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Review

Next Generation Self-Sanitising Face Coverings: Nanomaterials and Smart Thermo-Regulation Systems

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Abstract: Face masks are essential pieces of personal protective equipment for preventing inhalation of airborne pathogens and aerosols. Various face masks are used to prevent the spread of virus contamination, including blue surgical and N95 filtering masks intended for single use. Traditional face masks with self-sanitisation features have an average filtration efficiency of 50% against airborne viruses. Incorporating nanomaterials in face masks can enhance their filtration efficiency; however, using nanomaterials combined with thermal heaters can offer up to 99% efficiency. Bacterial contamination is reduced through a self-sterilisation method that employs nanomaterials with antimicrobial properties and thermoregulation as a sanitisation process. By combining functional nanomaterials with conductive and functional polymeric materials, smart textiles can sense and act on airborne viruses. This research evaluates the evidence behind the effectiveness of nanomaterials and thermoregulation-based smart textiles used in self-sanitising face masks, as well as their potential, as they overcome the shortcomings of conventional face masks. It also highlights the challenges associated with embedding textiles within nanomaterials. Finally, it makes recommendations regarding safety, reusability, and enhancing the protection of the wearer from the environment and underscores the benefits of reusable masks, which would otherwise pollute the environment. These self-sanitising face masks are environmentally sustainable and ideal for healthcare, the food industry, packaging, and manufacturing.

Keywords: face masks; nanomaterials; sanitisation; antimicrobial efficacy; thermal heaters

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1. Introduction

Face masks that self-sanitise can be used multiple times without requiring frequent washing or replacement. Sanitisation disinfects masks, eliminating harmful pathogens and reducing the need for frequent washing. However, washing is still recommended when masks become soiled. Self-sanitising face masks are environmentally beneficial and convenient for the user, as they reduce the waste produced by synthetic single-use and disposable masks and the need for water for washing [1]. Developing self-sanitising masks pushes the boundaries of science and technology as it encourages further innovation in other application areas, including self-sanitising personal protective equipment [PPE] [2–4].

The COVID-19 global pandemic generated an overwhelming awareness of facemasks among the public. Most of the published work has referred to developing single-use face masks. However, few studies have reported on self-sanitising facemasks [5]. After the COVID-19 pandemic, the use of face coverings in public places was advised. Still, they are necessary in healthcare settings, such as GP surgeries, hospitals, and care homes [6]. Though face coverings are not mandatory, they are still encouraged when travelling in public transport systems, like trains, buses, airport terminals, railway stations, office buildings, and public places [7]. Self-sanitising facemasks are required in medical and public health settings, and they may also lead to new applications in other industries.

During natural disasters or in refugee camps, where sanitary conditions such as those regarding access to water are compromised, and there is a high risk of disease outbreaks, self-sanitising masks are ideal for personal hygiene [8]. Maintaining high hygiene standards is crucial in food-processing and handling areas to prevent foodborne illnesses. Self-sanitising masks can help reduce the transmission of pathogens that could contaminate food products [9]. In a global pandemic, healthcare industries and the public will need more face masks, several times more than the number of currently produced or developed masks [10]. For instance, during the recent pandemic, the number of pieces of personal protective equipment (medical and fabric masks, as shown in Table 1) consumed daily was approximately 4 billion units, causing significant waste generation and environmental pollution [11]. Most of these masks were non-biodegradable and made from synthetic materials such as polypropylene and polyester.

These face masks are innovative pieces of personal protective equipment (PPE) that are particularly useful in public health crises [12,13]. These masks are designed to provide enhanced protection by actively deactivating airborne microorganisms on their surfaces, reducing the risk of respiratory disease transmission and making them safer to reuse [14]. Airborne pathogens stay infectious for an extended period and travel freely in the atmosphere due to suspension in the air [15]. Typical examples of airborne micro-organisms are the viruses responsible for measles, chickenpox, influenza, coronavirus, and adenovirus; mycobacterium tuberculosis; and possibly respiratory syncytial viruses [16]. The Spanish flu and swine flu pandemics were the worst in the world and were caused by the airborne H1N1 virus [17,18]. Most face masks protecting against virus contamination are single-use, like essential blue surgical masks and expensive N95 filtering masks [19]. Filtering facepiece respirators are examples of reusable facemasks, where the filter is a vital part, and they are tight-fitting particulate respirators. The entire face piece is a combination of a filtering medium that covers at least the mouth and nose and filters out harmful particles [20].

N100 respirators are designed to filter up to 99.97% of airborne pathogens. These respirators are costly, and even 0.03% filtration loss is a serious concern [17]. In addition, disposable face masks are a cause of concern, as they are frequently replaced [21,22]. However, a self-sanitising face mask developed using nanomaterials with antimicrobial and antibacterial properties can automatically remove airborne viruses from mask surfaces upon contact [23]. This function can be activated upon exposure to light, heat, or even the wearer's breath [24]. It is more effective at neutralising pathogens than standard masks [25]. These facemasks are typically designed to be reusable, reducing waste and long-term costs for consumers and healthcare systems [26]. Nanomaterials such as silver nanoparticles, copper oxide, zinc oxide, and titanium dioxide can be embedded in or coated on the fabric of these masks. These materials are known for their antimicrobial properties [27]. Some masks incorporate chemical coatings that can deactivate pathogens. These can be biocidal chemicals or polymers that can disrupt viral replication or essential bacterial survival processes [27]. Materials that are activated by light can be used to produce reactive oxygen species that can kill microbes [28]. Coatings with titanium dioxide can be activated by UV light and thus degrade organic substances and render pathogens nonviable [29]. Nanomaterials are coated on fabrics using metal and metal oxides whose affinity to the textile substrate depends on the concentration used, the type of finishing, curing, usage, location, and overall handling. Hence, a certain percentage of leaching of nanoparticles can be anticipated. Therefore, there are some implications for human health. However, this situation depends on the antimicrobial finishing and nanoparticles used. Incorporating heating elements within a mask to thermally deactivate pathogens is a novel approach [30]. These elements can heat a mask to a temperature that prevents the survival of viruses and the growth of bacteria, effectively sanitising the mask's surface [31]. Combining nanomaterials with heat treatment can offer superior efficacy in killing pathogens compared to conventional masks relying solely on physical filtration [32]. Paired with heat treatment, antimicrobial nanomaterials can denature proteins and disrupt the cell ultra-structures of pathogens, and this combination increases their effectiveness significantly [33]. In healthcare settings, where the risk of the transmission of pathogens is high, there is a constant demand for more effective protective personal equipment [34].

Table 1. A summary of face masks used by public and healthcare sector.

S. No.	Image of Mask	Description	Advantages	Disadvantages
Cloth Masks				
01		Reusable medical cloth mask	Reusable and washable, with customisable and eco-friendly designs	Depending on the fabric, the filtering efficiency varies, and they are less efficient against aerosols.
Disposable Masks				
02		Single-use blue disposable masks consumed by public	Cost-effective and convenient for one-time use in low-risk settings	These masks have a significant influence on the environment and provide insufficient protection against aerosols
Surgical Masks				
03		White surgical masks for medical use	Simple to manufacture, broadly accessible, and pleasant for prolonged use but provides minimal droplet protection	They are single-use products that provide limited aerosol filtration, which adds to waste, and the poor fit creates air-leakage holes.
04		Single valve-based surgical masks		
05		Dual-valve-based surgical masks		

Table 1. *Cont.*

S. No.	Image of Mask	Description	Advantages	Disadvantages
N95 Respirators				
06		N 95 surgical masks	High filtration efficiency (up to 95% of airborne particles are blocked) and a tight seal that reduces air leaking	Costly and uncomfortable to wear for extended periods of time
Nano-Finished Masks				
07		Silver nano-finished face mask	These provide antimicrobial properties, improved filtration, and self-cleaning capabilities and are made of lightweight materials.	They can release nanoparticles that need careful handling and testing, and they have a higher production cost
Smart Masks				
08		Smart masks with thermoregulation system	They have sophisticated features, including sensors and heating elements, and are appropriate for extreme circumstances.	They are expensive and require complicated maintenance
Powered Air-Purifying Respirators (PAPRs)				
09		Industrial respirator masks	Long-lasting and reusable, offering optimal protection, and comfortable for long periods of use	Costly, bulky, and require battery operation and maintenance

The market for self-sanitising face masks developed using nanomaterials and heat treatment methods reflects a growing trend towards advanced protective solutions [35]. It is worth noting that the market for self-sanitising masks will grow due to its advantages over conventional face masks, including with respect to sanitising capabilities, reuse potential, and reduction in waste. However, the challenge lies in the durability of these finishes, as efficacy deteriorates with every wash [36]. Many researchers also work on nano-finishing with metal and metal oxide materials that are antimicrobial and anti-viral and have muti-wash properties. Antimicrobial fabrics directly affect airborne viruses when they are directly in contact [37]. Integrating nanomaterials with a system that exposes a mask to UV-C light could offer a self-disinfecting feature [38]. As the nanomaterials interact with the pathogens trapped in a mask's fabric, periodic exposure to UV light can help further disinfect a mask by inactivating any pathogens that the nanomaterials have not already eliminated [39]. This combination could extend the practical life of a mask, reduce the need for frequent washing or replacement, and offer a higher degree of protection. While this technology is promising, practical applications are still ongoing, and rigorous testing is necessary to confirm the safety and efficacy of such masks [40]. Using heat as a disinfectant is generally safer for human exposure than UV-C light [41]. Heating methods incorporating heating elements provide gentle heating and do not pose a risk of skin or eye damage, which is a concern regarding UV-C radiation. This makes the heating method potentially more suitable for the self-sanitisation of face masks [42–44]. The textile and personal protective equipment industries, innovating with nanomaterials and heat treatment methods, can be a significant market differentiator, potentially capturing a larger market share as consumers look for masks that offer superior protection. If self-sanitising masks are comfortable to wear and do not pose any health risks due to the inclusion of nanomaterials or the generation of heat, they could provide substantial growth opportunities in face-covering applications in healthcare and other settings, including food and packaging.

Very few studies have discussed finishing textiles with nanomaterials and textile-based thermoregulation systems to self-sanitise face masks. Incorporating nanomaterials and advanced thermal control mechanisms into textiles could significantly enhance the functionality and effectiveness of face masks with respect to airborne viruses. Furthermore, there is a way of determining the long-term safety of the nanomaterials used in these masks, which are subject to direct skin contact and inhaled air. Although thermoregulated masks offer a desirable temperature and micro-climate, it is essential to investigate the long-term effects of these masks relating to safety, comfort, and wearability over an extended period. The stability of nanomaterials and their antimicrobial efficacy after repeated use and cleaning also need to be thoroughly investigated. Few research articles discuss the importance of face masks in controlling the spread of airborne viruses while highlighting the role of nanotechnology and textile innovations in enhancing mask efficacy, indicating a gap in the literature that needs to be addressed. Therefore, in this research, we investigate the following:

1. How do these nanomaterials interact with microbial entities and thus reduce contamination, including contact killing with antimicrobial-based nanomaterials?
2. The methods for incorporating nanomaterials into textiles, including embedding or bonding at the fibre level.
3. The ways of implementing textile thermoregulation technologies and electronically controlled heating elements.
4. How can these technologies be integrated into fabric or mask design to achieve self-sanitisation through temperature regulation?
5. The safety of these technologies for human skin and their impact on the comfort of the mask wearer.
6. The cross-disciplinary approaches to enhancing these masks' functionality and user acceptability in different industries, such as food processing, packaging, and healthcare.

Methods for the Selection of Articles for Research

A structured and meticulous approach was adopted to analyse articles relating to nanomaterial finishes for face masks and the use of heating elements for implementing self-sanitising concepts in personal protective equipment design. Well-defined inclusion and exclusion criteria were adopted to identify relevant research on this topic. One of the inclusion criteria was that the articles had to be published between 2014 and 2024; also, they had to focus on nanomaterials used in textiles, specifically in antimicrobial applications. Three databases were used: Google Scholar, Scopus, and Web of Science.

The articles were screened to ensure they met all the inclusion criteria. Boolean operators such as 'AND' and 'OR' were used in conjunction with the keywords for acquiring the research articles. For the keyword "Facemasks", Google Scholar generated 235,000 articles; Web of Science generated 16,100; and the Scopus database retrieved 13,338. To limit the search, specific keywords like "nanomaterial finished facemasks", "nanomaterial with antimicrobial finished facemasks", and "nanomaterial with antimicrobial finished and heat treatment facemasks" were used to prepare the database for the research work. A schematic illustration (Figure 1) of how the research articles were filtered using various keywords is presented below, and it shows how specific articles were selected from three databases.

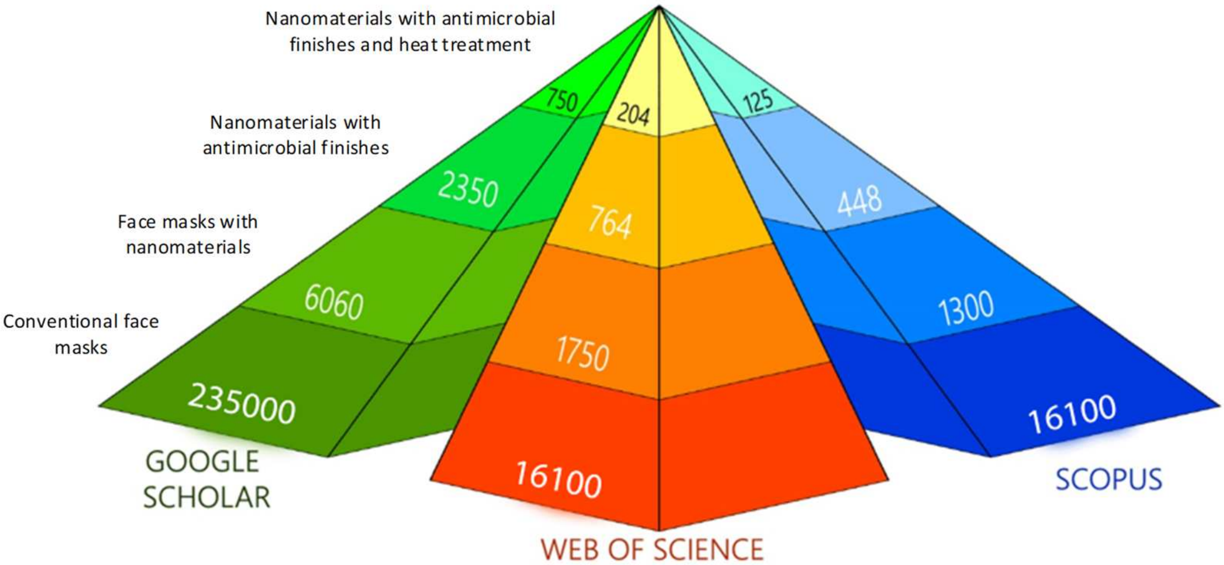

Figure 1. Selection of research articles from various databases.

A total of 750 articles were found on Google Scholar. Of these, 125 from the Scopus database and 204 articles from the Web of Science database were selected, and duplicates were removed for the literature survey. Of these 350 articles, 150 were selected for this study. We excluded studies unrelated to nanomaterials with antimicrobial properties. The articles do not specifically address textiles or face masks with thermal methods for sanitisation. This structured methodological framework ensured that the research in each article was thorough and replicable and provided a solid foundation for understanding the current landscape and future directions in self-sanitising face masks incorporating antimicrobial-based nanomaterials and heating elements. The PRISMA guidelines were followed to ensure this review is structured and comprehensive (Figure 2). In the next part, we elaborate on the various methods of finishing fabrics with antimicrobial agents and their advantages, including chemical vapour deposition, physical vapour deposition, thin-film coating, and electrospinning. In addition, this review critically analyses research on masks finished with nanomaterials and fabrics finished with conductive metal and metal oxides, which offer antimicrobial properties (Figure 3). It discusses the potential of thermal systems in face masks.

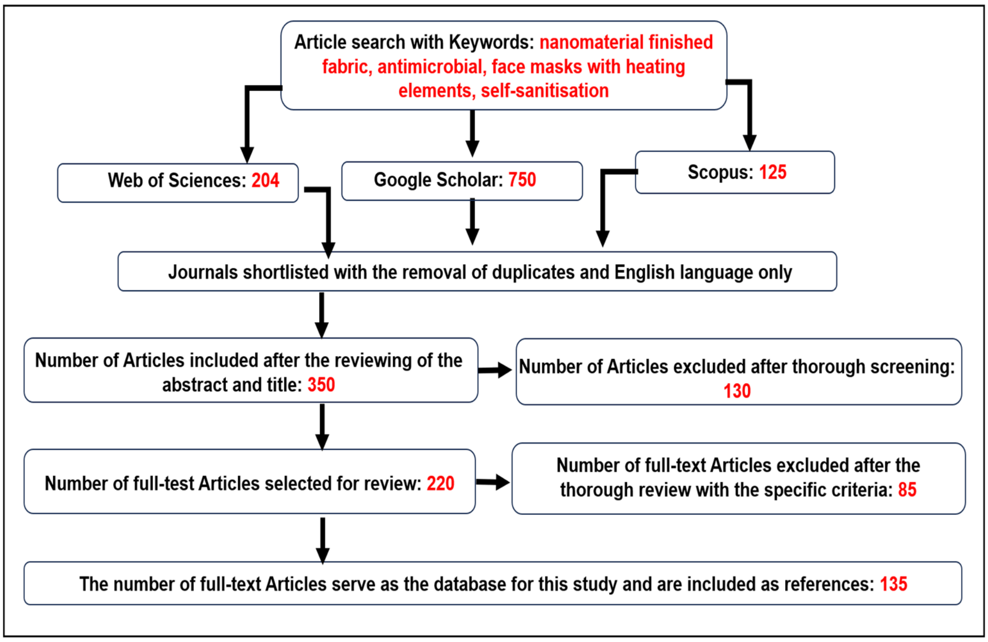

Figure 2. PRISMA diagram showing how the research articles were selected.

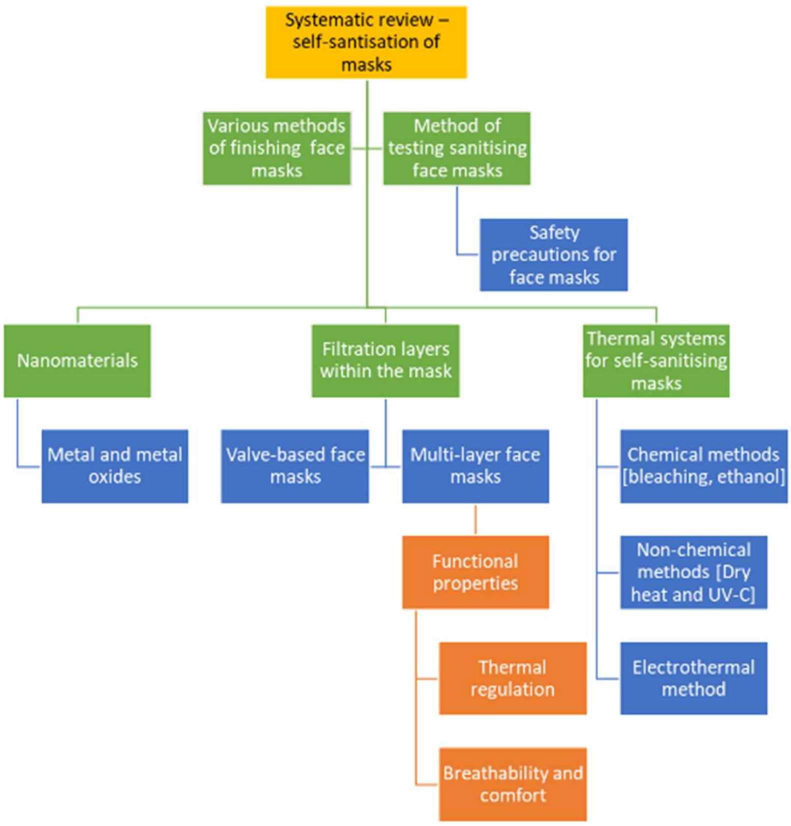

Figure 3. Breakdown of the contents of the research.

2. The Finishing Process of Nanomaterials on Face Mask Fabrics

Nanotechnology significantly enhances the surface area-to-volume ratio of textile fabrics, a critical factor that endows these materials with unique physical and chemical properties. These enhanced properties facilitate various applications, including integrating antibacterial, anti-viral, and self-sanitising functionalities into fabric finishes. Such technologies apply to various textile substrates ranging from natural fibres like cotton to synthetic polymers, broadening their utility across different applications [45]. Consequently, a diverse array of nanocomposites has been developed, featuring advanced physicochemical characteristics and functional capabilities that surpass those of both primary materials and simpler composites. These innovative materials have undergone extensive assessment to validate their performance and applicability in real-world settings [46]. In the healthcare, food processing, and packaging sectors, metal and metal oxide nanomaterials with antimicrobial properties are increasingly valued for their broad application prospects. Despite their potential, the challenges of effectively loading and immobilising these nano-compounds onto various substrates present significant hurdles in textile science and technology [47]. These challenges stem primarily from the difficulty of achieving stable and functional formulations that can undergo the rigorous conditions of textile usage.

Researchers have used various innovative methods to address the significant challenges of embedding nanomaterials into textile substrates. A noteworthy example is the study conducted by Abazari and their team. In their approach, they tried to improve the attachment of nanoparticles to cotton surfaces using a two-step process: initially, silane-containing compounds were chemically modified under acidic conditions to optimise their reactivity; subsequently, these modified compounds were attached to the cotton using epoxy groups in an alkaline environment [48]. This technique highlights the sophisticated strategies being developed to facilitate the effective integration of nanomaterials into textiles. Enhancing the bonding between nanoparticles and textile fibres improves the functional properties of these materials and ensures that the structural integrity of the textiles is maintained. Researchers at Northwestern University in Illinois have innovated by integrating anti-viral chemicals into the nonwoven fabric typically used in standard masks [18]. They aimed to neutralise viruses in aerosol droplets that might permeate through the mask [49].

Researchers have employed various chemical modification techniques to create reusable, durable, and comfortable nanoparticle-finished fabrics suitable for diverse applications [50]. Traditional methods such as chemical vapour deposition (CVD), physical vapour deposition (PVD), thin-film coating, electrospinning, and simple immersion techniques have faced several challenges. These include low efficiency, uneven coating, limited stability, restrictions regarding the number of metals that can be coated, and cost-ineffectiveness [51]. In contrast, the in situ deposition of metallic materials using ultrasonic irradiation presents a more effective coating method for textile-based substrates. Particularly for metal oxide nanoparticles, this method involves the generation of nanoparticles through a bubble cavitation mechanism. The nanoparticles are then propelled onto the fabric surface at high velocity, resulting in a more uniform and stable coating [52].

In sanitisation applications involving nanomaterials, it is essential to deliver active compounds with antimicrobial agents in a controlled manner. This involves encapsulating these compounds within nanomaterials, ensuring precise control over their release rates to maintain effective therapeutic concentrations for the required durations [21]. Developing reliable, simple methods for depositing these nanomaterials on textile fibres and accurately monitoring their release profiles is central to maximising the effectiveness and safety of these antimicrobial-based textiles. The concern regarding the toxicity of nanomaterials extends beyond their intended antimicrobial effects. The potential release of nanomaterials into the environment or their ingestion by users poses a significant safety risk, necessitating stringent controls over material stability and release kinetics [53].

Additionally, the mechanical properties of the textiles used, especially in protective gear like face masks, are a dominant factor. These products effectively filter out chemical and biological agents along with dust and particulate matter that could carry pathogens [21]. These fabrics facilitate quick moisture transportation, increasing wearer comfort and allowing them to exhibit effective antimicrobial properties that actively kill viruses [54]. Metals like silver, copper, and gold and metal oxides like zinc oxide and titanium dioxide are renowned for their antimicrobial, antifungal, and antiviral properties, deactivating airborne viruses while providing thermal conductivity that aids in the self-sanitisation of textile fabrics.

2.1. Using Conductive Metals as Finished Nanomaterials for Textile Fabric

Conductive materials are more efficient than non-conductive materials in transferring heat due to their higher thermal conductivity. This principle can be applied to textile fabrics by incorporating nano-metals, which can be blended or mixed with or coated on these fabrics. Traditional fibres generally possess lower thermal conductivity and act as thermal insulators. However, heat transfer can be expedited by integrating high-thermal-conductivity metals into mask fabrics, thereby enhancing thermal comfort [55]. Among various metals, silver nanoparticles (SNPs) are notable for their antibacterial and antiviral properties. Masks enhanced with silver and copper ions, bonded to zeolite particles, and silver and titanium particles with a size of 250 nm have been developed for nano-finishing on fabrics. Additionally, when used in nanomaterial form within facemasks, conductive metals like silver and gold are effective against targeted viruses, as detailed in Table 2.

Table 2. Conductive metals used as finished nanomaterials for facemasks.

Sl. No	Nanomaterial with Chemical Composition	Finishing Method	Facemask Type	Source
1	Silver nanoparticles	Dip-coating	Surgical mask	[56]
2	Silver nanocluster/silica composite	Thin-film deposition	FFP3 respirator	[57]
3	Polyvinyl alcohol/silver nanoparticles composite nanofiber (PVA/AgNPs)	Electrospinning process	Surgical mask	[58]
4	Nylon6 nanofiber/silver nanoparticle	Electrospinning process	Surgical mask	[59]
5	Gold nanoparticles	Spray coating	Surgical mask	[60]

A significant challenge associated with nano-metal-finished fabrics is the potential leaching of nanoparticles, which can occur during laundering or through mechanical abrasion. This leaching issue is particularly problematic when nanoparticles are weakly bonded to the fibres, compromising the fabrics' functional integrity [61]. Currently, there are no standardised guidelines specifically designed to assess the leaching of metal-based nanoparticles from functionalised fabrics. Pollard et al. conducted an investigation into the release of silver (Ag) and copper (Cu) nanoparticles, known for their antimicrobial and antiviral properties, from face masks into various leaching solutions, including detergent, deionised water, and artificial saliva [62]. This research highlights the need for a rigorous evaluation of nano-finished facemask fabrics. When selecting functionalised textile fabrics for the manufacture of face masks, it is crucial to assess the effectiveness of the face masks along with the potential risks posed to users from exposure to chemicals and nanoparticles released through leaching. Establishing comprehensive safety protocols and guidelines is essential to ensure that the benefits of nanotechnology in textile applications do not inadvertently pose health hazards.

Nano-metal oxides offer several advantages over nano-metals as finishing materials for textile fabrics. Their enhanced stability, broad-spectrum antimicrobial activity with reduced leaching, lower toxicity than their metal counterpart, and safety make them ideal for sanitisation applications. Additionally, their functional properties, cost-effectiveness, durability, thermal stability, and conductive properties contribute to improving the performance and longevity of antimicrobial textiles for self-sanitisation.

2.2. Metal Oxide Nanomaterials as Finished Materials for Textile Fabric

Metal oxide nanoparticles of zinc oxide (ZnO), copper oxide (CuO), and titanium dioxide (TiO_2) are increasingly being utilised as finishing agents in fabric textiles to confer antimicrobial properties or other functional enhancements [63]. Among them, TiO_2 nanomaterials are particularly valued in textile science for their multifaceted applications. These include UV protection, self-cleaning properties, hydrophobicity, and wrinkle resistance, making them highly versatile and useful for various textile products [64]. In one specific example, when copper oxide was embedded in PAN (polyacrylonitrile), decreases of 10^8 in *S. aureus* and *E. coli* bacterial counts were observed when compared with untreated nanofibre controls [65]. A list of different metal oxide nanomaterials, including their specific finishing methodologies, is documented in Table 3.

Table 3. Metal oxides used as finished nanomaterials for facemasks and the corresponding finishing methods.

Sl. No	Nanomaterial	Finishing Method	Facemask Type	Source
1	ZnO	Sonoenzymatic	Surgical mask	[66]
2	TiO_2	Hydrothermal/Sol-gel	Surgical mask	[67]
3	Au/TiO_2 film	Hydrothermal/Sol-gel	Surgical mask	[68]
4	polyurethane-based MnO_2-$FeTiO_3$	Acid extraction/Sol-gel	Surgical mask	[69]
5	CuO	Dip-coating, in situ	Respiratory mask	[65]

Recent studies have focused on the implications of incorporating metal oxide nanoparticles in fabric face masks. Face masks in which ZnO nanomaterials were embedded, designed to exhibit antimicrobial properties, were found to release zinc when washed with water or detergent. Notably, up to 3% of the total zinc content was released due to the in situ nanoparticle deposition method employed during the fabric's functionalisation process [70]. Nanoparticles should be rigorously evaluated for cytotoxicity against key mammalian cell lines, including the skin, lungs, and the respiratory system. Leaching or detachment, if any, should be minimal. Standardised test methods are used to evaluate the cytotoxicity and function of face coverings and materials (ISO 10993-5:2009 applies to in vitro cytotoxicity tests used for medical devices, and ISO 16900-7:2020 applies to respiratory protective devices and methods for test and testing equipment) [71,72].

Incorporating nanotechnology into textile manufacturing has enhanced the functional qualities of fabrics and enabled precise control over their production to meet specific quality standards. It is also crucial to optimise textile finishing processes involving specific nanomaterials to consider safety, reusability, and cost carefully. These factors must be thoroughly evaluated and explained to ensure informed usage and sustain consumer trust [73]. Enhanced filtration efficiency, improved thermal management, increased durability, and better moisture management are the main factors for self-sanitising facemasks. Multi-layer nano-finished fabrics offer significant advantages, providing excellent protection, comfort, and sustainability. In nano-finished face masks, the outer layer is a nano-finished fabric, while the middle and inner layers are not finished. In masks with thermal elements, the elements should be placed in the middle layer, which may penetrate the outer layer after prolonged use or during high temperatures, potentially increasing nanoparticle release. However, the inner layer will remain unaffected, mitigating the risk of direct contact with the human respiratory system. These fabrics effectively meet the growing demand for self-sanitising facemasks.

2.3. Multi-Layer Facemask Fabrics for Filtration and Thermal Regulation

Introducing nanomaterials into face masks has significantly impacted their ability to filter out pathogens, particularly in aerosol removal. Research indicates that most nanomaterials display impressive filtration efficiency, capturing over 50% of particles of 2 microns in size and over 75% of those measuring 5 microns [74]. The fabric structure, including factors such as diameter, the thickness of the nonwoven mat, packing density, and the efficiency of individual fibres, plays a crucial role in determining overall filtration effectiveness. The World Health Organisation and other public health agencies recommend employing a three-layer mask structure, typically including a middle layer of woven or nonwoven material to enhance filtration without compromising breathability, as shown in Figure 4.

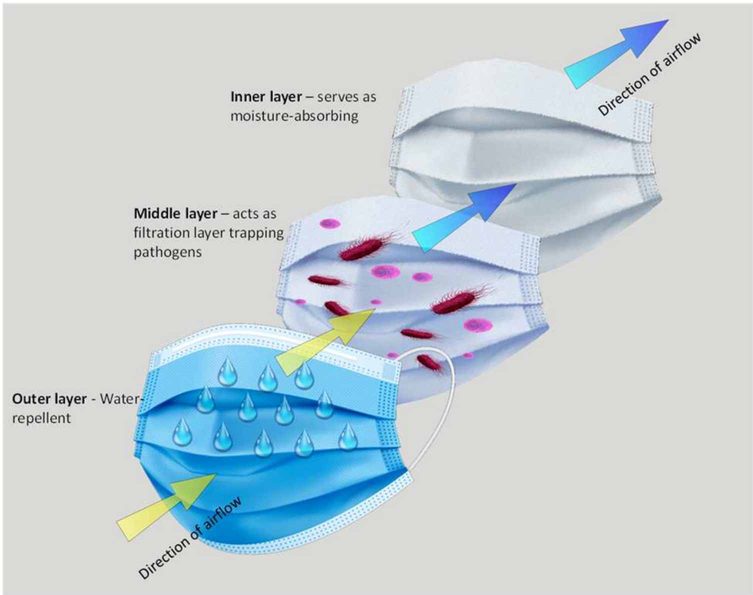

Figure 4. Multilayer facemask structure.

This design leverages the unique properties of each layer, optimising both protection and comfort [75]. For example, standard surgical masks incorporate a melt-blown microfiber filter layer sandwiched between two spun-bond fabric layers. The melt-blown layer is crucial for microbial filtration, while the outer nonwoven layer provides liquid resistance, and the inner layer offers moisture absorption and skin-friendliness [76]. One of the critical aspects of a mask's effectiveness is its fit to the user's face. A well-fitting mask can increase filtration efficiency by minimising gaps through which particles can enter or escape. However, adding more layers to improve filtration can adversely affect breathability. Therefore, when designing a mask, one should consider optimising the layers so that the breathability of the mask is not compromised at the expense of filtration abilities [77].

2.4. Textile Fabrics as a Filtration Layer for Face Masks

Material selection and structural design are crucial in optimising face masks for providing protection against pathogens while maintaining user comfort. Flannel and gauze-like loose fibres and nonwoven materials are noted for their superior filtration efficiency compared to traditional woven fabrics made of cotton, rayon, or polyester [78]. More recently, PLA [polylactic acid] derived from natural sources like starch and sugar, which are biodegradable, has demonstrated excellent filtration capabilities [79,80]. Several fibre and fabric types are used in face masks to create the desired filtration layers (Table 4).

These nonwoven materials incorporating nanomaterials often incorporate an electrostatic charge, which enhances their filtration capabilities [81]. They are characterised by a three-dimensional porous fibrous structure that allows for high breathability and effectively captures particulate matter. The varied compositions and specific manufacturing processes of these fibres result in diverse fibrous web structures and mat densities, each with unique filtration properties. Economically, these materials are advantageous as they provide an effective alternative to more expensive commercial filters like MERV 13 [minimum efficiency rating values of filter], vacuum bags, or HEPA filters. Rayon/polyester blend cellulose-based fibres have been modified with nanomaterials to enhance their filtration efficacy beyond standard polypropylene [78]. However, challenges such as reduced filtration efficiency due to moisture exposure necessitate further innovations. Increasing water repellence in these fabrics could mitigate this issue without compromising the fabric's performance [82]. Moreover, some of the multiple layers in masks like the KN95 consist of cotton, nonwoven cotton, melt-blown fabric, and a hot-air cotton filter, which enhances filtration efficiency and can also impact heat transfer and breathability [83]. The design of these multi-layer masks, including the popular three-layer disposable masks with a distinct blue outer layer and white inner layer, addresses these issues by balancing filtration needs with thermal comfort [84]. This is crucial as masks must prevent viral transmission and be comfortable enough to wear for extended periods, particularly in medical settings and in food-processing and -packaging-like sectors.

Table 4. Different fibre types and fabrics used in conventional masks.

Fibre Type	Fabric Structure	Filtration Layer
Polypropylene	Spunbonded nonwoven	Outer and middle
Polylactic acid [PLA]	Spunbonded and melt-blown nonwoven	Middle and inner
Cotton	Woven	Outer and inner
Polyester	Woven/Knitted	Outer
Wool—fine grade	Nonwoven/woven	Outer and inner
Viscose	Woven	Middle and inner

Manufacturers have introduced valves to address the issue of breathability, especially in masks designed for prolonged use or in more physically demanding environments. These valves allow for easier exhalation, reducing moisture build-up and heat inside the mask, thus enhancing comfort [85]. However, it is important to note that while valve masks increase user comfort, they may not filter exhaled air, which can be a concern in sterile or infection-sensitive environments.

2.5. Valve-Based Mask

Valve-based masks, shown in Figure 5, significantly enhance wearer comfort, particularly in hot and humid conditions. The valve facilitates easier exhalation, reducing heat and moisture accumulation within the mask [86]. This feature is particularly appreciated by individuals who wear masks for extended periods or in environments where physical exertion is standard, as it helps to mitigate discomfort and the challenges associated with prolonged mask use. However, the design of valve-based masks also introduces notable drawbacks, particularly concerning public health during a viral-pandemic-like situation. These masks protect wearers by filtering inhaled air; the exhalation valve allows unfiltered air to escape. In that case, the virus can be expelled through the valve and spread to others [87]. Additional measures are necessary to mitigate the risk of spreading viruses. Innovations in mask design might offer solutions, such as valves incorporating filters to clean exhaled air, though these filters still need to be standardised. Endowing facemasks with thermal sanitisation capabilities offers significant potential for reusability. Users can sanitise their facemasks by exposing them to a specific temperature that effectively kills pathogens without degrading the mask material [88].

Figure 5. Valve-based facemask.

3. Thermal Sanitisation Methods for Facemasks

Thermal sanitisation can inactivate pathogens accumulated on a mask's surface, including the valve, thereby reducing the risk of disease transmission even when the mask design includes valves. Integrating thermal elements that can be activated to heat a mask to a sanitising temperature could be a viable solution [6]. These elements must be designed to evenly distribute heat without compromising the mask's structural integrity and comfort.

Washing facemasks with detergent and water is the simplest way to sanitise and reuse them. Boiling is another simple and effective sanitisation method [89]. Unique microwave steam bags sterilise face masks made from cloth fabrics [90]. Chemical solutions like hydrogen peroxide vapour or bleach solutions can be used to sanitise masks [91]. An autoclave is also an effective sterilisation method for medical-grade masks. It uses high-pressure saturated steam at high temperatures to kill all microbes [92]. Heat and certain chemicals might degrade or alter the materials used in facemasks, impacting their durability and safety [93]. Using dry heat from an oven or a specialised device can effectively sanitise masks. Studies suggest that heating a mask at 70 °C (158 °F) for about 30 min can help deactivate viruses without compromising the integrity of the mask [94]. Dry heat sanitisation is indeed recognised as a simple and cost-effective method for reducing microbial contamination on various surfaces and materials, including textiles. It involves using high temperatures to denature proteins and oxidise metabolic and structural chemicals, ultimately killing microorganisms [95]. Both chemical and non-chemical methods can achieve thermal sanitisation. Figure 6 shows a block diagram of thermal sanitisation used in chemical and non-chemical methods. Chemical methods can be designed to function at elevated temperatures, enhancing the effectiveness of certain chemical agents. Specific disinfectants might require activation at higher temperatures to improve efficacy. Non-chemical methods directly apply heat without additional chemical agents [96].

Figure 6. Illustration to highlight various thermal sanitisation methods.

3.1. Thermal Sanitisation Using Chemical Methods of Disinfection

Face masks used in medical settings or areas with high exposure to pathogens require effective sanitisation methods to ensure they can be reused safely without compromising their integrity and filtration efficiency. Chemical methods and thermal treatments are preferred for sanitising the materials used in facemasks, particularly for non-washable facemasks like N95 respirators and surgical masks.

Figure 7 illustrates a few examples of chemicals used to sanitise a facemask. Hydrogen peroxide vapour (HPV) is a powerful oxidiser that destroys microorganisms by breaking down cell components. It leaves no residues and is compatible with many materials, including the filtering material in N95 masks [22]. Ethanol spraying can effectively inactivate viruses and bacteria by denaturing proteins and dissolving lipids. After spraying or dipping masks in ethanol, they are air-dried and sanitised [97]. Sodium hypochlorite solution, commonly known as bleach, is an effective disinfectant at a 0.1% concentration for inactivating viruses on surfaces. The masks are soaked in a dilute bleach solution and then thoroughly rinsed and dried, which can sanitise them [98].

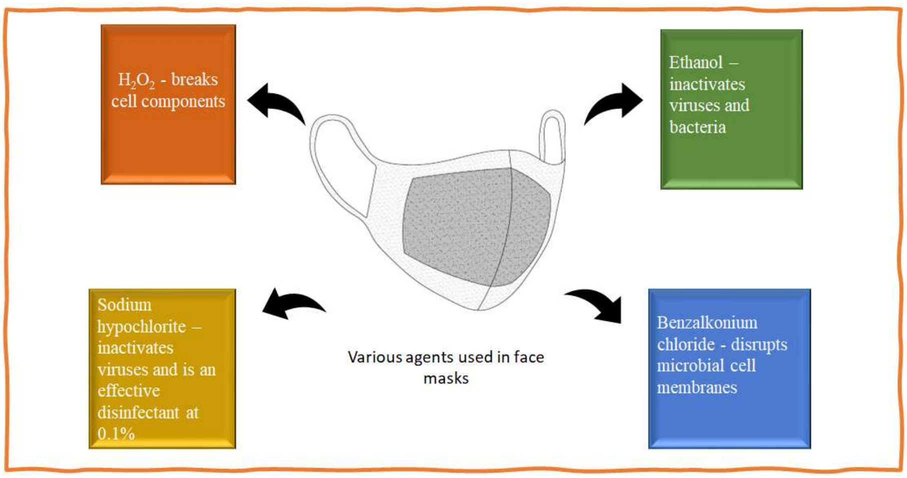

Figure 7. A visual illustration showing the chemicals used for the sanitisation of facemasks.

Benzalkonium chloride is a quaternary ammonium compound that disrupts microbial cell membranes. The non-fabric surfaces of a mask, such as elastics and stiffeners, can be wiped with benzalkonium chloride disinfectant wipes [99]. Standard face masks are composed of non-biodegradable polypropylene (PP) nonwoven fabrics. A high moisture level, such as steam and chemicals like ethanol, can damage a mask's physical structure and reduce its filtering performance, even dissolving PP fabrics [39]. It is worth noting that non-chemical methods like heat and ultraviolet light are preferable to chemical methods for sanitisation, as they are safe to use on the skin. Cotton, polyester, and nylon-based fabrics are durable materials that can withstand washing, drying, and heating. Polypropylene, commonly used in surgical masks and N95 respirators, can be effectively disinfected using UV-C radiation without being degraded and maintains filtration efficiency for short durations at temperatures of 70–80 °C.

Due to several advantages, non-chemical methods, such as heat and ultraviolet (UV) light application, are often preferable to chemical methods for sanitisation. Heat-based sanitisation can effectively inactivate various pathogens, including viruses and bacteria, without leaving harmful chemical residues. This method is particularly beneficial for materials that can withstand high temperatures without degrading, making it suitable for reusable masks. Ultraviolet light, especially UV-C, is another effective non-chemical sanitisation method. UV-C light has germicidal properties that can rapidly inactivate microorganisms by disrupting their DNA and RNA [100]. UV-C technology is still under development, and rigorous testing is necessary to confirm its safety and efficacy [40]. Using heat as a disinfectant is generally safer for human exposure than UV-C light [41]. It also avoids the use of potentially hazardous chemicals and allows for quick and efficient mask sanitisation. Moreover, these non-chemical methods can extend the lifespan of masks by allowing for multiple sanitisation cycles without significant wear and tear.

3.2. Thermal Sanitisation via Non-Chemical Methods for Disinfection

Thermal treatment is one of the simplest and most accessible methods for sanitising face masks, especially at home and in the industrial environment. The dry heat pasteurisation method effectively kills pathogens while preserving the filtering ability of masks, making it a practical option when the aim is reusing masks, especially those unsuitable for washing or treatment with chemical disinfectants [101]. Typically, this process involves heating a mask at around 70 °C for a certain period, usually between 30 and 60 min. This temperature is sufficient to deactivate most viruses and bacteria without damaging the structural integrity of a mask [102]. Regarding photo-thermal masks, the conversion of light energy, typically sunlight, into heat is used, rapidly elevating the surface temperature of a mask to levels that can effectively kill pathogens. This method is particularly beneficial in sunny environments [103]. Photodynamic masks involve a technology in which light-responsive materials are used to generate reactive oxygen species (ROS) when exposed to light. ROS are highly effective in killing microorganisms, offering a way of self-sterilising the surface of a mask. Both photo-thermal and photodynamic masks depend significantly on light exposure. Their effectiveness diminishes when light levels are insufficient, such as during the rainy season, at night, or indoors. This limitation is a significant drawback as it restricts the usability and reliability of these masks in everyday scenarios [104]. Electrothermal materials used as flexible textile heaters offer controlled targeted heating, integration and portability, safety, durability, and greater cost-effectiveness compared to other thermal sanitisation methods. These benefits make them ideal for self-sanitising facemasks, providing reliable protection while enhancing user convenience and comfort.

3.3. Electrothermal Materials Used as Flexible Textile Heaters

Electrothermal performance depends on the high electrical resistance of carbon and conductive-polymer-like materials. High driving voltages are required to heat these materials [105]. Fibres and micro-meshes from silver materials are highly suitable for this application due to their high conductivity and low heat capacity. Electrically conductive silver-yarn-based heaters comfort the wearer and retain the properties of traditional knitwear. The temperature of the surface of a fabric-based heater should not exceed human body temperature [106]. The fabric heater should be kept at a safe distance from the skin and provide proper electrical insulation. The fabric used with the heater should be washable and reusable.

The physical parameters of the heating element include resistance, driving voltage, and exact temperature, depending upon the number of rows and columns of electrically conductive yarn [107]. Scientists have modified and designed a self-disinfecting and reusable face mask by adding a layer of carbon fibres to an N95 surgical mask, which is heated by the use of a USB charger to destroy viruses [15]. Table 5 shows the different heating elements in different textile fabrics added to allow the fabrics to act as textile heaters.

Table 5. Heating elements in different textile fabrics, such as textile heaters.

Sl. No	Heating Element	Textile Material	Finishing Method	Heating Temperature	Reference
1	Carbon fibres	Nonwoven fabric	Wet paper process	94.6 °C	[108]
2	Stainless-steel yarns	Polyester knitted fabric	Yarns are woven into the fabric	60 °C	[109]
3	Silver nano ware	Cotton fabric	Impregnation	70 °C	[110]
4	Silver-coated polyamide conductive thread.	Polyester	Conductive threads are knitted to form the fabric	70 °C	[111]
5	MXene [2D material]-based heater–composite cellulose nano-fibre	Nonwoven fabric	Special MXene cellulose fibre interaction	67.5 °C	[112]
6	Graphene	Cotton woven fabric	Spraying	162.6 °C	[81]

Researchers developed a mask with three layers, two conductive textile layers, and an insulating fleece in between them. Voltage is applied to the two conductive layers. The moisture generated by breathing and the oxygen in the air together generate reactive oxygen species (ROS). ROS, like oxygen peroxide and other compounds, will act as a chemical weapon, killing viruses and bacteria [113]. Filtration and passive inactivation are the two significant functionalities of these masks.

A stretchable heater embroidered onto a textile fabric with a driving voltage of 3 to 5 V can generate temperatures up to 150 °C over a small surface area. Flexible heaters may be designed on graphene, carbon nanotube sheets, silver nanowires, silver micromesh, and nanoparticle networks. In one case, various design patterns used for textile heaters, like serpentine, rounded curve, and Gosper curve, were stitched on fabrics, and different thermal parameters were characterised [114]. A thermistor may be stitched onto the textile heating patch to respond to the actual temperature of the surface and allow for thermal regulation. Table 6 below shows different textile-based temperature sensors used to measure temperature.

Table 6. Textile-based temperature sensors for measuring the temperature.

Sl. No	Key Aspects of Sensor Materials	Operating Temperature	Source
01	Temperature-sensing yarns used as a micro-pod embedded within the fibres of a polyester yarn	25–38 °C	[115]
02	Knitted polyester yarn with an embedded thermistor encapsulated in a polymer resin and connected to an Arduino Microcontroller	65 °C	[116]
03	NTC thermistor soldered to copper interconnects and encapsulated within a cylindrical micro-pod made of conductive resin and then embedded in a polyester yarn	0–40 °C	[115]
04	A commercially available temperature-sensing element within a polymeric resin micro-pod embedded in polyester yarn	25–38 °C	[117]
05	Embroidered hybrid resistive thread detector (RTD) incorporating conductive silver yarn as a humidity sensor and chromium-nickel austenitic stainless-steel yarn as a thermal sensor embroidered on a cotton substrate	20–100 °C	[118]
06	Dip-dyed yarn via PEDOT-PSS used as an RTD	−50–80 °C	[119]
07	Metal wires incorporated in a knitted fabric	20–60 °C	[120]
08	Flexible platinum-based resistance temperature detector (RTD) integrated into textiles	25–90 °C	[121]

The materials used to design these sensors are made from conducting yarn, using textile materials as a base substrate. Therefore, the measurement of temperature is dependent on the resistance of the materials. The conductive yarn's total electrical resistance reduces when the fabric is heated. In conductive yarns, linear resistance decreases with an increase in temperature. The contact points between the covered conductive polymer yarns in the knit structure are required in order to apply voltage and measure temperature changes [122]. The operating temperatures of different sensors vary according to their use. Microcontrollers like the Arduino UNO or textile-embroidered tiny microcontrollers like Flora mainly control the heating elements and the thermistors. The electronic components are designed to have a constant current mode to avoid overheating the textile heating patch in case of a short circuit [118].

Figure 8 shows a circuit diagram of a textile-based heater controlled by a microcontroller. Using different design patterns, conductive yarns [SP-3, DP-3—different patterns] are embroidered onto the fabrics as flexible textile heaters [123]. An electronic driver circuit controls these heaters. The driver circuit drives through a microcontroller. The power supply unit or battery gives power to the heater and the electronic circuits.

Ensuring the safety and comfort of the wearer is a priority when integrating textile heaters and electronic circuits into facemasks. This involves using insulated materials, implementing temperature controls, designing lightweight and breathable components, and ensuring user-friendly operation. By prioritising these aspects, these masks can provide effective self-sanitisation while maintaining high standards of safety and comfort for the wearer.

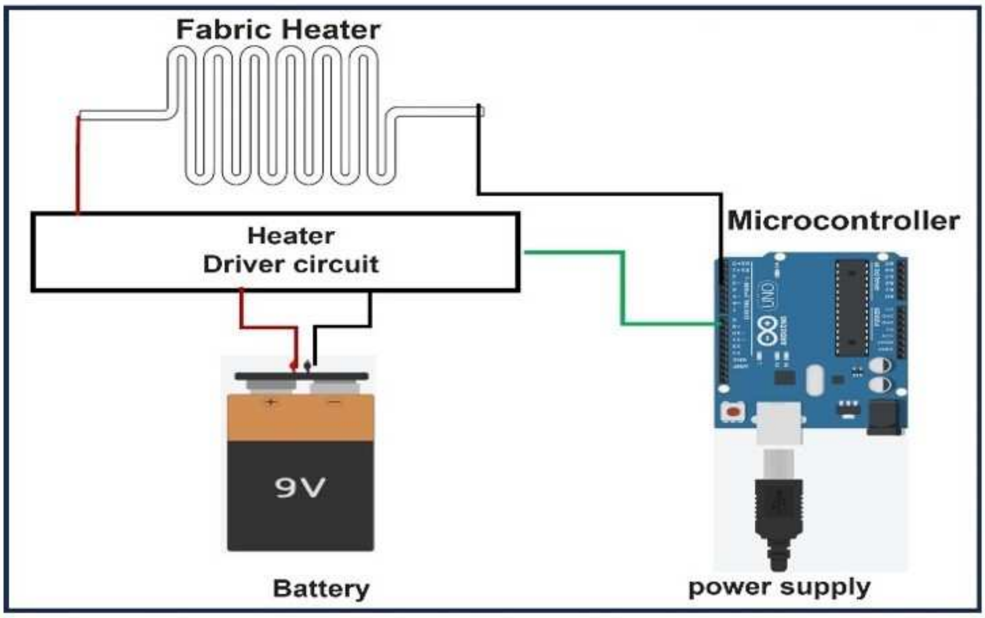

Figure 8. Different fabric design patterns of flexible textile heaters are embroidered onto fabrics with a driving circuit controlled by the microcontroller.

3.4. Safety and Comfort of the Wearer When Using Textile Heaters and Their Electronic Circuits

It is essential to maintain the temperature of a mask between 10 and 28 °C when it is worn, and doing so also offers comfort for the wearer. However, if the mask is being used for heat sanitisation, it should not be worn during the process [124]. The wearer should remove the mask and sanitise it at the prescribed heating temperature for the specified duration. The electronic circuits in the heaters are housed within an electrically insulating textile-based envelope within the facemask to protect the wearer from electrical hazards [125]. For sanitisation, the heaters' driver circuits, which may include a microcontroller or simple regulator circuits without a microcontroller, are designed to generate higher temperatures and are positioned away from the face, ensuring these circuits pose no risk to the wearer [118].

The integration of cooling technologies like liquid-cooling circulation, air ventilation, and PCM (phase change material)-encapsulated systems into face masks represents a significant advancement in enhancing the wearer's comfort by ameliorating the effects of the heat used for sanitisation. PCMs can store and release large amounts of energy at a constant temperature as they change from solid to liquid, and vice versa. PCMs can be encapsulated in microcapsules and integrated into the fabric of a mask. Adding these systems can increase the weight and bulk of a mask, which might affect comfort and wearability [126]. Liquid cooling involves a system where a coolant fluid circulates through channels embedded within a mask. The fluid absorbs heat from the wearer's face and is then cycled back to a cooling reservoir to dissipate the heat [127]. Enhanced air ventilation systems use small, battery-powered fans to actively push warm air, draw the exhaled air out, and simultaneously draw cool air inside the mask [128]. For active systems like liquid-cooling and ventilated air systems, energy sources (like batteries) are required, which need to be lightweight, safe, and have sufficient capacity to last through the usage period. Integrating a thermoelectric module into a facemask and a hollow tubing network represents an innovative approach to personal temperature regulation. This system typically uses a Peltier element [a thermal module that can provide warming and cooling effects]. These thermoelectric modules are bulky and less energy-efficient, potentially limiting mobility and comfort [129]. To overcome the obstacles the chemical and non-chemical methods face with regard to thermal sanitisation, flexible fabric-based heaters with common electrothermal materials like graphene, carbon nanotubes, and conductive yarns have been broadly considered.

The combination of nanomaterials and thermoregulation for sanitisation processes improves the safety, reusability, and overall effectiveness of face masks, addressing both health protection and usability in various working environments, such as cold storage, food processing, packaging, and in dusty conditions in industries like garment manufacturing and cement production. The sanitisation testing of nano-finished facemasks with thermal methods is also essential to ensure their effectiveness, safety, and durability before their use in various sectors. This helps designers optimise sanitisation protocols, comply with regulatory standards, and boost user confidence. Rigorous tests, including bacterial filtration efficiency (BFE), viral filtration efficiency (VFE), and particle filtration efficiency (PFE) tests, significantly contribute to public health by ensuring that facemasks provide reliable protection against pathogens. Finally, electrostatic adsorption filtration may be achieved using triboelectric nanogenerators. Melt-blown nonwoven fabrics, which are normally used as a mid-layer in face masks, can be reused, provided their electrostatic charge can be restored via a triboelectric nanogenerator (TENG) recharging technique using a polyamide nanofiber filter, which allows electrostatic interactions between the particles and the filter [130].

3.5. Sanitisation Test of Nano-Finished Facemasks

Nanomaterial-finished facemasks are evaluated rigorously to confirm their efficiency via bacterial filtration efficiency (BFE), viral filtration efficiency (VFE), and particle filtration efficiency (PFE) tests, as shown in Figure 9. The PFE test ensures that particles of specific sizes, including most viruses and bacteria, are effectively prevented from passing through a mask. PFE tests are critical in evaluating the effectiveness of facemasks finished with nanomaterials. These tests measure a mask's ability to filter out particles, typically in the range of 0.1 to 1 micron, under specific conditions. Nanomaterial-finished facemasks are likely to show high particle filtration efficiency due to the increased surface area and enhanced antimicrobial properties of nanomaterials. Combined with thermal regulation, these facemasks show high particle filtration efficiency for self-sanitisation [53].

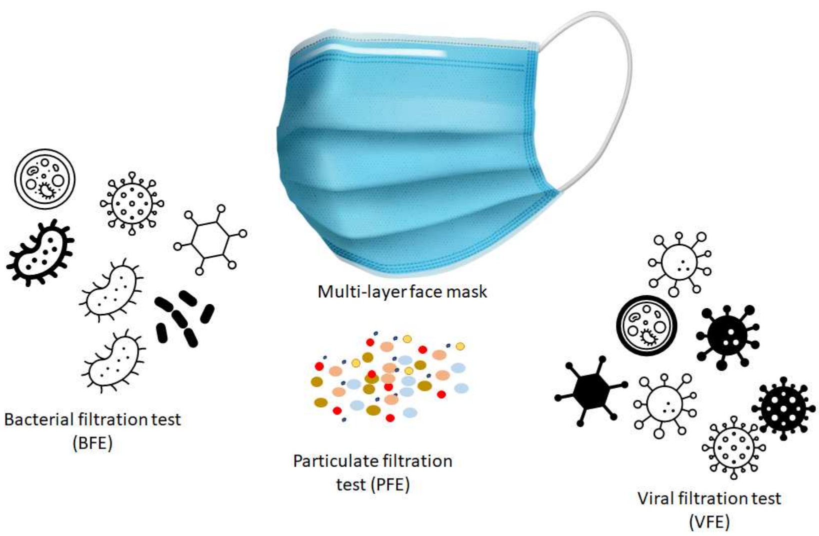

Figure 9. Different facemask filtration tests for sanitisation.

Nano-finished facemasks are also tested using BFE and VFE tests, particularly for seven pathogenic bacteria—namely, the Gram-positive bacteria *Staphylococcus aureus* and *Corynebacterium pseudodiphtheriticum* and the Gram-negative bacteria *Escherichia coli*, Pseudomonas aeruginosa, *Klebsiella pneumonia*, and *Acinetobacter baumannii*—and the fungus Candida albicans, and by using the inactivation test of the H1N1 indicator virus via a hemagglutination (HA) assay [131].

In one study, all seven common respiratory pathogens were killed by applying 60 °C and 70 °C for 1 h, indicating that dry heat can kill a wide range of pathogenic bacteria. The H1N1 and SARS-CoV-2 viruses are RNA enveloped viruses that spread via the respiratory tracts of human beings. A higher temperature range is the safest for the deactivation of SARS-CoV-2. N95 masks, like surgical face masks, showed 97% filtration efficiency in a fit test and in a filtering efficiency test on aerosols conducted using the heat pasteurisation method [132]. Table 7 documents the different virus environments used to test these fabrics for their antimicrobial, antifungal, and anti-viral properties.

Table 7. Nanomaterials finished on different textile fabrics tested in different virus environments.

Sl. No	Nanomaterial with Chemical Composition	RPE Type	Targets	Reference
1	99% polyacrylonitrile (PAN) nanofber + 1.00% copper oxide nanoparticles (PAN/CuO)	FFR respirator	Microbes and viruses	[133]
2	Matrix of polylactic acid and cellulose acetate containing copper oxide nanoparticles and graphene oxide nanosheets	Medical mask	Bacteria (*E. coli*)	[26]
3	99% polyacrylonitrile (PAN) nanofber + 1.00% copper oxide NPs (PAN/CuO)	Breath mask	Microbe	[65]
4	TiO_2	Respirator mask	Bacteria	[134]
5	A mixture of silver nitrate and titanium dioxide	Surgical masks	Bacteria	[135]
6	Silver nanomaterial	Surgical masks	Bacteria	[136]
7	Silver nanoparticles	Surgical mask	Bacteria (*E. coli* and *S. aureus*)	[56]
8	Silver nanocluster/silica composite	FFP3 respirator	Coronavirus (SARS-CoV-2)	[57]
9	Polyvinyl alcohol/silver nanoparticle composite nanofiber (PVA/AgNPs)	Surgical mask	Bacteria (*E. coli*)	[58]
10	Polyacrylonitrile (PAN) nanofiber/silver nanoparticle composite	FFR respirator	Microbes and virus	[137]
11	Nylon6 nanofiber/silver nanoparticle composite	Surgical mask	Bacteria (*E. coli*)	[59]
12	Gold nanoparticles	Surgical mask	Bacteria (*E. coli*)	[60]

For decontamination, masks should be placed inside an oven or steel box to ensure uniform heating. When a facemask is used in heavily contaminated air, the oven must be a waterproof incubator, and the steel box must provide uniform heating and ensure safety [138]. This process can be challenging at home, in an office, or in an industrial environment. However, flexible textile-based heaters offer the best solution to these challenges.

4. Challenges of Developing Thermally Regulated Self-Sanitising Masks

Combining nanomaterials and thermoregulation in facemasks made of cotton and polyester fabric offers numerous benefits for self-sanitisation and user safety. It also presents several challenges that must be addressed to ensure practical and safe implementation. Integrating nanomaterials and thermoregulatory systems into a facemask adds complexity to the design and manufacturing processes. This can lead to higher production costs and a need for specialised equipment and expertise, potentially limiting scalability and increasing the final product's price. Commercial conductive threads offer a low-cost approach to designing textile heaters, which can be embroidered onto ordinary facemasks. The components for developing textile heaters are commercially available at affordable prices. It is difficult to control the heat generated by thermoregulatory elements to ensure user comfort and prevent burns or skin irritation. Ensuring this heat is uniformly distributed and kept within safe temperature limits requires precise control systems, which can complicate mask design. Including electronic components for thermoregulation in a textile-based product poses challenges to safety, durability, and the ability to withstand repeated use (50–100 wash cycles), especially under different environmental conditions and after multiple sanitation cycles. Depending on the embedded electronic circuits and material quality, the lifecycle can vary from six to twelve months with proper maintenance. Electronic components, such as those needed for thermoregulation, require power. Ensuring long battery life and convenient recharging options is necessary to maintain a mask's practicality for everyday use. Although nanomaterials are generally safe, there is still ongoing research into their long-term health impacts, mainly when used in products in close contact with the human body. There is a risk of nanoparticles detaching and being inhaled, requiring careful design to ensure particle containment. To mitigate the inhalation risks associated with the shedding of nanoparticles from fibres in smart thermo-regulation system masks, the following recommendations may be taken into consideration: The development of advanced binding techniques or methods such as the pad–dry–cure method or batch process [139] enhances the adhesive properties of nanoparticles on cotton-based substrates. In addition, layer-by-layer deposition [140], or using a confined impinging jet mixer, produces nanoparticles with functional compounds, ensuring stronger adhesion of the nanoparticles to the fabric [141]. On the other hand, the ultrasound-irradiation-assisted water/oil/water microemulsion method with UV curing enhances antimicrobial properties [142]. Using these techniques and keeping the nano-finished materials away from direct contact with the human respiratory system can prevent the risks posed by inhaling shed nanoparticles. Addressing these challenges requires multidisciplinary collaboration across textile technology, electronics, materials science, and health sciences to create solutions that are effective, practical, safe, and accessible to the general public.

Implications and Scope

The finishing of textiles made of woven/knitted structures blended with cotton, wool, and polyester fibres with nanomaterials offers excellent opportunities for developing self-sanitising masks with advanced functional properties, including antibacterial and filtration capabilities. Nanomaterials such as metal oxides, e.g., silver oxide and zinc oxide, are less toxic compared to their metal counterparts when combined with thermoregulation; the elevated temperatures can further enhance the efficacy of these materials in killing microbes, including viruses and bacteria, by disrupting their structural integrity. The self-sanitising properties enabled by nanomaterials and thermal elements reduce the need for frequent washing or replacement, extending a mask's usable life and making it more environmentally friendly. Thermoregulation technologies can be adjusted to maintain a comfortable temperature for the wearer. This is crucial in preventing discomfort after prolonged use, especially in varying climatic conditions. Moreover, the nanomaterials used are often designed to be non-toxic and safe for direct contact with skin. With the integration of intelligent technologies, such as sensors and microcontrollers, self-sanitising masks can activate the heating mechanism based on specific triggers, such as humidity or time intervals. This on-demand sanitisation ensures that a mask remains sterile without user intervention.

Implementing a flexible textile-based thermoregulation system has shown promising future prospects for the e-textile industry. These innovative thermoregulation systems have significant potential for enhancing personal protective equipment, contributing to the development of more effective and accessible sanitisation methods. This design process eliminates the need for a complex and expensive manufacturing setup, reducing costs and enabling widespread use. Incorporating UV-C LEDs with heating filaments made from conductive yarn into wearable e-textiles could enable faster activation, resulting in a reusable mask with self-sanitisation and germicidal properties. This innovative combination would enhance a mask's ability to effectively eliminate pathogens, providing advanced protection and hygiene. Future research should also focus on the importance of designing masks with features that improve their fit. Particular attention should be given to the shape of and material used for the ear loops, the bendable wires, the nose pads, and the cut. When all these features are considered in face mask production, the resulting improvements in comfort, safety, reusability, and self-sanitisation will enhance the masks' overall effectiveness and user experience. Table 8 summarises the benefits of self-sanitising masks over conventional ones and recommends ways of improving them.

Table 8. Comparison of single-use face masks with self-sanitising masks and suggestions for improvement.

Categories	Single-Use Mask	Nanomaterials Finished with Heating for Self-Sanitising Face Masks	Suggested New Approaches
Filtration efficiency	Surgical masks are about 50% efficient, while N95 masks can achieve up to 95% efficiency.	Nanomaterials provide 60–70% filtration efficiency, which can be increased to 99% when combined with thermoregulation systems.	Nanomaterials can be used to enhance filtration efficiency by reducing pore size in textiles, limiting airborne particles and improving overall protection.
Breathing resistance	These masks have 2–3 layers of polypropylene-based nonwoven fabric, which will not affect the breathing.	This factor is potentially improved due to denser nanomaterial filtration; heating elements may increase resistance further.	Develop advanced nanomaterials and heating elements for high filtration efficiency and minimal breathing resistance, with added ventilation for improved airflow and comfort.
Reusability	Single-use only	They are designed for multiple uses	A self-sanitising feature can be designed to enable repeated wear with multiple washings.
Antimicrobial properties	Limited antimicrobial properties	They have enhanced antimicrobial properties due to the incorporation of nanomaterials.	ZnO-, TiO_2-, and silver-like-nanomaterial-finished fabric with antimicrobial properties can be incorporated, allowing masks to be reused multiple times.
Contaminant	Provides essential protection against contaminants like aerosols and viruses.	Enhances protection via antimicrobial nanomaterials and heating elements.	To enhance contaminant protection, antimicrobial nanomaterials can be finished on mask textiles, along with extra filtration layers and heating elements.
Self-sanitisation	It relies on materials inherently possessing antimicrobial properties or treated with antimicrobial agents.	Face masks finished with nanomaterials and heating elements provide self-sanitisation.	These masks can be developed using nanomaterials with antimicrobial properties to minimise bacterial and viral contamination, while the heating element enhances self-sanitisation through thermal disinfection.
Safety for the wearer	Increased exposure to contaminants from aerosols and viruses may exacerbate skin irritation or allergic reactions due to the materials used.	Masks enhanced with nanomaterials' antimicrobial properties and heating elements should avoid discomfort and burns for prolonged skin contact.	Nanomaterial-finished masks should ensure antimicrobial safety, while those with heating elements must prevent discomfort and burns and adhere to electrical safety standards for user protection.
Environmental impacts of mask disposal	Disposing of non-biodegradable masks poses environmental risks like landfill accumulation and long-term chemical or microplastic leaching.	Reusable masks offer extended durability, minimising the need for frequent disposal.	Enhance mask materials' biodegradability or implement dedicated recycling programs for reusable masks to promote sustainability.

5. Conclusions

This comprehensive study has highlighted the potential of nanomaterials and thermoregulation-based smart textiles for use in developing self-sanitising face masks, which could reduce the environmental impact of traditional non-biodegradable face masks sent to landfills after a single use. In this study, evidence relating to how nanomaterials can be used as antimicrobial agents, in addition to thermal heaters for developing self-sanitising masks, has been discussed. It can be noted that textiles finished with nanomaterials using zinc oxide, titanium dioxide, silver, copper, and gold are known for their antimicrobial properties. Thermoregulation systems can significantly enhance face masks' filtration efficiency and self-sanitisation capabilities. These advanced masks provide extended durability, reduced bacterial contamination, and minimised skin and ocular irritation, making them a superior alternative to conventional single-use masks. Moreover, the longer-term benefits of nanomaterials and the optimisation of thermoregulation systems to achieve consistent self-sanitisation efficiency remain areas for further investigation.

Furthermore, future research should focus on developing reliable systems to enhance self-sanitisation capabilities, testing their performance, and enhancing human safety. Beyond the healthcare sector, the applicability of these advanced face masks extends to various industries where contamination control and personal protection are paramount, such as food processing, packaging, textiles, and other manufacturing industries. Investigating the use of these masks in such environments could offer substantial benefits, enhancing safety and operational efficiency while contributing to a more sustainable approach to waste management. These self-sanitising masks overcome the shortcomings of conventional face masks. Future research can also focus on the use of bio-degradable [such as plant-based lycra for adequate elasticity and fit and poly-lactic-acid-based nonwoven materials—derived from corn] materials in the development of self-sanitisation masks, which can be reusable, durable, antimicrobial, and sustainable. Once these masks reach their end-of-life stage, they can be safely composted. It is suggested that future research, development, and investment be directed toward these eco-friendly self-sanitising masks, which could be used in different settings, be prepared for future pandemics, and reduce the waste generated by disposable conventional face masks.

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