcements, laminates or plastic-film are often added.[7] However, such membranes or reinforcements may impair the wearing comfort of the reinforced gowns due to less heat transfer and more sweating in areas where the gown is covered by another layer of fabric or a plastic. To provide enhanced protective medical garments without comprising the comfort/breathability, several advanced technology-based approaches have been introduced to increase the permeability and flexibility of the fabric. For example, phase change materials have been used to improve the regulation of the temperature of treated fabrics within the normal comfort range.[206] Another approach is to use layered, breathable materials with an active cooling mechanism. Because of the environments in which they work and the nature of the tasks which they must perform, surgeons tend to express a preference towards comfortable products which have moisture

management properties while also provide a high level of protection. To achieve such clothing, an impervious "breathable" plastic film is sandwiched between two layers of spun-bonded nonwoven, allowing moisture vapor to pass through the fabric from the inside of the garment, but prevent the passage of fluids or pathogen from outside.[207]

Biocompatibility

A biocompatibility test of protective medical clothing has been developed to determine its compatibility with a biological system, and fitness for human use. The International Organization for Standardization (ISO) established ISO *10993-1: Biological evaluation of medical devices - Part 1: Evaluation and testing within a risk management process,* for evaluating the biocompatibility of a medical device prior to a clinical study. The biocompatibility test involves the application of a high temperature to a medical device to extract leachable materials, and then investigating potentially harmful chemicals or cytotoxicity in the leachable extracts. There are range of biocompatibility tests available, from a skin irritation test to hemocompatibility and implantation tests, which could be *in vitro* or *in vivo* or both depending on the intended use. The FDA recommends that cytotoxicity (ISO 10993-5), sensitization (ISO 10993-10), and irritation or intracutaneous reactivity (ISO 10993-10) is evaluated for a medical device that is contact with the skin.[27, 208]

Global Market and Supply Chain for Personal Protective Clothing

The global market size of personal protective products was valued at ~ $50.93 billion in 2018, and is expected to grow up to ~$79.66 billion at a compound annual growth rate (CAGR) ~6.6% from 2018-2024, Figure 6a.[209] In 2019, China was the largest exporter of personal protective products with a ~17.2% market share followed by Germany and USA, Figure 6b.[210] The protective clothing market for healthcare industry was valued at ~$1.2 billion, and forecast to reach ~$1.7 billion by 2024 at a CAGR ~6.5%.[211] As expected, the demand for medical

protective clothing in North America was the highest (~$0.49 billion) followed by Europe (~$0.32 billion), and was forecast to continue to grow until 2024 (Figure 6c) at a CAGR of ~6.9% (North America) and ~5.7% (Europe), respectively, due to the presence of technologically advanced countries in these regions and stringent regulations regarding the use of protective clothing in every industry. South America and Asia-Pacific (APAC) are also projected to experience high growth in the global protective clothing market during the forecast period. The markets in these regions are estimated to register CAGRs of 7.0% and 6.4%, respectively, between 2019 and 2024. Such growth is mainly driven by the manufacturing industry and rapid urbanization in these regions. China is the largest market for protective clothing in APAC.[211]

Since the outbreak of COVID-19 in December 2019, there has been a surge in demand for personal protective equipment (PPE) products, notably surgical masks and gowns which are made from polypropylene nonwoven fabrics. In 2018, nonwoven fabrics accounted for a 64.3% share of the global medical textiles market in volume terms. Prior to the COVID-19 pandemic, global demand for nonwoven fabrics for the medical sector was projected to grow by an average of 5.0% per annum between 2018 and 2025.[212] However, during the Covid-19 pandemic, several hospitals around the world reported that supplies of PPE were running low. Indeed, a recent survey showed that over 30% and 21% of doctors working in high-risk areas during the pandemic reported shortages of long-sleeved disposable gowns and FFP3 masks or respirators, respectively, Figure 6d.[213] Therefore, it can be assumed that this growth figure will have accelerated in light of the global Covid-19 outbreak.

Overall, producers of nonwoven fabrics account for some 70% of global polypropylene fibre demand. As a result of the surge in demand for nonwoven fabrics following the Covid-19

pandemic, prices for polypropylene fibre in Asia increased during April 2020 particularly in China. China is the largest producer of many of the raw materials required in the manufacture of PPE, and it is also the largest supplier of finished PPE products. Other PPE supplying countries include Taiwan, India, Japan, South Korea, Malaysia, Mexico, Thailand, the USA, and several countries in Europe.[214] The supply of PPE and associated raw materials has been disrupted during the Covid-19 pandemic, not least because government-imposed lockdowns in China disrupted manufacturing operations in the country during February 2020. Since March 2020, PPE manufacturing operations in China have largely returned to normal, although there is still some concern regarding the supply of raw materials.[214] However, increasing numbers of companies in China are turning to the manufacture of polypropylene fibre in light of the increase in demand.[215]

Some countries have imposed export bans on PPE products following the COVID-19 outbreak. The Indian government, for example, has imposed an export ban on all PPE products and associated raw materials. In addition, the EU has enforced a regulation to prevent the export of PPE without authorization from the manufacturing member state. Overall, demand for PPE during the Covid-19 pandemic appears to be outstripping supply,[216] and this is a cause for concern. Furthermore, ensuring adequate supply of PPE is particularly challenging for low income countries and middle-income countries, whose governments cannot afford to compete against high income countries in bidding wars for PPE. To help meet increasing demand for PPE and other medical apparel such as scrubs, several companies which usually manufacture consumer products have converted their production lines to manufacture PPE or medical scrubs. Several such companies are concentrating on boosting domestic supplies in the light of global shortages of PPE and other medical apparel.[214]

Environmental Impact

The environmental impacts of the textile industry are well-documented, and the textile industry is reported to be the second largest polluter of the environment after the oil industry, by contributing to ~8-10% global CO_2 emission and ~20% of the global waste.[217] About 95% of textiles are fully recyclable, however 85% of all textiles are still sent to landfill or incinerated.[218] Synthetic fibres such as polyester, which dominate the textiles market due to their low cost and performance characteristics, are biggest source of carbon emission. Since synthetic fibres provide better protection against pathogens, protective clothing products for healthcare applications-particularly single-use surgical products- are predominantly made of polypropylene or polyester. At the end of their useful lives, such products are either incinerated, thereby generating further carbon emissions, or sent to landfill, where they can persist for years (~450 years) due to their non-biodegradability. Thus, the environmental impacts of such clothing are significant. Indeed, it is estimated that, during the Covid-19 pandemic, frontline workers worldwide are using some 44mn nonwoven PPE items on a daily basis, the majority of which are made from polypropylene. This, in turn, is resulting in the generation of some 15,000 tons of waste every 24 hours.[219] However, it is challenging to accurately assess these environmental impacts due to their complex supply chains and lack of extensive studies in this area. Nevertheless, in this section we discuss the current understanding of the environmental impacts of the protective medical clothing on energy consumption, carbon footprint, blue water consumption and solid waste generation. We also compare the environmental impacts of synthetic fibre-based clothing with the most commonly used natural fibres such as cotton.

Polyester dominates worldwide fibre consumption with ~55% of the total textile fibre by volume, followed by cotton (~27%). By contrast, the consumption of polypropylene fibres is far less as they are used for very specialized applications such as surgical masks and medical gown. However, the consumption of polypropylene fibres has seen a significant rise in recent

months due to the Covid-19 pandemic. Synthetic fibres consume the highest amount of energy during the fibre manufacturing, as they are usually manufactured from fossil fuels. For example, the production of polyester and polypropylene consumes almost double the amount of energy compared with that of cotton fibres. Additionally, greenhouse gas emission (GHG) is also influenced by the energy consumption rate and the sources of the energy consumption during textile processing including spinning, weaving, dyeing and finishing. For example, coal-based energy sources used in China have a higher carbon footprint than that of other 'greener' sources used in Europe. The textile industry also uses large amounts of water, ~79 billion m^3 in 2015 alone, and about 90% of this consumption is associated with the cultivation and wet processing of cotton-based textile materials. Cotton fibres therefore have the highest water-footprint among textile fibres. In reviewing the Higgs Materials Sustainability Index (MSI) score from the life cycle assessment (LCA) to understand and quantify the sustainability impacts of polyester, polypropylene and cotton textiles, it is apparent that the fossil fuel consumption associated with polyester and polypropylene is higher, which, in turn, results in higher global warming, Figure 6e-f. However, the cotton fibre contribution to water usage/scarcity is substantial, and to eutrophication is higher than polyester and polypropylene, Figure 6e-f. Nevertheless, natural fibres such as cotton are biodegradable unlike synthetic fibres which can remain in the environment for hundreds of years.

Medical textiles including surgical gowns are available as reusable and disposable products. The recent Covid-19 pandemic has driven the market towards single-use disposable products due to hygiene concerns, and the need to avoid spreading infection or diseases. After use, all single-use PPE are discarded using standard infection control measures. NHS England usually labels waste as either infectious (contaminated with bodily fluids), offensive (contaminated but not infectious) or municipal (similar to household disposals). All infectious PPE waste is incinerated at high temperature. However, such processing is expensive and emits unwanted

toxic gases, which contributes toward the overall pollution and carbon emission. Nevertheless, modern gas cleaning or 'scrubbing' technologies can remove these potentially harmful gases and additionally, the heat generated from waste incineration could be used as a source of energy. In the UK, waste incineration contributes ~2% of the total energy generation. Other medical waste, which is not incinerated, is usually discarded in a landfill, while a very small proportion is recycled. It is worth noting that, in the case of non-PPE clothing, by doubling a garments' lifetime it is possible to reduce GHG emission by ~44%, and save $460 billion each year. To become environmentally sustainable, it is therefore important to reuse and recycle textile materials. Similarly, there is a growing interest in reusable medical textiles due to better environmental sustainability. A recent study shows that the selection of reusable medical apparel could reduce natural resource energy consumption (~64%), greenhouse gas emissions (~66%), blue water consumption (~83%), and solid waste generation (84%), Figure 6f.[152]

The environmental impact of anti-microbial textiles is also a growing global concern, which is mainly associated with anti-microbial chemical production, their application on textile materials, and the subsequent use and disposal of such products.[66] The ideal anti-microbial agents would have high efficacy at low dosing, be durable to washing, and their effectiveness should outweigh the potential environmental consequences and the cost of their usage.[50] In addition, the removal of such agents from textile waste water is important in order to avoid discharge to the wider aquatic environment. For example, silver is one of the most popular anti-microbial agents and is non- biodegradable. Silver is immobilized by the formation of stable sulphide complexes, which are insoluble and much less toxic and bioavailable than dissolved silver. Thus, the potential risk with silver in the aquatic environment is reduced by removing 85%–99% of silver during the textile waste water treatment.[66, 220] Additionally, the health impact of anti-microbial agents needs to be considered in order to evaluate the safety of anti-microbial compounds for animals and humans. The extent to which humans could be exposed

to anti-microbial textiles is usually influenced by the type of action of the anti-microbial agent (diffusion or contact), its concentration in the textile, the exposure routes and the frequency of use. The risk associated with anti-microbial textiles is usually evaluated *via* acute and chronic toxicity, skin sensitization and irritation, and the disturbance of skin ecology. For instance, silver may interact with so called 'good' bacteria such as skin flora to weaken the skin defense barrier,[221, 222] and also lead to the deposition of Ag metal/Ag sulfide particles in skin, causing discoloration (argyria) or even ocular discoloration (argyrosis), which although not life threatening is cosmetically undesirable.[221]

Future Directions and Conclusions

Towards Smart and Sustainable Protective Clothing

Smart wearable electronic textiles (e-textiles) are becoming increasingly popular due to their ability to make human life safer, healthier and more comfortable.[97, 99] Such smart e-textiles could potentially interface with the human body, and continuously monitor, collect and communicate various physiological data and the vital signs of the wearer-including temperature, heart-rate and oxygen saturation level-and communicate these data wirelessly to a processing device. Such data relating to vital signs can alert health care professionals of any deterioration in a patient's health at a very early stage and enable them to intervene more quickly. This could be considered to be particularly important in health care settings such as care homes where staffing shortages are a major issue. Smart textiles could also allow patients to monitor their health at home, thereby freeing up hospital beds. Self-monitoring of medical conditions with connected wearable devices could potentially reduce NHS costs by ~60%. In addition, the health and well-being of HCWs is immensely important in order to ensure that they are available to treat patients with infectious diseases, such as Covid-19. As such, e-textiles could be a useful tool in monitoring the health of HCWs, who regularly experience

stress during long shifts or in operation theatres, and are exposed to several risks in their work environment.

Smart wearable e-textiles technologies could be integrated with protective clothing to produce truly "Smart" wearable medical clothing, which can then continuously monitor the physiological conditions of both HCWs and patients, Figure 7a. Furthermore, recent studies have also shown promise in tracking Covid -19 symptoms continuously *via* wearable sensors, which could potentially monitor coughs, fever and respiratory activity. Researchers have developed such a wearable device, and are creating a set of data algorithms specifically tailored to detect early signs and symptoms associated with Covid-19, and to monitor patients as the illness progresses.[223] Recently, we also reported washable, durable and flexible graphene-based wearable e-textiles, which are highly scalable, cost effective and potentially more environmentally friendly than existing metals -based technologies.[98, 101-103] In addition, graphene and other 2D materials have drawn significant interest in flexible and wearable electronics applications, due to their outstanding electrical, mechanical, and other performance properties. Such properties could also be exploited in heterostructures,[224] where different 2D materials are inkjet printed on top of each other *via* rapid, precise and reproducible deposition of controlled quantities of 2D materials in a non-impact, additive patterning and mask-less approach. Therefore, integrated graphene-based wearable e-textiles for protective clothing could potentiality address current challenges associated with the early detection of highly infectious diseases, ensuring good health and well-being of front-line workers.

The outbreak of the Covid-19 pandemic has resulted in significant increases in the consumption of disposable face masks and gloves. Such plastic-based disposable items, used by the general public, are often not disposed of properly, thereby adding to the mass of plastic pollution which poses a significant threat to oceans and marine life.[225] Recent news has highlighted concerns from conservationists about such "new" pollution, which is set to become ubiquitous after

millions of people around the world have turned to single-use plastic-based protective products (*e.g.* surgical mask made of polypropylene plastics) to help prevent the spread of Covid-19.[226] Such plastic-based products are not are biodegradable, and could stay in the environment for many years. In addition, used PPE is incinerated because it is classified as a bio-hazard. Increased volumes of PPE consumption as a result of the Covid-19 pandemic, and the subsequent incineration of these products will, in turn, contribute to increased carbon emissions which is also a problem. Therefore, the textile industry now has an opportunity to design new types of environmentally sustainable protective clothing that would be washable and reusable, which could potentially reduce the amount of medical waste contributing towards environmental pollution. In addition, new technologies that sterilize waste, and separate/reduce the mixing of infectious waste with general waste need to investigated urgently.[227] Furthermore, the use of biodegradable polymers (*e.g.* polylactic acid, PLA)[228] and recycled polymers (*e.g.* rPET or rPP) for manufacturing protective clothing, and recycling of current disposable plastic-based protective clothing products would help to reduce the environmental impact, and support a shift towards more sustainable protective medical clothing and a circular economy.

Towards Safe and Green Functional Materials and Techniques

Although the benefits of anti-microbial textiles that protect the wearer from pathogens are evident, there are some concerns associated with the use of anti-microbial agents on textiles, including their potential to kill good flora bacteria from the skin, their toxic breakdown products and the consequent risks to human health and environment.[50] It is important that the overall advantages and effectiveness of anti-microbial agents should outperform any the potential environmental concern and the cost of the product. Therefore, future anti-microbial agents should be highly effective at very low dosages while also being extremely durable to ensure the development of products with longer useful lives. Thus, in turn, will help to reduce

the quantities of textiles waste disposed of, and improve the overall carbon footprint associated with protective clothing. In addition, anti-microbial agents should not release unwanted toxic chemicals in aquatic environment, and should efficiently be removed *via* green and less energy intensive waste-water treatments. Furthermore, there must be efforts from researchers and manufacturers to develop safer and environment-friendly "green" agents, namely natural anti-microbial agents, which may present an efficient anti-microbial effect, with safety, easy availability and nontoxicity to skin.[229, 230] Natural biopolymers extracted from animals or plants-including chitosan, cyclodextrin, sericin and alginate-are renewable, and could be used as key resources for sustainable bioactive textiles, Figure 7c.[231] Polyelemental nanoparticles (PE NPs) containing four or more elements in a single NP could also be explored to enable a multifunctional ant-microbial agent with a new physical and chemical phenomena.[232]

In addition to the growing interest in natural green anti-microbial agents, there has also been drive towards the introduction of green processing techniques in textile manufacturing due to rigorous ecological legislation and growing environmental concerns, Figure 7d. For example, a "solvent free" dry plasma treatment could be employed to apply anti-microbial finishes onto textiles. Unlike conventional treatments, the dry plasma treatment does not produce contaminated water or create mechanical hazards for treated fabrics.[233] In addition, the uses of enzymes, UV radiation and ultrasound energy could be considered to be more environmentally friendly processes which promote the adhesion of natural dyes with anti-microbial properties.[234, 235] Furthermore, a broader perspective and knowledge of anti-microbials, with considerations into risks and benefits of their use compared to alternative anti-microbial substances, is needed for the regulatory assessment of the single anti-microbial substance.[66] For example, it has been reported that the textile industry uses the highest amount of triclosan (~210 metric tonnes), which could be replaced by either <2 metric tonnes of silver nanoparticles or by ~180 metric tonnes of Si-QAC, achieving similar anti-microbial results but

with a lower environmental impacts.[50] Microencapsulation of anti-microbial additives into textile polymer matrix could also be explored to avoid the human and environment safety level. New fibre or fabric manufacturing techniques such as electro-spinning and additive manufacturing could also be explored for making protective clothing with improved comfort and effective protections from pathogens.[171, 236, 237]

Towards Sustainable Supply Chain

The recent Covid-19 pandemic has resulted in unprecedented demand for PPE needed to protect the health of HCWs and prevent the spread of the disease. Hospitals around the world have experienced significant shortages in supplies of PPE, and the global supply chain was severely challenged[216] due to rising demand, panic buying, hoarding and misuse. The shortage of safe and effective PPE has been one of the major causes for the deaths of frontline workers treating Covid-19 patients around the world. PPE prices have also increased significantly with long delay in supplies, widespread market manipulation, and stocks frequently sold to the highest bidder. As per WHO's modelling, an estimated 89 million medical masks, 76 million gloves and 1.6 million googles are required for the Covid-19 response each month. The WHO has also recommended that the industry should increase the PPE production by ~40%.[238] The WHO has additionally provided recommendations for the rational use of PPE in healthcare and community settings, and strategies to optimize the availability of PPE including minimizing the use of PPE, recommending the appropriate use of PPE and coordinating with the PPE supply chains.[23] However, these are temporary measures to optimize the PPE supply chain in order to tackle the current Covid-19 pandemic. Sustainable and commercial approaches are needed to avoid similar shortages into the future and could involve the followings.

Firstly, the creation of government-backed local or regional (*e.g.* EU, America, South Asia, Middle East *etc.*) manufacturing, sourcing and distribution facilities for PPE, Figure 7e.

Secondly, the introduction of digital technologies in manufacturing and processing (*e.g.* waterless colorations, inkjet printing, digital finishing techniques and 3D printing) of protective clothing. The traditional manufacturing and processing techniques of protective clothing may be challenging for some countries or regions such as the EU or US due to higher labor costs and the associated environmental legislation. Nevertheless, the introduction of new technologies including robotics, additive manufacturing and artificial intelligence (AI) in manufacturing facilities (*Industry 4.0),* would enable cost-effective manufacturing of such devices at scale, Figure 7f. Thirdly, governments should encourage and introduce legislations to increase the use of sustainable and reusable protective equipment to lessen any environmental impacts, Figure 7g. In addition, more effort and resources should be invested into the design and development of environmentally sustainable recycling processes for single-use plastic-based PPE. Finally, governments should increase annual expenditure on research and development for developing innovative technologies to produce smart, highly effective and extremely durable PPE with longer useful life, as well monitoring the wearer's physiological conditions, Figure 7h.

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Acknowledgement

The authors respectfully acknowledge all the front-line workers ("Heroes") around the world for the wonderful care and work they are providing on a daily basis during the current Covid-19 pandemic. This research was supported by E3 Research England Funding (UK), and KAIST Institute for the NanoCentury and Global Singularity Research Project (N11200030).

Vocabulary

An **anti-microbial** is defined as any substance of natural, semi-synthetic or synthetic in origin that kills (biocidal) or inhibits (biostatic) the growth of pathogens but causes little or no damage to the host; **Covid-19** is short form of coronavirus disease 2019 and it belongs to a large family of viruses called Coronaviruses (CoV); **virucidal agents** attack and inactivate viruses outside of host cells by damaging their protein shell capsid, destroying the genetic materials such as RNA and DNA or damaging the virion structure; **Virustatic agents** are used on surfaces to stop the growth of viruses; **personal protective equipment (PPE)** is equipment (such as gloves, eye protection, face masks *etc*.) to protect the user against health or safety risks at work;

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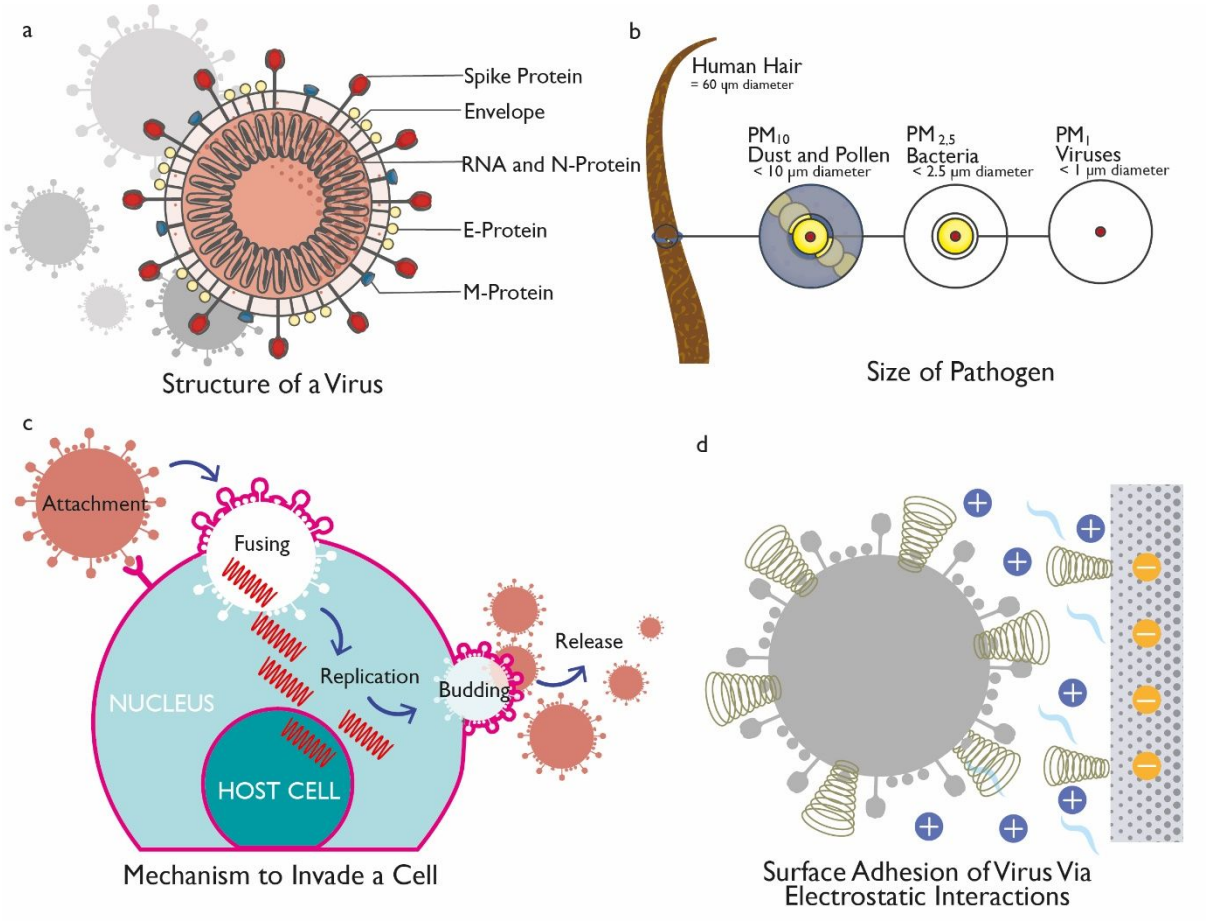

Figure 1 Structure of virus and mechanistic action. *a) The structure of a corona virus; b) Relative size of various pathogens; c) Mechanism to invade a cell via a virus. d) Surface addition of viruses via electrostatic interaction.*

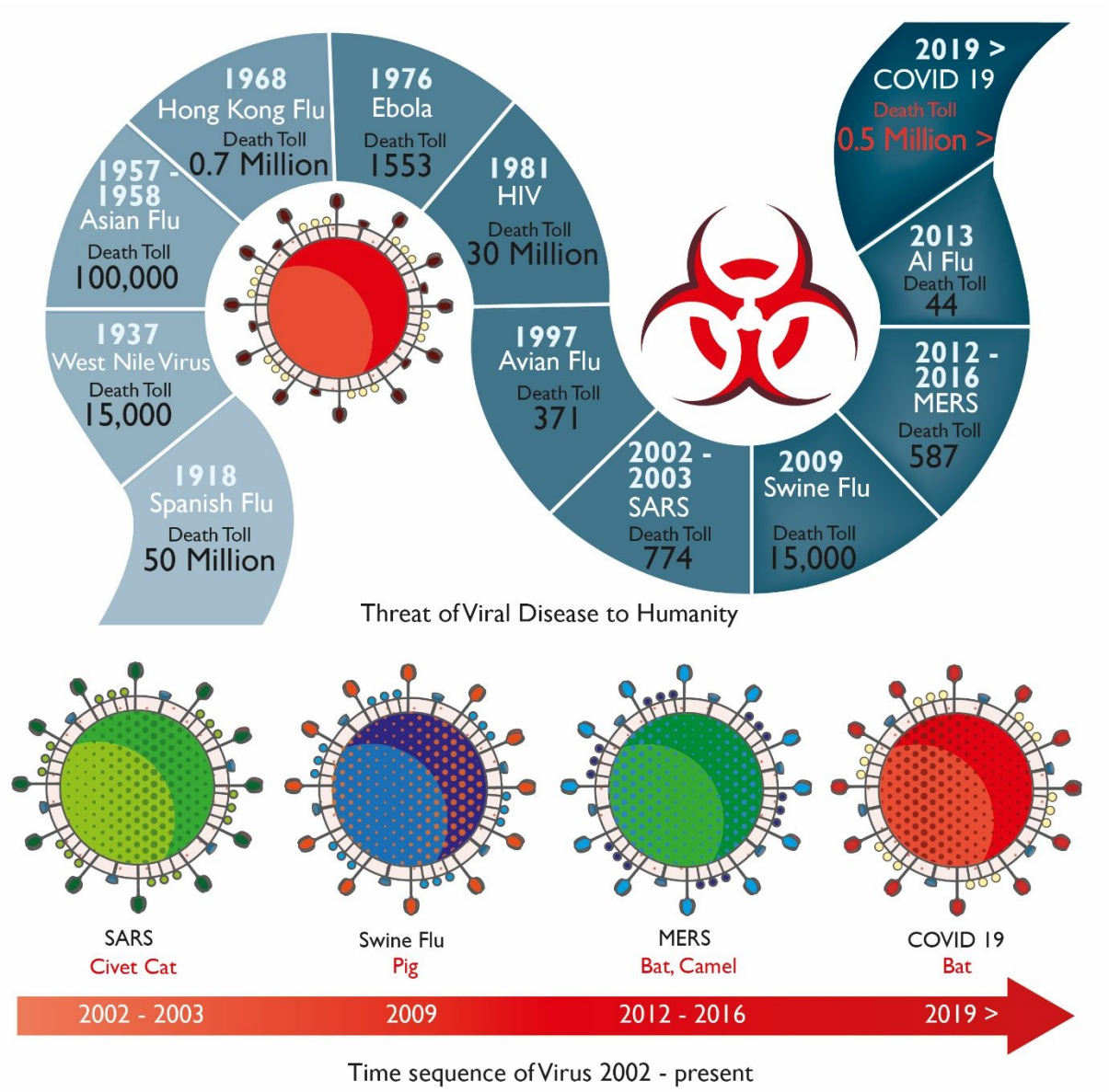

Figure 2 History of viruses. *a) The threat of viral diseases to humanity at various years with number of human deaths. b) Timeline of recent highly infectious viruses such as SARS, Swine Flu, MERS and Covid-19.*

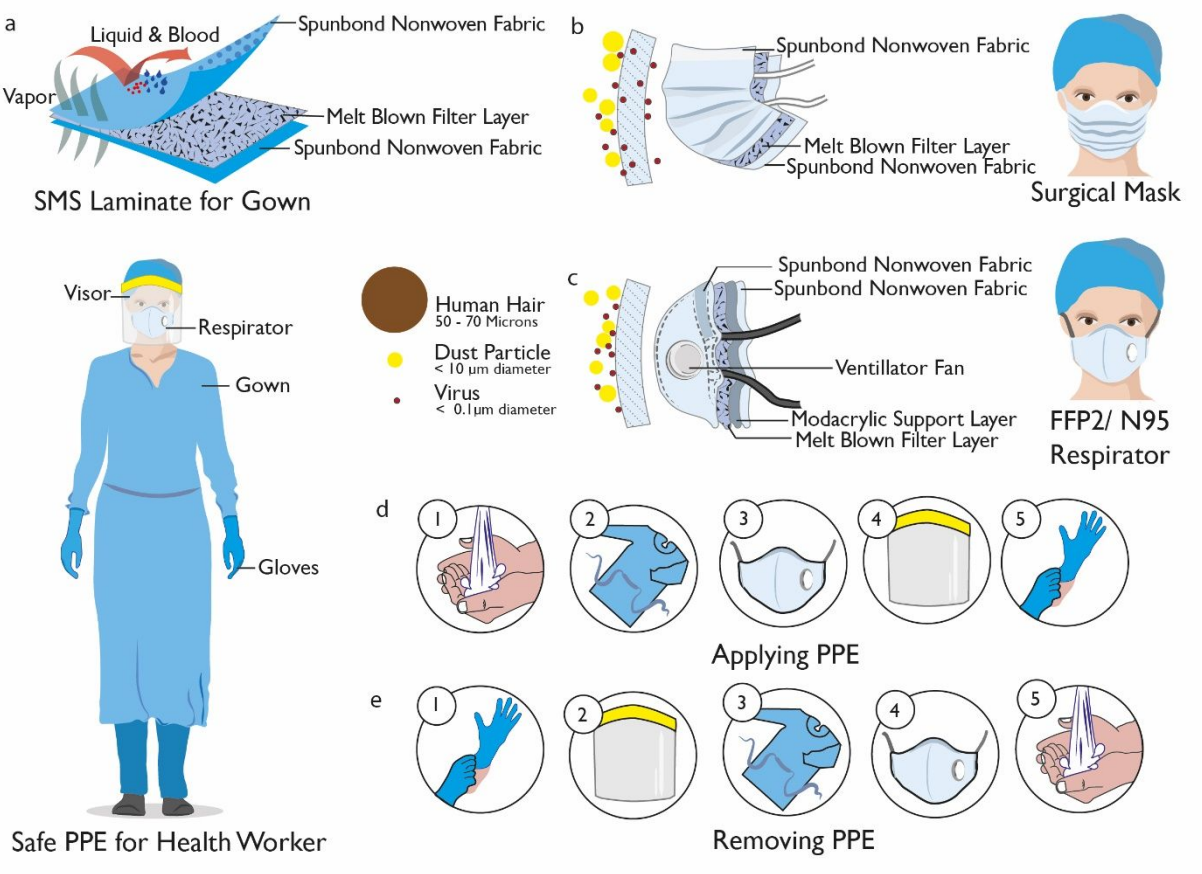

Figure 3 Personal protective equipment (PEE) for HCWs. *a) A healthcare worker with safe PPEs such as gown, visor respirator, visor and gloves. Spunbond–meltblown–spunbond (SMS) laminate fabric used for the disposable medical gown. It provides protection from the liquid and blood at the same time maintaining comfort. b) Surgical mask with SMS structure which only provides protection against larger particles but not effective against airborne viruses. c) FFP2/N95 respirator which provide efficient protection against airborne viruses by stopping >95% of particles. d) Stages to put on PPEs for healthcare setting and e) steps to remove PPEs safely without any contamination.*

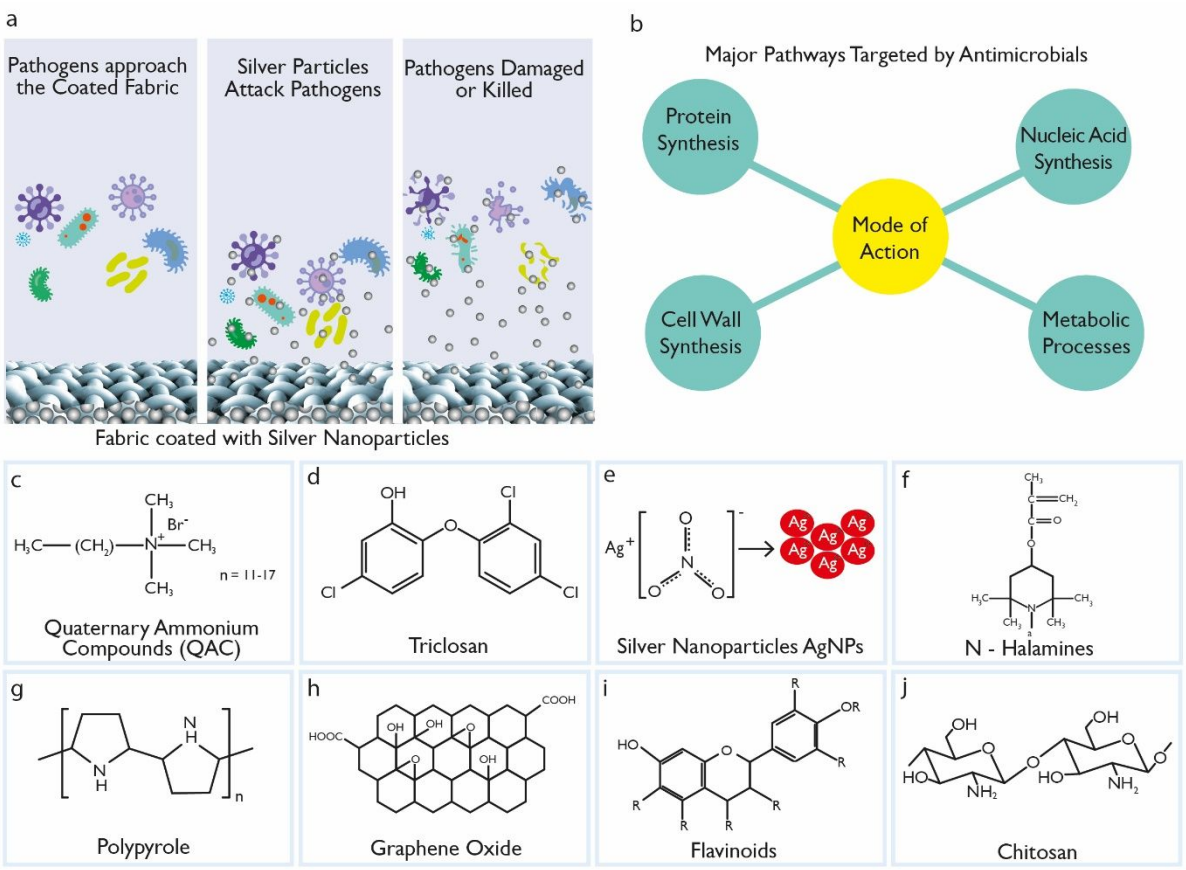

Figure 4. Anti-microbial agents and their mechanism. *a) Anti-microbial action via silver nanoparticle coated fabrics. b) Major pathways targeted by anti-microbial agents to inhibit or destroy pathogens. The chemical structure of some commonly used anti-microbial agents: c) Quaternary Ammonium Compounds (QAC), d) Triclosan, e) N-Halamines, f) Graphene Oxide, g) Silver Nanoparticles, h) Polypyrrole, i) Chitosan and j) Flavonoids.*

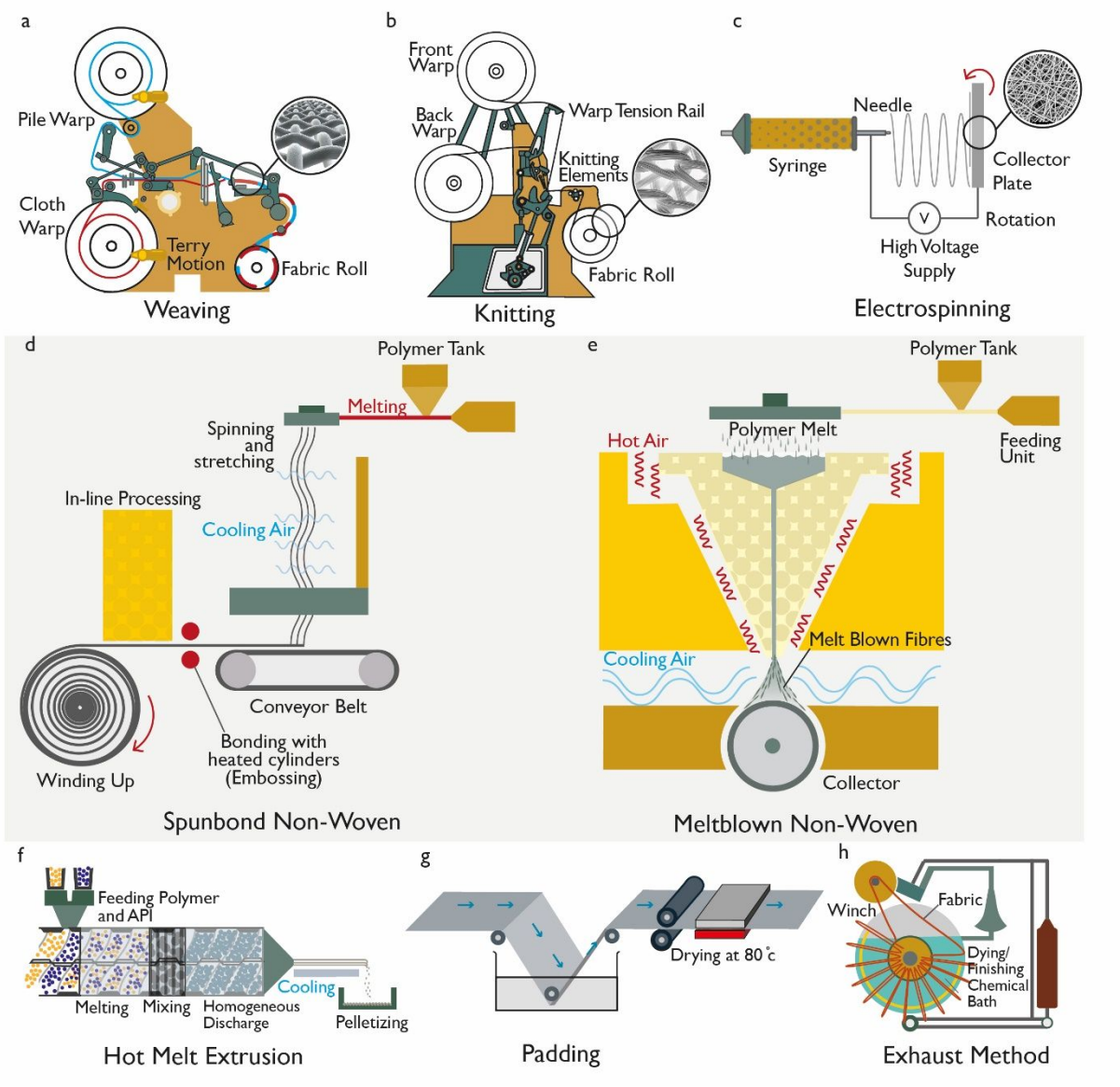

Figure 5. Manufacturing processes for personal protective fabric. *a) Weaving mechanism and woven fabric structure (inset), b) Knitting mechanism and knitted fabric structure (inset), c) Electrospinning process and resulting fabric with random orientation (inset), d) Spun-bond nonwoven fabric manufacturing technique, e) Melt-blown nonwoven fabric manufacturing technique. Application of anti-microbial finish into/on textiles: f) Hot melt extrusion process for melt-mixing anti-microbial additives to fibre polymers, g) Pad-dry-cure technique to apply anti-microbial finish on fabric and h) Exhaustion method to apply anti-microbial finish on fabric*

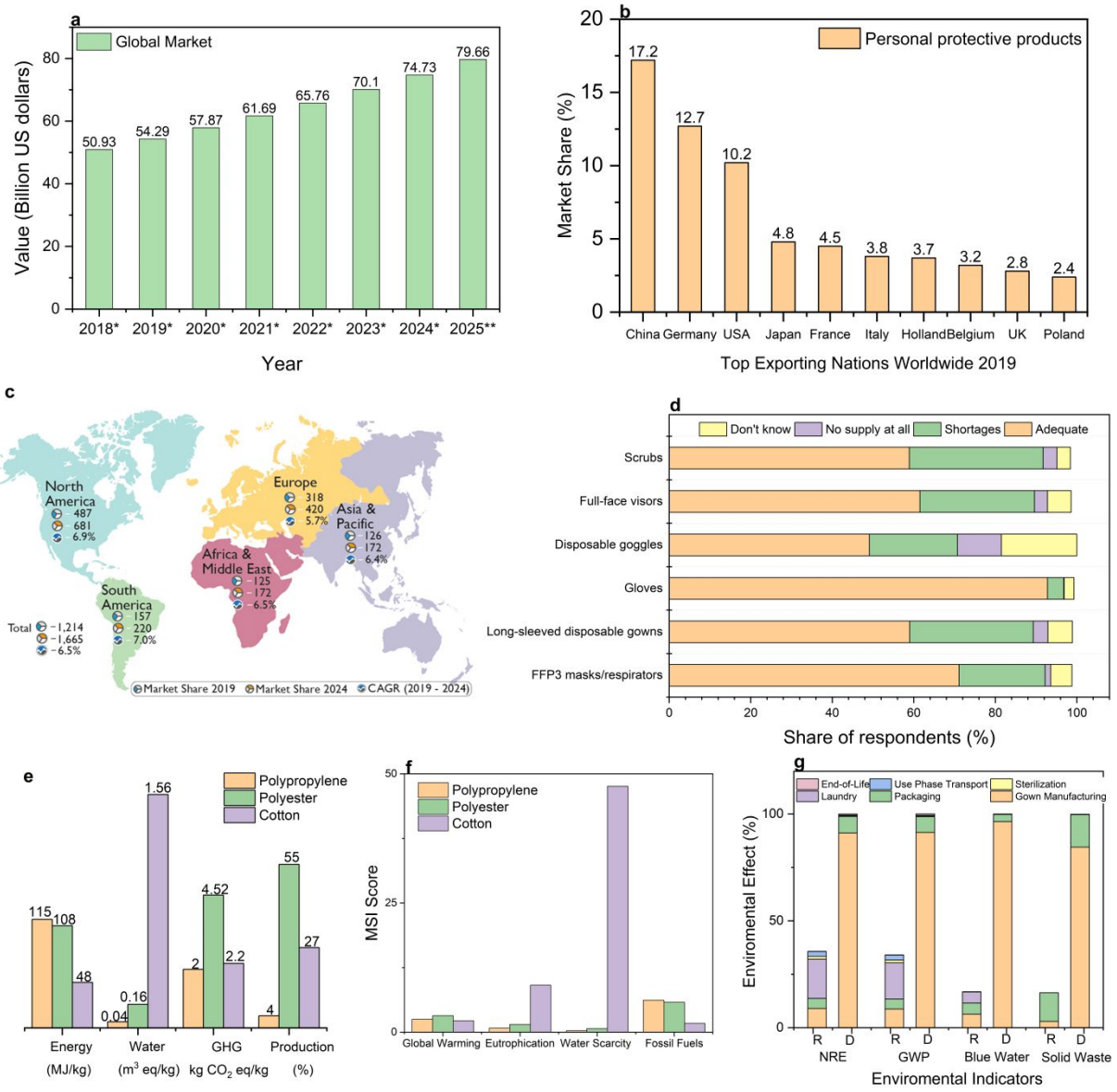

Figure 6. Global personal protective equipment and clothing market and their environmental impacts. *a) Value of the personal protective equipment market worldwide from 2018 to 2025 in billion US dollars (Source: Statistica), b) Share of the leading exporters of personal protective products worldwide in 2019 (Source: Statistica), c) Protective Clothing Market in Healthcare/Medical Industry, By Region, 2019-2024 in USD Million (Source: Market and Market Research) d) PPE supply levels for doctors working in high risk areas in the UK during Covid-19 pandemic as of April 2020, e) Energy consumptions, water consumptions, greenhouse gas emission (GHG) and fibre production for polypropylene, polyester and cotton fibres, (f) Materials Sustainability Index (MSI) score for polypropylene, polyester and cotton fibres and g) Comparison of environmental impact of reusable (R) and*

disposable (D) surgical gowns.[152] NRE = natural resource energy, GWP = global warming potential.

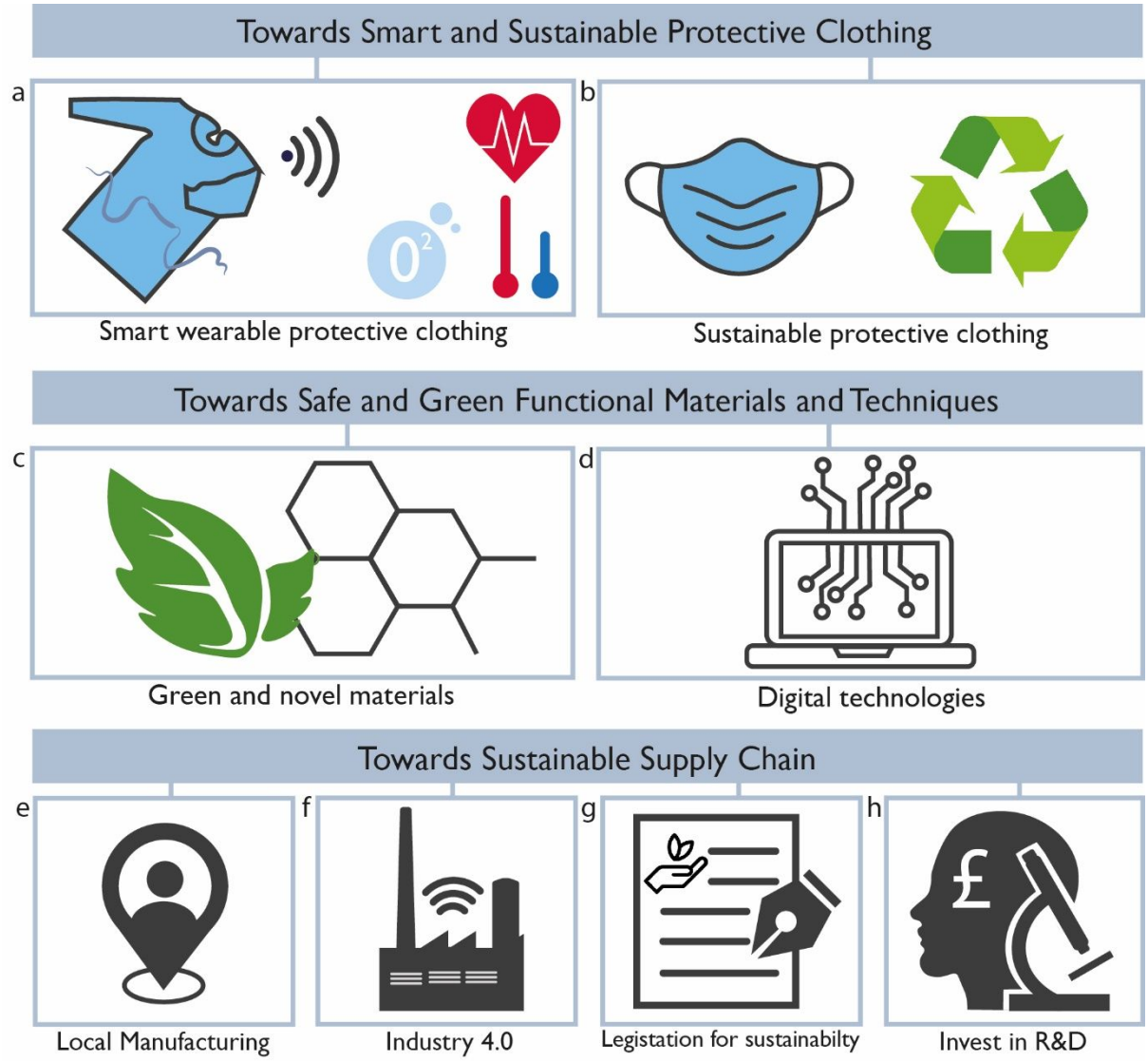

Figure 7. Future research directions and recommendations. *a) Smart wearable protective clothing that can monitor wearer physiological conditions such as temperature, heart rate and oxygen saturation level, b) Sustainable protective clothing which are reusable, washable and recyclable; c) The use of green, natural and novel materials for functional finishes on textiles, d) The use of digital technologies for processing protective clothing. e) Local manufacturing of personal protective clothing for healthcare applications, f) Industry 4.0 for manufacturing of protective clothing, g) Governments legislation for using sustainable PPE and h) Public and private funding in R&D to develop new and innovative technologies.*

Table of Content (TOC)

We review the current state-of-the-art in personal protective clothing used to protect the wearer from highly infectious diseases such as Covid-19. We provide an overview of protective medical fabric manufacturing techniques, their supply chains and environmental impacts with current single-used synthetic fibre-based protective clothing. Finally, we discuss future research directions, which include increasing efficiency, safety and availability of personal protective clothing worldwide without conferring environmental problems.