

Advanced materials used in wearable health care devices and medical textiles in the battle against coronavirus (COVID-19): A review

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Abstract

The novel coronavirus disease (COVID-19) has generated great confusion around the world, affecting people's lives and producing a large number of deaths. The development of portable and wearable devices is of great importance in several fields such as point-of-care medical applications and environmental monitoring. Wearable devices with an ability to collect various types of physiological records are progressively becoming incorporated into everyday life of people. Physiological indicators are essential health indicators and their monitoring could efficiently enable early discovery of disease. This would also help decrease the number of extra severe health problems, in disease avoidance, and lower the overall public sector health cost. Protective clothing is nowadays a main part of textiles classified as technical or industrial textiles. Protective clothing aims to protect its wearer from the harsh environmental impacts that may result in injury or death. Providing protection for the common population has also been taken seriously considering the anticipated disaster due to virus attacks. This review highlights the properties of the materials that are used in wearable health care device and medical textiles.

Keywords

COVID-19, wearable device, health care device, nanomaterials, medical textile, smart textile, sensors, face mask

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Introduction

The novel coronavirus disease (COVID-19) pandemic appeared in Wuhan, China, in December 2019 and has become a serious public health problem worldwide. As the COVID-19 pandemic continues to grow, researchers worldwide have been working to better understand its spread, mitigate, and suppress it. The main areas of research include studying the transmission of COVID-19 and facilitating its detection, developing possible vaccines and treatments, and understanding the social and economic impacts of the pandemic.¹⁻⁵ Also researchers worldwide have been working to provide clothing and protective tools for doctors as well as the nursing staff to provide protection from disease transmission as well as providing comfort and flexibility for ease of work.⁴⁻⁶ In addition to provide tools for patients for ease of household insulation, such as devices for measuring temperature, respiration and pressure.

Wearable devices are devices that can be worn directly on the skin in different parts of the body. These devices have gained great attention due to their ease of collection of important information in real-time regarding a wearer's health, both continuously and non-invasively.⁷⁻⁹ The usage of wearable health care devices also encourages people to take more interest in their own health care in a more useful and cheaper way, thereby improving their compliance. Wearable devices are becoming smaller and more mobile with time, opening novel alternatives to traditional methods that providers have cooperated with patients, carried out tests, collected data, and delivered treatments. Wearable devices come in many forms; there are smart wristbands, watches shirts, shoes, headbands, eyeglasses, shirts, shoes, and necklaces. Most of them have sensors that collect raw data that is fed into a database or software application for analysis. Analysis usually triggers a response that would, for example, alert a physician to contact a patient who is experiencing abnormal symptoms.¹⁰⁻¹² By frequent detection of the level of physical markers, for example, body temperature and pressure pulses using different sensing techniques, wearable devices can provide one of the most comprehensive feedback on human health state.¹³⁻¹⁵

Textile materials contain fibers, yarns, filaments, and different structures of fabrics that are made from natural or synthetic fibrous materials. The applications of textile materials in various fields have significantly enlarged with the development of new fibers and manufacturing technologies for yarns and fabrics. One of the most essential applications of textile materials is in the medical textile industry. In recent years, the results from the tremendous research in the field of material, surface, aerosol science, and engineering have enhanced the textile materials with properties crucial for successful prevention of the spread of infectious diseases, for example, improved filtration, antibacterial and antiviral activity, and breathability.¹⁶ Materials science plays an important role in the effective protection against COVID-19 by numerous means, for instance, disinfection, isolation, and inactivation.^{17,18} Personnel protective equipment kits, such as face shields, masks, gloves, protective suits, and goggles, help in physically isolating the human body from viral infection to stop the spreading of COVID-19.^{19,20} This fact is placing textiles on the front line in the battle against the current pandemic. The textile industry is an important player since many textile companies are presently implementing the production of

protective masks and protective clothing using their production facilities. Another specification of COVID-19 is the exponential growth in the number of new cases that can easily lead to systemic health care failure. Therefore, the World Health Organization (WHO) recommends patients with mild symptoms and without cardinal chronic conditions to be cared for at home while keeping a communication link with the health care personnel. At this time, the smart textile role for sensing and monitoring of body physiological parameters as part of telemedicine could play an essential role. Smart textiles and nanotechnology are promising in tackling the pandemic.^{21,22} In this article, we discuss how advanced materials can contribute to the development of medical textiles as well as wearable health care devices.

Wearable health care devices

Wearable health care devices are a major branch that gradually evolved with the development of wearable devices.²³ It mainly uses multimedia, wireless communication, and sensor technology to collect various physiological parameters of the human body to achieve monitoring of various physical signs of the human body.²⁴ Wearable devices have features such as wearability, mobility, and sustainability that can overcome these shortcomings of traditional medical devices.²⁵

Smart wearable systems are designed to be the next generation of personal mobile devices for remote health monitoring.²⁶ Wearable electronics technology is one of the most important recent innovations that are regularly becoming abundant. Wearable technologies engaged in the health care sector for monitoring physiological parameters include body temperature, physical pressure, blood pressure, respiratory rate, humidity, heart rate (HR), skin conductance, and body movements.²⁷ Some representative examples are mentioned in the schematic of [Figure 1](#).²⁸ Flexible sensing electronics will change conventional diagnosis methods and revolutionize medical instruments by bestowing them with portable, wearable, remote, and timely features.²⁶

Currently, accurately acquiring real-time health signals has been realized in medical institutions, which helps a lot in diagnosing disease and selecting proper medical measures. But, most medical institutions are highly concentrated in central hospitals, making health care services laborious and time-consuming when people were there in large numbers. Patients, especially the ones in the developing areas, may feel more pain and even death for the lack of timely and actual treatment. Moreover, the high cost of purchasing, using, and maintaining these medical facilities also brings heavy economic burden to hospital and patients, which can further hinder the diagnosis and treatment of diseases. Developing wearable sensors for health care-related applications faces a multitude of challenges, which include the selection of suitable substrates, biocompatible materials, and manufacturing techniques, as well as the instantaneous monitoring of different analytes, the washability, and uninterrupted signal display circuits.²⁸

The flexible/stretchable sensors involve three basic components: containing substrate, active element, and electrode/interconnect. The organic materials have excessive mechanical flexibility and chemical stability, but very few of them expose favorable active characters. While, traditional inorganic electronic materials are sensitive to many stimuli,

but not competent to mechanical compliance due to their rigidity and fragility. So, the collaboration between different materials can be a solution to compacting high measuring performance, flexibility/stretchability, and mechanical robustness in one device. The novel approaches in material preparation, such as scaling down measurement and manufacturing composites, can be useful in device development. The next parts will focus on the commonly used materials and their participation in substrate, active element, and electrode.²⁹

Materials selection for wearable health care devices

In the past few years, the configurations of wearable systems with unique sensing materials and device structures have proved to be highly sensitive in simulating human somatosensory systems and to be able to easily and non-invasively track biophysical and biochemical signals such as body temperature, body movements, blood pressure, metabolites, functional proteins, and oligonucleotides.^{30,31} In addition, these wearable health care systems can not only improve health status, but also contribute greatly to the development of medical technology by collecting human health information into a system and collecting large amounts of data.³²

However, compared with the rapidly growing wearable device market, the development of wearable health care systems used in practical applications is slow, which can be attributed to the following challenges. Firstly, the health care system must be wearable, combined with skin or human body surface, with compatibility, durability, and abrasion resistance.³³ Hence, brittle materials and integrated circuit technology usually used in

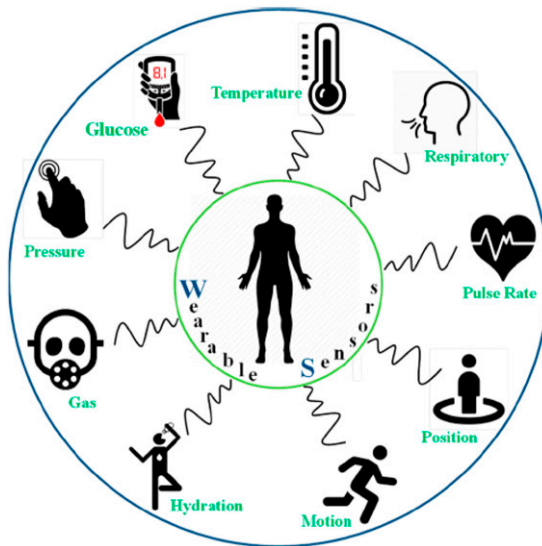


Figure 1. Schematic representation of wearable health care sensing devices.²⁸

semiconductor industry are not feasible. Secondly, the human body has very complex attributes. Recently, several good overviews have been reported on the advanced achievements in wearable sensors for health monitoring.³⁴ Although material selection is an important issue in fabrication of different types of sensor, it has found a crucial role in fabrication of wearable health sensors. Owing to the applications of wearable health sensors, material selection significantly affects the performance of the sensor. Literature investigation indicates that different types of materials have been proposed for fabrication of prototypes suitable for different applications. It is noteworthy that based on the diversity of sensor technologies, sometimes demands can be answered via more than one type of sensor. This issue can affect the research and planning of wearable sensor materials, though this material selection ought to satisfy not only technical and metrological features but also economic criteria. In Figure 2, main criteria and some relevant sub-criteria in material selection of wearable health sensors are shown. It includes technical properties of the material, metrological, and economic issues. However, based on application of the sensor, other properties, such as elastic linearity, accuracy, and manufacturing aspects must be considered.³⁵

Materials used for wearable health care devices

In the recent years, the application of brittle and hard metals and silicon in wearable device needing large deformation has been limited. Table 1 includes a representative list of well-known, traditional materials that have been used in biomedical systems. A stretchable sensor with high performance and elastic mechanical response is an ideal choice for the next generation of health care applications.³⁶ Commonly, metal foils, rubber, and elastic polymers are widely chosen as substrates because of their great mechanical elasticity, good chemical resistance, and thermal stability.^{37,38} For flexible wearable sensors, utilizing a flexible substrate is necessary in order to impart stability to the active material. In this respect, polyurethane, polydimethylsiloxane (PDMS), polyethylene naphthalate (PEN), polyethylene terephthalate (PET), and polyimide (PI) are most commonly used

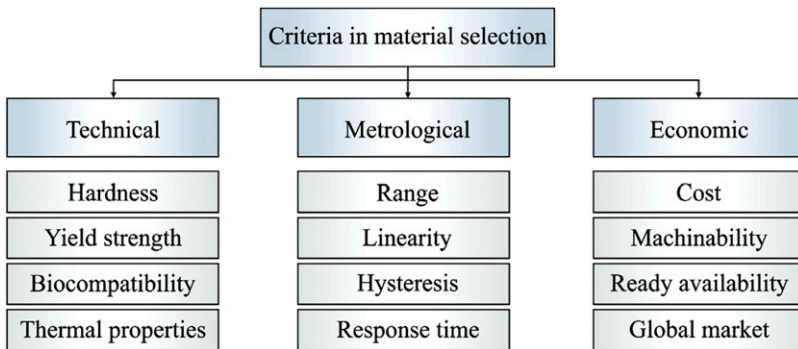


Figure 2. Main criteria in material selection for wearable health sensors.³⁵

flexible substrates in wearable sensors for health monitoring.³⁹ Most of the polymeric materials are soft, lightweight, RF-transparent, and low cost, and hence can address the current challenges associated with metallic and ceramic materials for implantable electronics.⁴⁰

Table 2 summarizes the list of applications of several important polymeric materials in flexible electronics. In addition to synthetic substrates, some natural materials have also been opened for manufacture of wearable system substrates. Biomaterial is the largest material system in nature. It has good biocompatibility, biodegradability, versatility, sustainability, and low cost.⁴¹ Fibers and textiles are ideal for wearable sensing systems because they are supposed to be the closest natural materials to human skin. For instance, natural silks are not only an abundant and attractive biomaterial, but also satisfy the mechanical requirements of irregular deformation.⁴² The next generation of wearable devices is expected to perform functions including recording more accurately. Therefore, all kinds of advanced materials will promote the innovation of wearable equipment with unique functions quickly, continuously, and predictably. Appropriate assembly methods and materials are essential for acquiring wearable sensors with good stability, high sensitivity, and strain range. In recent years, different kinds of materials, including nanowires (NWs,) metal nanoparticles (MNPs), conductive polymers (CPs), and carbon materials, have been widely used to manufacture wearable health care devices due to their remarkable mechanical and electrical characteristics.^{43–45} Compared with other candidates, advanced carbon-based materials such as carbon black nanoparticles (CBNPs), carbon-based nanofibers, graphene, and CNTs have unique advantages, including high chemical and thermal stability, good electrical conductivity, and easy to be functionalized, which give them great potential in wearable electronic products and applications.^{46,47} Graphene is another important carbon-based material for developing wearable health care systems. Because of its small size, strong mechanical properties, and excellent electrical conductivity, it can be used as an active sensing material for flexible sensors.⁴⁸ Inorganic nanomaterials with strong adaptability, large surface area, excellent sensing performance,

Table I. A summary of the traditional materials with applications in bioelectronics.³⁶

Materials	Properties	Device component	Applications
Silicon	Compatible with microfabrication	Substrate	Intraocular pressure and cardiovascular monitoring
Silicon	Compatible with microfabrication	Structural diaphragm	Blood pressure and shunt pressure sensor
Silicon oxide	High-quality factor	Structural diaphragm and substrate	Surface acoustic wave blood pressure sensor
Silicon nitride	Thermally stable	Dielectric layer	Orthopedic sensor
Silicon nitride	Thermally stable	Insulation layer	Cerebrospinal fluid flow monitoring
Stainless steel	Compatible with stents	Substrate	Capacitive pressure sensor

and compatibility with low-cost manufacturing process are widely used as components for the development of wearable sensors.^{49,50}

Metal possesses excellent electrical conductivity and has been widely used in wearable sensors. Specific to active material, metal often appears in the following forms: (1) nanowires or particles; (2) flexible or stretchable configurations; and (3) liquid state at room temperature. Nanowires (NWs) and nanoparticles (NPs) are often taken advantage of as fillers to prepare piezoresistive composites and conductive ink. Currently, a wide variety of nanomaterials have been used in fabrication of wearable temperature sensors. More in deep, graphene, conductive polymers, CNTs, nickel, and copper metal nanoparticles have been utilized as thermal sensing element.^{51–54} For flexible wearable sensors, utilizing a flexible substrate is necessary in order to impart stability to the active material. In this respect, polyurethane, PDMS, polyethylene terephthalate, Ecoflex, and polyethylene naphthalate are the most commonly used flexible substrate in wearable sensors for health monitoring.³⁹ As most of the wearable health sensors are in connection with human skin, utilizing biocompatible materials is a vital issue. In this area, both inorganic piezoelectric materials (e.g., zinc oxide, lead zirconate titanate, and lithium niobate) and organic ones (e.g., poly-L-lactic acid, polyvinylidene fluoride, and poly-D-lactic acid) are biocompatible. These have been used in fabrication of piezoelectric sensors.^{55,56} It is notable that piezoelectric polymers have garnered noteworthy attention because of low-cost and ease of use. In wearable electromechanical sensors, polyvinylidene fluoride is the most extensively used flexible piezoelectric material. This material offers unique physical properties and semi-crystallinity, to its compact linear molecular structure. In addition to the mentioned inorganic and organic piezoelectric materials, silk is a flexible, natural, and great material for utilizing in textile-based wearable sensors. Based on piezoelectric property of silk, it can be used in different types of wearable sensors.⁵⁵ Table 3 (which is relevant throughout the previous paper) contains a condensed summary of details extracted from the literature, including information on materials, properties, general applications, and fabrication process.²⁸

Table 2. Summary of organic materials with applications in biomedical devices.

Materials	Properties	Device component	Applications
PDMS	Low modulus, high dielectric strength, and low chemical reactivity	Dielectric layer	Pressure and oxygen sensor in blood
		Substrate layer	Physiological recording
PVDF	Piezoelectricity	Structural diaphragm	Intracranial and endovascular pressure monitoring
		Substrate layer	Intraocular and cardiovascular pressure monitoring
Polyimide (PI)	High heat resistance	Structural diaphragm	Intraocular pressure monitoring

PDMS: polydimethylsiloxane; PVDF: polyvinylidene fluoride.³⁶

Table 3. Summary of representative materials, substrates, mechanisms, and fabrication procedures.²⁸

Sensor type	Materials	Substrates	Mechanism	Fabrication
Respiratory/ breath	Graphite, SiO ₂ , Graphite	Cellulose Acetate	Humidity	Hand-painting
	Silicon-nanocrystal	Paper	Conductometric	Hand-painting
	CNTs	PI	Humidity	Spin coating
	PVDF-TrFE	PDMS	Strain Piezoelectric	Laser Scribing
	ZnO, Au	PDMS	Impedance	Molding E-beam, Sputtering
Temperature	CaCl ₂ , Aliphatic	PI (nanoporous)	Conductometric	Injection
	Diols	PLA	Resistive	Transfer Printing
	Graphene, Ag,	PET	Resistive	Inkjet Printing
	PDMS	Polyurethane	Resistive	Printing
Pressure and strain	Graphene/PEDOT-PSS			
	MWCNTs, Al ₂ O ₃ ,	PI	Pressure/TFTs	ALD Vacuum
	Cu, CNTs	PDMS	Piezoresistive	Deposition Casting
	Conductive self-healing	PDMS	Piezoresistive	3D printing
	hydrogel	PI	Piezoresistive	E-beam evaporation
	SWCNT/paper, Au,			
Hydration	PDMS			
	Graphene, Ag/AgCl	PMMA	Impedance	Wet transfer, Dry
	Ag, PDMS	PDMS	Impedance	Patterning
	Ag/AgCl	PET	Electrochemical	Drop Casting
Pulse rate	Graphene oxide	PET, PI	Conductometric	Screen Printing
	PEDOT-PSS,	PEN	Piezoelectric	Transfer printing
	PVDF-TrFE	PI	Piezoelectric	Screen printing
	PVDF-TrFE, Al, Ag	Fabric (facemask)	Piezoelectric	Drop casting
	Graphene oxide, Au		Humidity	

(continued)

Table 3. (continued)

Sensor type	Materials	Substrates	Mechanism	Fabrication
Gas sensors	AgNPs, Carbon, CNT Reduced graphene Oxide Ag, Au	Silk PET PI	Chemiresistive Chemiresistive Chemiresistive	Spray and Drop Coating Drop casting, Spin coating Inkjet printing
Alcohol/acetone	ZnO, TiO ₂ , Cu Au, ZnO ITO, ZnO	Alumina PI PET	Chemiresistive Chemiresistive Chemiresistive	Screen printing E-Beam, sputtering Drop casting, Laser ablation
Motion and activity Monitoring	Carbon black Carbon, Ag MWCNT, Cu MWCNTs,	Polyurethane PDMS, Cotton PDMS Polyurethane	Strain, conductivity Strain Piezoresistive	Drop and dry Impregnation, Casting Casting 3D printing

Wearable health care devices and COVID-19

In the COVID-19 pandemic, wearable health care devices and nano-biosensors have gained significant publicity because of the contactless-based health care instructions. The wearable sensors are capable of measuring vital signals of the human physical body, for example, body temperature, respiratory rate, heart rate, blood pressure, skin coloration, sleep duration, and body motion. These measured parameters are clinically essential and can be gained through contactless processes.⁵⁷ The wearable technology achieves a substantial role in the discovery of COVID-19 symptoms to assist the patients infected by this unusual virus. There are three signs that can be considered as key of coronavirus symptoms. These are respiratory distress/difficulty, fever, and cough.⁵⁸ These signs are universal to all the clinical demonstrations of COVID-19. Hence, it is vital to assess respiratory, cardiovascular monitoring, and estimation of other parameters as body temperature and oxygen saturation (SpO₂). Various investigations have been conducted based on the usage of wearable health care devices to handle the COVID-19 pandemic. [Figure 3](#) offers an overview of the wearable assistive technology for the patients infected by COVID-19.⁵⁹⁻⁶⁴

Temperature measurement is very important for COVID-19 detection and has been used by many countries as an instant test to conclude if citizens have been infected with COVID-19. Many researchers have already offered wearable health care devices for continuous body temperature monitoring which can be intended for COVID-19 patients. Liu et al.⁶⁵ offered a wearable device as a physiological monitoring system that monitors body temperature, electrocardiography (ECG), blood pressure, and some other physiological parameters. The proposed device is easy to use, and especially developed for home application that can be used for COVID-19 patients. Song et al.⁶⁶ suggested a wearable system based on multiple artificial neural networks which monitors the body temperature very precisely with squatter reaction time. Zakaria et al.⁶⁷ established the

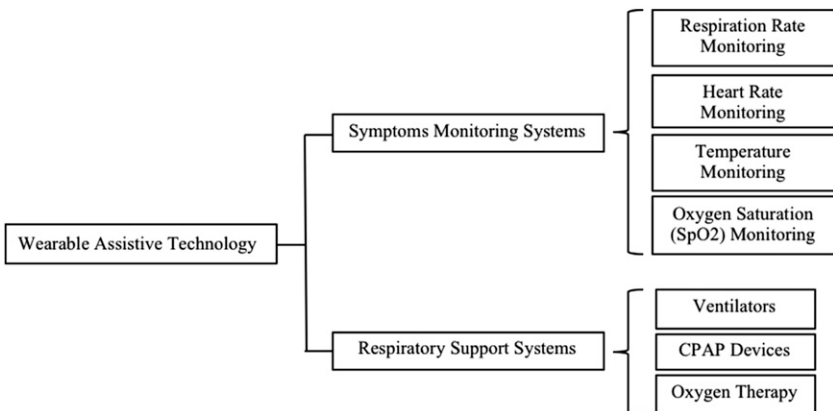


Figure 3. Overview of the wearable assistive technology for the patients infected with COVID-19.

Internet of Things (IoT)-based body temperature monitoring, particularly for infants. The proposed device is lightweight, very small in size, and continuously monitors the body temperature and can be comfortably used by the baby. Kulkarni et al.⁶⁸ proposed another IoT-based device named Health Companion using wearable computing which monitors the temperature and pulse. This proposed device aims to determine and collect different parameters of the human body. This assists the users to monitor their physical condition and aids the doctors to closely study the patients' ailments. This device can be used for fever tracking for the period of illness.

Respiration rate (RR) for respiratory assessment is one of the greatest crucial parameters in COVID-19 infection finding as the virus has a severe effect on the lungs area. Liu et al.⁶⁹ suggested an RR system which is used to be located on the upper lip which is mainly a flexible epidermal respiratory system based on the thermal convection. Charlton et al.⁷⁰ suggested a system for RR estimation from electrocardiography (ECG) and photoplethysmogram (PPG) which improved the estimation accuracy. The advantage of the system is that it can be incorporated into commercial wearable health care devices, thus adding RR monitoring functionality in existing systems. Therefore, this technology would be very efficient for COVID-19 patients to monitor their RR. Tamilselvi et al.⁷¹ suggested a system for health monitoring which can monitor primary metrics of a patient, for example, body temperature, heart rate, eye movement, and percentage of oxygen saturation. Xue et al.⁷² established a wearable health care device that continuously monitors SpO₂ and body temperature in real-time. Jarchi et al.⁷³ proposed a wearable health care device for heart rate variability (HRV) and SpO₂ estimation which used commercial wrist-worn pulse oximeter for attaining accurate results. Mujawar et al.⁶² discuss the nano material-based biosensor for health care monitoring and diagnosis of COVID-19 in supposed patients. The nano-biosensors contain the geno sensor and immuno sensor that are embedded on-chip to execute assessment of COVID-19 patients. The data collected from the sensors are additionally analyzed through artificial intelligence (AI) supported data processing and analysis algorithms. Interfacing of nano sensor-based bio chip with the IoT is identified as the Internet of Bio-Nano Things (IoBNT). This IoBNT can be used in many ways, for example, data sharing with other medical and health care centers across the globe, contact tracing, faster assessment of COVID-19 infection, quarantine management, and targeted COVID-19 patient sensing.

Wearable technologies enable the continuous monitoring of human physical activities and behaviors as well as physiological and biochemical parameters during daily life. Hence, wearable technologies have demonstrated a tremendous ability in dealing with infectious diseases like the new corona virus. There is no doubt wearable technologies can not only act as an early warning but also as lifesaving devices. When we go out from this crisis, it is very important that we should continue our undivided attention and research into these paradigm changes and technologies.

Medical textiles

Medical textiles refer to a textile structure, which has been produced for use in any of a variety of medical applications. Medical textiles are a major growing area within the scope

of technical textiles, which is defined as textile materials and products manufactured mainly for their technical performance and functional properties rather than their esthetic or decoration characteristics. Technical textiles include, in addition to medical textiles, marine, military, aerospace, industrial, safety, and transport textiles.⁷⁴ Generally, textile materials have many special characteristics, for example, air permeability, strength, extensibility, flexibility, and availability in three-dimensional structures, variety in fiber length, fineness, cross-sectional shape, and absorbency. These features sort them suitable materials for medical applications. On the other hand, in some cases, different designs and characteristics or a combination of several features are required.⁷⁵ Hence, it is necessary to develop the characteristics of a product based on its end use. High surface areas, absorbency characteristics, and large diversities in product forms donate to the emergence of additional smart products in the medical textile industry.

A number of surface modification and finishing techniques can considerably enhance some specific characteristics of textile materials such as blood coagulation, wound healing, anticoagulation, water and blood absorption, antimicrobial, and so on. Moreover, by using these modern technologies, we can impart improved multifunctional properties to a certain textile-based product. There are different applications for medical textiles including the application such as wound dressing, hygienic, and personal care products. In addition, hospital textiles such as bedding, clothing, surgical gowns, and hospital cloths are expected to fulfill comfort and hygienic properties such as moisture management, thermal conductivity, breathability, antimicrobial activity, and odor resistance.^{76,77} The classification of medical textile is denoted in [Figure 4](#).⁷⁸ Extensive progress in tissue engineering and nanotechnology has had a great influence on advanced medical textile products in these areas. On the other hand, the developments of biomaterials, nanomaterials, and biotechnology have led to fabrication of new polymers, hydrogels, composites, and fibrous structures with unique characteristics for different medical applications. Subsequently, with these developments in textile and medical industry, the risk of health care associated-infection and contagious diseases will decline. In contrast, patient compliance with medication and treatment and standard of living will grow.⁷⁹

The market for functional textiles is steadily increasing due to the increased interest among people in personal health and hygiene products and a decrease in disposable time. On most of the occasions, natural fibers such as cotton, silk, lyocell, and other regenerated fibers are used to make the medical textiles. Due to the limitations of natural fibers in medical textiles, synthetic fibers were used for durable applications in the medical industry. Recently, the most widely used synthetic fibers in medical textiles are polyester, viscose, polyamides, and polypropylene. They are enormously improving and their blends are used for developing new products. [Figure 5](#) shows that a chain of traditional textile transformation processes fibers composed of natural or synthetic polymers are turned into yarns, followed by being woven or knitted into fabrics and additional fabricated into specific products, containing apparel.⁷⁸

New production methods have also been developed to create fibrous structures other than woven and knit. For example, nonwoven technology has aided the manufacturing of fabrics without the yarn spinning process, which not only significantly reduces production cost but also causes the end products to have porous and greatly absorbent structures to

meet the requirement of hygiene products. The technology of electrospinning permits the production of ultrafine fibers in the size of nanometers, which is way beyond the capacity of traditional fiber spinning technology. Mixture of a fibrous material and another material such as polymer, metal, or ceramic helps produce various kinds of composite materials that will bring about a synergy between two dissimilar materials.^{80,81} Nanoparticles of metal oxides and ceramics have been used to vary surface properties and to impart textile functions. Photocatalytic activity of metal oxide nanoparticles such as TiO₂ and MgO can destroy toxic chemicals and decompose organic matters in the air such as odor molecules, bacteria, and viruses. Moreover nanoparticles can convert fabrics into sensor-based materials, thus assisting them to convert exerted mechanical forces into electric signals and can therefore be used to monitor bodily functions such as heart rhythm and pulse if worn next to the skin.⁸² Nanotechnology deals the possibility of representation textiles certain properties that protect humans and their natural environment. Nanotechnology use in textiles further allows for the control of crystal structure, enhanced mechanical properties, enhanced resistance to chemicals, microbes, flame and heat, enhanced electrical properties, enhanced coloration, and production of self-cleaning clothing.⁸³

Textiles have been improved using polymeric nanocomposites and metallic and inorganic nanostructured materials. Preceding researches have revealed bulk modification of filament yarns by various concentrations of nanocomposites fillers like Ag–Zn and Ag–TiO₂, and various polymer powders by using different mixing methods. Nano titanium dioxide has been used to develop wrinkle resistance of cotton fabrics.⁸⁴ Earlier, resin was used to impart wrinkle resistance, but it causes a reduction in abrasion resistance, tensile strength, and water absorbency. ZnO nanoparticles have been used to remove the UV component of sunlight, thereby decreasing the fading rate of the dyes used for textiles.⁸⁵ TiO₂ nanoparticles have been used with Ag to produce bactericidal textiles. The fabric

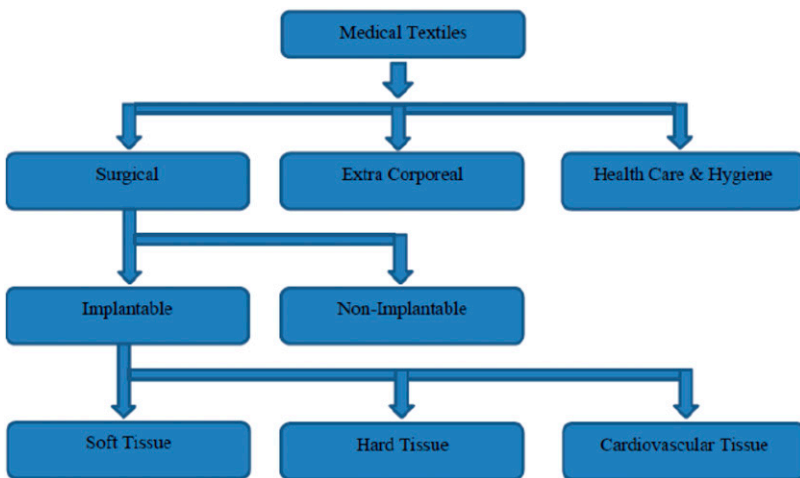


Figure 4. Classification of medical textiles.⁷⁸

modified with TiO_2 is treated at a specific temperature to activate the bactericidal property and Ag was deposited on the activated cotton or polyester. This increases the bonding capacity of TiO_2 and Ag with the textile surface by the induction of surface oxygen functionalities. Biocidal cotton bandages coated with CuO nanoparticles revealed killing of *E. coli* bacteria. Nanoactive materials have been confirmed to not only adsorb but also destroy a variety of chemicals containing chemical and biological warfare (CWA) and its simulants. New materials and methods for combining protective chemical additives into advanced fabrics are being established and tested for new-generation protective clothing that will provide barrier protection and detection, trapping, and decontamination of toxic particles, liquids, and vapors that contact these advanced fabrics.⁸⁶

Smart textiles for medicine and health care

Current advances in nanotechnology, electronics, materials science, and the collaboration between scientists in these fields have caused the development of intelligent or smart textiles that can sense and/or respond to mechanical, light, thermal, chemical, electrical, and magnetic stimuli. This is possible because of, these stimuli are able to change the appearances (e.g., color) and/or structures of the smart materials integrated into the textiles during their fabrication, these changes will produce a warning signal (e.g., a flashing light). Smart textiles might have application in such end uses as sports/recreation or special work wear for first responders or for consumption in extreme environments (e.g., space exploration), where early signals of distress would aid timely interventions. Smart textiles for health care contain textile sensors, actuators, and wearable electronics systems implanted into textiles that enable registration and transmission of physiological

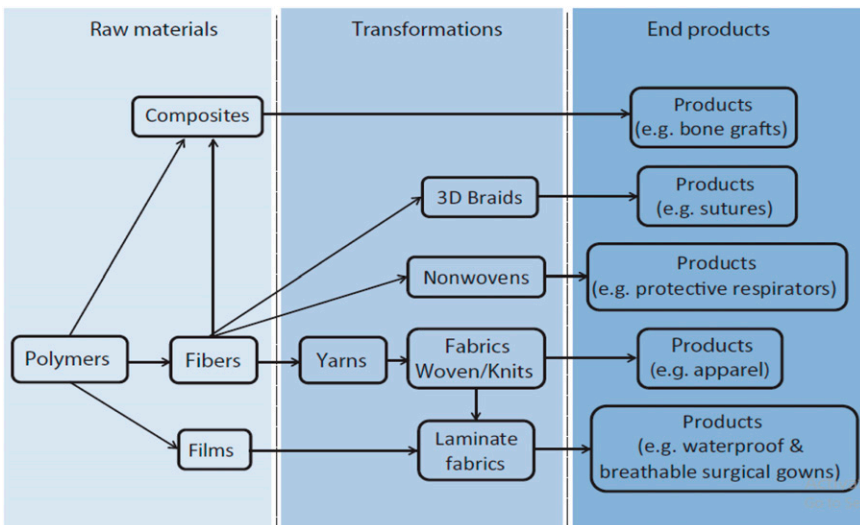


Figure 5. Process of medical textile production from polymers.⁷⁸

data and wireless communication between the wearer and the operator, for example, patient and medical personnel. Such systems make sure patients' mobility, thereby providing a greater level of psycho-physiological comfort, especially when a long-term bio-monitoring is required. Table 4 summarizes main applications fields of smart medical textiles.^{87,88} Smart devices made from intelligent textiles are estimated to provide remote monitoring of a patient's physiological and physical data and signs through non-invasive sensors implanted in clothing materials. These data or signs may be used to support diagnosis and personalized management of chronic diseases like diabetes, arthritis, lung and heart disease, and hypertension. Such technologies allow patients to be treated at home instead of hospitals; they also allow quick detection of diseases and timely treatment.^{89,90}

Smart materials

Smart materials find application in hospital textiles and clothing for medical personnel. Moreover, functionality of these textiles can be obtained by different approaches according to specific applications. For this type of medical textiles though, functional textiles bring most solutions. For hospital textiles, those normally are textile materials with antimicrobial and antibacterial properties or low friction coating. Clothing for medical personnel is also made of functional textiles that assure efficient moisture transport and biological protection. However, conductive textile materials are more often used in fabricating of heating textiles that find applications in blankets for operating rooms. Moreover, conductive textile materials can be a benefit in improvement of distanced communication between medical personnel and patients through wearable technologies integrated into clothing. In addition, smart textiles deal solution for decubitus prophylaxis and associated health disorders which are a significant problem in the

Table 4. Applications of smart textiles for medicine and health care.⁸⁹

Application	In vitro	In vivo
Surgery	Bandages Wound care	Sutures Soft tissues Orthopedic implants Cardiovascular implants
Hygiene	Uniform for medical personnel hospital textiles	—
Drug-release systems	Smart bandages and plasters	—
Bio-monitoring	Cardiovascular and hemodynamic activity Neural activity Muscle activity and kinematics Respiratory activity Thermoregulation	—
Therapy and wellness	Electrical stimulation therapy Physiotherapy Auxiliary systems Active thermoregulation systems	—

hospital environment. Currently, there are already a number of developments that contribute in managing these difficulties through innovative and smart textile solutions. Namely, those can be instigated by stimulating blood flow in sensitive areas through textile-based sensors and systems, optimizing and controlling moisture management through textile sensors.⁸⁷ The most communally used materials for the sensor implementation are conductive textile materials. These materials can be yarns that ensure manufacturing of textile electrodes through such conventional textile manufacturing technologies as weaving, knitting, and embroidery. Another approach offers solutions implemented through inkjet and screen printing and thin film technologies such as sol-gel and sputtering methods.⁹¹ The textile electrodes fabricated by the mentioned conventional techniques demonstrate via higher efficiency in performance and usage (washing).

Medical textiles and COVID-19

From the time when the coronavirus outbreak started, the demand for personal protective equipment (PPE) has increased.⁹² PPE like protective suits, masks, gloves, face shields, and goggles aids in physically isolating the human body from viral infection. PPE is considered an important infection control measure.^{93,94} It has become a new normal in many societies in the COVID-19 pandemic. The surge in demand for surgical masks and respirators has led to a global shortage of resource and raw materials. Therefore, many people have resorted to produce their own masks, recycling used masks, or settling for masks providing less protection than actually needed. Researchers and industry actors have been working hard to address the issue of shortage as well as to enhance the protection afforded by existing mask models. These efforts include sourcing and engineering alternative materials with sufficient filtering capacity, engineering the design of masks and respirators for better protection, and user comfort, emergent and engineering multifunctional masks and materials with hydrophobic, self-disinfecting, antimicrobial and even sensing properties, and exploring novel technologies for efficient production and customization of masks.^{95,96}

Materials science plays an essential role in the effective protection against COVID-19 virus by different means like isolation, disinfection, and inactivation.⁴ In the recent years, several studies have stated the filtration performance of natural polymer-based electrospun nanofiber membranes which established their potential to be used for filtration applications. Akduman et al.⁹⁷ informed that as the fiber diameter decreases, the most penetrating particle size decreases and the capture efficiency of the utmost penetrating particle size rises. Nanofibers could be the main elements for filter materials in face masks or respirators. They have very great surface area per unit mass that improves capture efficiency and other surface area-dependent phenomena that might be engineered into the fiber surfaces. They might improve filter characteristics for capture of naturally occurring nanoparticles such as viruses, as well as micron-sized particles such as bacteria.

Zhu et al.⁹⁸ stated that the filtration membrane developed with chitosan-based natural biopolymer displayed excellent air and microbial filtration, while the addition of silica nanoparticles to the membrane improved the roughness, which more enhanced the

filtering efficiency. Ahne et al.⁹⁹ stated 99.8% filtration efficiency of the electrospun cellulose-based nanofiber. Leong et al.¹⁰⁰ proposed cellulose-based nanofiber as a viable filtration medium over N95 masks. Soybean protein-based nanofiber textile was settled by Souzandeh et al.¹⁰¹ Desai et al.¹⁰² established chitosan and polyethylene oxide-based filter media using the electrospinning process whereby the properties were considered as a function of varying chitosan fiber content and fiber diameter. The investigation revealed that the size and content of the chitosan fibers were the dominant factors that influenced the filtration performance. Wang et al.¹⁰³ compared the characteristics of silk nanofiber air filter membrane to the commercially existing KN90 respirator as well as the polypropylene nanofiber membrane. The silk nanofiber membrane revealed the same filtration characteristics as the commercially existing filter membranes. The findings of the study suggested the use of silk nanofiber as a suitable alternative to the petroleum-derived polypropylene for fabricating the air filter medium. Furthermore, some investigations reported the use of hybrid nanofibres in air filter applications in the current years.^{104,105} Developing a hybrid natural polymer-based biodegradable filter medium can boost the filtering properties and also help to achieve the preferred water resistance, microbial resistance, and mechanical strength properties.¹⁰⁶ These findings establish the potential of the natural polymer-based nanofibres for use in air filtration applications that also may be considered to construct the filter material for face masks. Konda et al.¹⁰⁷ verified multiple layers of silk, chiffon, and observed enhancement in filtration efficiency when more layers were stacked. They also tested several types of hybrid samples and establish that filtration efficiency enhanced slightly when cotton was used in combination with chiffon or silk, while the benefits from using polypropylene or cotton quilt were more noteworthy.

Hao et al.¹⁰⁸ studied household air filters, vacuum bags, and coffee filters in adding to cloth materials. They detected that the performance of multiple layers of household air filter was comparable to N95 respirators or KN95 masks in terms of both filtration efficiency and flow resistance for particles in the range of 10–600 nm size. Drewnick et al.¹⁰⁹ also stated that the performance of vacuum bag for particles in the range of 0.02–10 mm size was comparable to N95 respirators among the 44 household materials tested in their investigation. Zhang et al.¹¹⁰ fabricated an efficient air filter based on ionic liquid polymer (ILP) composite that was dispersed on the spongy network of melamine-formaldehyde (MF). Such type of masks retains nanofibrous filter which may filter out even nano sized particulates and let clean air for comfort in breath. In another investigation, a specialized mask was fabricated by combining a layer of cotton along with a layer of chargeable natural silk.¹¹¹ The removal mechanism involves the combined action of mechanical and electrostatic filtration.

In recent times, we faced the problem of shortage of PPE kits for the duration of COVID-19 pandemic. Hence, the development of reusable masks, gloves, and other PPE is in continuous thrust. Tebyetekerwa et al.¹¹² suggested the use of durable and yet reliable electrospun nonwoven filters with very small fiber diameters. The filter may be processed by suitable disinfection methods and protocols to achieve reuse without compromising the filtration efficiency. Beyond these, future face masks need to be antiviral as well as

veridical. The present electrospinning technology is mature making the recommended strategy relatively low-cost with mass production capacity.

The surface treatment or the surface coating offers self-cleaning ability to the gloves, masks, and protective suits and consequently, made these protective tools reusable.^{113,114} Therefore, the filter of gloves, masks, and protective gown can be coated by graphene oxide to disinfect the virus. More recently, it has been stated that graphene coating increases the hydrophobicity of the surface of masks that restricts the viability of the virus on its surface. Furthermore, such type of graphene-coated masks can be reusable due to its excellent photothermal properties that make these masks self-sterilized in the exposure of sunlight.¹¹⁴ Atab et al.¹¹³ manufactured a polymeric membrane made of polyamide with intrinsic hydrophobicity which may easily bounce off the aqueous droplets of virus. Apart from hydrophobic surfaces, sunlight sterilization feature was also incorporated in a membrane, as settled by Zhong et al.³⁵ For this purpose, graphene-coated masks have been prepared with highly hydrophobic surface and excellent photothermal properties, due to which the temperature of the outer layer of mask reaches 80°C and accordingly becomes sterilized in sunlight.¹¹⁴

Recent efforts have demonstrated the potential of reusable mask development enabled by material innovation and technology advancement in addressing the mask shortage while reducing the greenhouse gas (GHG) emissions and negative environmental impact. However, continuous efforts are needed to ensure feasible developments can be transit to existing manufacturing facilities. In addition, there are more scientific opportunities to progress new and environmentally friendly mask materials with functions of interests, such as self-sanitizing and degradable materials, and to develop a low energy consumption technique or process for a nonwoven fiber that could replace a carbon-intensive melt-blown process in the near future.⁹⁶

Summary

The novel coronavirus disease (COVID-19) has caused great confusion around the world, affecting people's lives and producing a large number of deaths. The development of portable and wearable devices is of great importance in several fields such as point-of-care medical applications and environmental monitoring. Wearable technologies employed in the health care sector for monitoring physiological parameters include body temperature, physical pressure, blood pressure, respiratory rate, humidity, heart rate (HR), skin conductance, and body movements. High performance and reliable wearable health care monitoring system requires flexible/stretchable sensors with different performances, containing the basic ones (sensitivity, linearity, hysteresis, response time, and durability) and specific ones (self-power, wireless communication, biocompatibility, and biodegradability). Continuing progress in the enhancement and combination of these properties has been further exciting the wearable sensors to appear in more health care applications. However, some challenges still exist in the intellectualization, the systematization, and mass production of wearable health care devices. The application of natural materials may afford more low-budget options and further diminish the economic burden. Wearable technologies allow the continuous monitoring of human physical activities and behaviors,

as well as physiological and biochemical parameters during daily life. Hence, wearable technologies have demonstrated a tremendous ability in dealing with infectious diseases like the new corona virus. There is no doubt wearable technologies can not only act as an early warning but also as lifesaving devices. When we go out from this crisis, it is very important that we should continue our undivided attention and research into these paradigm changes and technologies.

In recent years, the results from the tremendous research in the field of material, surface, aerosol science, and engineering have enriched the textile materials with properties (improved filtration, antibacterial and antiviral activity, breathability, etc.) crucial for successful prevention of the spread of infectious diseases. This fact is placing textiles on the front line in the fight against the current pandemic, and the textile industry is an important player since many textile companies are currently implementing the production of protective masks and protective clothing using their production facilities. Another specification of COVID-19 is the exponential growth in the number of new cases that can easily lead to systemic health care failure. Therefore, WHO recommends patients with mild symptoms and without cardinal chronic conditions to be cared for at home while keeping a communication link with the health care personnel. Here, the smart textile role for sensing and monitoring of body parameters as part of telemedicine could play an important role. Nanotechnology and smart textiles are promising in tackling the pandemic. Nanotechnology offers the possibility of rendering textiles certain properties that protect humans and their natural environment. Nanotechnology use in textiles further allows for the control of crystal structure, enhanced mechanical properties, enhanced resistance to chemicals, microbes, flame and heat, enhanced electrical properties, enhanced coloration, and production of self-cleaning clothing. Smart textiles find multiplicity applications and own sensing and actuating functions that can be professionally used in medicine. Finally, smart devices made from intelligent textiles are estimated to provide remote monitoring of a patient's physiological and physical data and signs through non-invasive sensors implanted in clothing materials. These data or signs can be used to support diagnosis and personalized management of chronic diseases such as diabetes, arthritis, lung and heart disease, and hypertension. These technologies permit patients to be treated at home in its place instead of hospitals; they also let early detection of diseases and timely treatment.

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