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Internet-of-nano-things (IoNT) driven intelligent face masks to combat airborne health hazard

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Face masks have been used as the most effective and economically viable preventive tool, which also creates a sense of social solidarity in collectively combatting the airborne health hazards. In spite of enormous research literature, massive production, and a competitive market, the use of modern age face masks-respirators (FMR) is restricted for specific purposes or during public health emergencies. It is attributed to lack of awareness, prominent myths, architect and manufacturing limitations, health concerns, and probable solid waste management. However, enormous efforts have been dedicated to address these issues through using modern age materials and textiles such as nanomaterials during mask fabrication. Conventional FMRs possess bottlenecks of breathing issues, skin problems, single use, fungal infections, communication barrier for differently abled, inefficiency to filter minute contaminants, sourcing secondary contamination and issue of solid-waste management upon usage. Contrary, FMR engineered with functional nanomaterials owing to the high specific surface area, unique physicochemical properties, and enriched surface chemistries address these challenges due to smart features like self-cleaning ability, biocompatibility, transparency, multiple usages, anti-contaminant, good breathability, excellent filtration capacity, and pathogen detecting and scavenging capabilities. This review highlights the state-of-the-art smart FMR engineered with different dimensional nanomaterials and nanocomposites to combat airborne health hazards, especially due to infectious outbreaks and air contamination. Besides, the myths and facts about smart FMR, associated challenges, potential sustainable solutions, and prospects for "point-of-action" intelligent operation of

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smart FMRs with the integration of internet-of-nano-things, 5G wireless communications, and artificial intelligence are discussed.

Keywords: Airborne hazards; Internet-of-things; Nanotechnology; COVID-19; Smart and intelligent masks; Sustainable solid-waste management

Rise of face masks: Old civilizations to the modern age

Face masks have always been a vital part of human lives, since the time of old civilizations. The research and development are quite evident from numerous research publications, industrial start-ups, and a highly dedicated and competitive market. However, their use is not still normalized due to unawareness, design and manufacturing limitations, health issues and solid waste production. These bottlenecks have been challenged from time to time by modifying their architecture, choice of material used for manufacturing, and spreading awareness. Major devotion is attributed to employing and evaluating a variety of materials and textiles for their manufacturing in accordance with the targeted application. This has resulted in the availability of numerous varieties of masks fabricated from modern age materials and textiles such as nanomaterials and biomaterials in the present-day market. However, their use is still limited, enforced by policymakers, and under protection from devastation due to public health emergencies such as viral outbreaks or air contamination and other medical policies. It clearly indicates the lack of awareness and education regarding pros, cons, facts, and myths related to modern age masks in the masses. It includes fear of nanoparticle inhalation, waste production, secondary infections, low breathability, and adverse health concerns. This review gains motivation to address these facts, myths, pros, and cons and create awareness in the masses about modern age masks with intends to fill the market gap between availability and usage of masks, and to normalize the usage of masks.

Traditionally, face masks have been part of numerous old civilizations with evidence mentioned in historical and mythological literature. The initial annals of the practice of face mask-like cloth cover are evident on entrances of Persian tombs. With the requirement and traditions of society, the form of masks has been changed from 13th century skin scarves in the Yuan dynasty, to beak masks containing herbs and wet clothes coverings adopted in London in the 16th century to prevent the plague, to lose animal bladder skin in the 18th century. Afterward, the development of masks took prompt growth with a patent in 1877 for a smoke-face mask consisting of a sequence of water-saturated sponges to filter out smoke, and a six-layer gauze-based mask with a provision to tie on face designed in 1899. This initiated the modern time mask development, which is evident in the usage of facemask-like coverings during the Manchurian plague-1910, Spanish flu-1918, world war-I, Gibb's respirator-1920, and single-use paper face mask-1960. The variation in features of masks and personal protection kits was monitored by establishing the Occupational Safety and Health Administration (OSHA) and the National Institute of Occupational in the 1970s. This leads to an incessant growth in research and development of face masks leading to a single piece of silk cloth to intelligent FMRs as depicted in the timeline of FMR in Fig. 1.

Modern age FMRs are usually prepared by nonwoven polymeric fibres of variable thickness and porosity. Thus, the FMRs have always been a part of our civilizations from old ages to modern ages for various purposes including combatting infectious outbreaks, preventing the air and particulate contaminants, and as a choice of personal hygiene. However, they are mostly adopted to address air-borne health hazards due to contaminants and infectious pathogens.

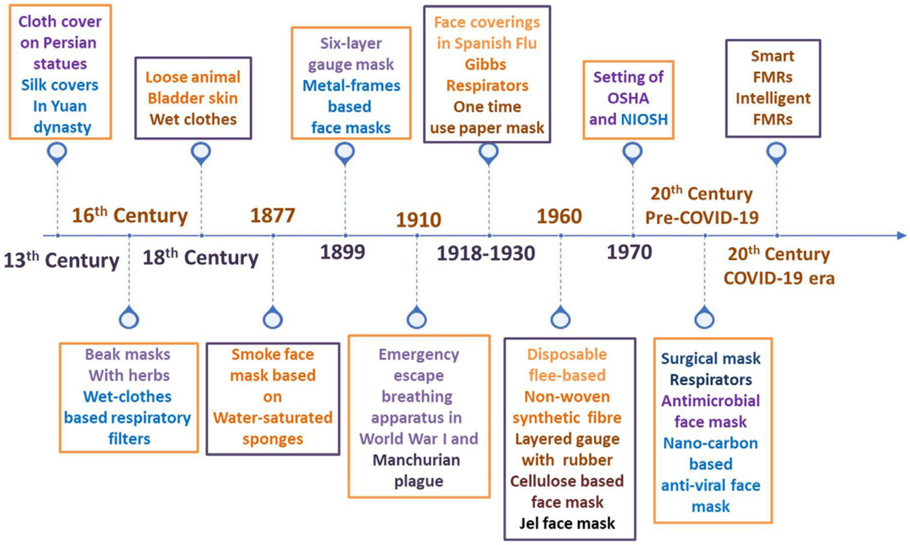

FIGURE 1

Timeline for illustration of growth in the development of face masks from early-stage skin cloth pieces to smart and intelligent FMRs.

Airborne infections and pollution: A gigantic enemy for humanity

The expanding requirements of the growing global population have led to extensive urbanization, technological advancements, globalization, and industrialization. These technological and urban developments have contributed to challenging global threats including climate change, water scarcity, and environmental contamination. As well globalization has contributed to the rapid spread of infectious diseases as evident in the current scenario of coronavirus disease (COVID-19) due to severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). Amongst all, air pollution and airborne infections are one of the foremost concerns to disrupt planetary health and are major contributors to global human mortalities directly and indirectly [1,2].

Numerous studies have pointed out that the contaminated air serves as one of the transmission modes of contagion and affects the human respiratory, immune, and nervous systems on inhalation [3–6]. For instance, there are several transmission routes of viral infections including droplet-based transmission, airborne transmission, and physical mode transmission [7,8]. The droplets produced during sneezing, coughing, and salivation by the infected person cause the transmission of these contagions. Additionally, it is less known that fundamental action like talking is also capable to release potentially contagious droplets and aerosols. A study based on laser light scattering and aerodynamic particle sizing technique showed that on average 1000 droplet particles are emitted in a second while talking. In another study, it was revealed that the droplet particle emission increases in direct proportion with the loudness of sound. Typically, these contaminated droplets produced from different means can reach a healthy person's respiratory tract either through physical contact (when the droplets are around 5–10 μm in diameter) or through airborne aerosols (where the size of droplets is less than 5 μm in diameter) [8,9] (Fig. 2).

In airborne transmission, the contaminating particles remain afloat for some span and can transmit to a longer distance. Various respiratory viruses including measles, varicella-zoster, SARS-CoV-2, rhinovirus RNA, and influenza are capable to transmit through airborne routes [10]. Similarly, the inhalation of air contaminants including oxides of nitrogen, sulphur, and carbon, ammonia, particulate matter adversely damages the human respiratory, immune, and nervous systems turning them more susceptible to airborne infections like influenza. Moreover, the varying composition of air contaminants depending on the source aids in the continual re-assortment of airborne infectious pathogens. It creates challenges for state-of-the-art preventive and therapeutics available for specific contagions. Additionally, several air contaminants play an active role in the transmission of causable airborne pathogens like PM act as secondary transmission airborne source for COVID-19, and ammonia alkalinizes the environment favouring survival, transmission, and entry of various airborne pathogens into a human [11,12]. The effect of various air contaminants on human health and their function in aiding airborne infections is summarized in Table 1.

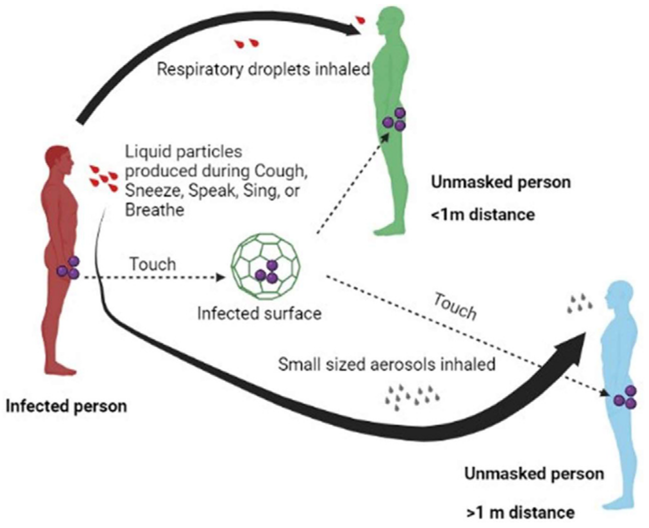

FIGURE 2

Different transmission routes for SARS-CoV-2 infection from an infected person to the healthy persons present either less than 1 m distance or more than 1 m distance.

The paradigm of intelligent face masks-respirators: Most effective preventive measure

The hazards caused by air contaminants and airborne infections suggest the rapid adoption of preventive measures to halt the entry of air contaminants and causable pathogens into the human respiratory tract. There are various strategies available to prevent and reduce airborne health hazards including face masks-respirators, air purification devices like air purifiers and smog towers, adopting green fuel and technologies, and maintaining personal hygiene. In severe conditions, strict preventive measures such as restricting partial transportation, isolating infected individuals, and employing lockdown have been adopted. However, the restrictions on anthropogenic activities are not medically, socially, and economically feasible, whereas air purifiers are majorly limited to indoor usage [23,24]. Additionally most of the personal hygiene strategies include harmful chemicals and possess short-term prevention capabilities [8]. Particularly for airborne infections, vaccination is observed to be the most successful preventive measure [7,25–27]. However, the advent of more resistant strains with large contagion potential like the Omicron strain in the case of SARS-CoV-2, due to mutation or re-assortment of pre-existing pathogens are turning current vaccines and therapeutics incompetent [28]. Additionally, the vaccine's production, transportation, distribution, and administration are challenging to most developing nations, keeping their economy, population, and resources with geographical limitations. Moreover, no such preventive therapeutics are available to combat the hazards of inhaled air contaminants on human health. It points out that the utilization of FMRs is most economical due to their affordability (low cost) and sustainability (long-term protection) compared to other preventive measures. Additionally, the vaccine's production, transportation, distribution, and administration are challenging to most

TABLE 1

Various sources of air contaminants, their role in aiding airborne infections, and hazards on human health and the environment with the lowest human exposure limit.

Air contaminant	Anthropogenic sources	Hazards to environment	Hazards to humans with severe exposure limit	Contribution towards airborne infection
Ammonia (NH_3) [13,14]	Industries, Livestock, Agriculture, Human waste	Eutrophication, formation of particulate matter, smog	Severe to the human respiratory and nervous system (35 ppm for 8 h)	Alkalinize environment favourable for pathogen growth and transmission
Nitrogen oxides (NO_x) [6,15]	Fuel combustion transportation, domestic heating	Formation of smog and particulate matter, damage to agriculture	Severe to the cardiovascular and respiratory system (100 ppm for 30 min)	Cytokine-mediated inflammation
Carbon oxides (CO_x) [16,17]	Industries, fuel combustion, household appliances, transport, cement manufacture	Global warming and climate shift due to the greenhouse effect	Severe to nervous and respiratory system, affects consciousness (50 and 5000 ppm of CO and CO_2 for 8 h, respectively)	Weakening immunity
Sulphur Dioxide (SO_2) [18–20]	Petrochemical and winemaking industries	Acidification of water bodies and air	Severe to respiratory, nervous, and epithelial system (5 ppm for 10 min)	PM formation which acts as a secondary transmission route, weakening immunity
Particulate Matter ($PM_{2.5}$ and PM_{10}) [6,15]	Construction, sea salt, transportation	Smog, climate shift, and acidification	Severe to immune, respiratory, and nervous system (35 $\mu g/m^3$ for 24 h)	Virus transmission and weakening of immunity
Volatile organic compounds (VOCs)[21,22]	Industries, laboratories, petroleum production	Formation of smog, PM, and ground-level ozone, water contamination	Severe to respiratory, nervous, and cardiovascular system	Weakening immunity

developing nations, keeping their economy, population, and resources with geographical limitations. Moreover, no such preventive therapeutics are available to combat the hazards of inhaled air contaminants on human health. It points out that the utilization of FMRs is most economical due to their affordability (low cost) and sustainability (long-term protection) compared to other preventive measures.

Consequently, the sound, economic, and practical approach to combating airborne health hazards is to cover the face using masks, shields, and respirators. For instance, in the case of airborne communicable diseases, FMR is advised to use by both infected and non-infected individuals [10]. A sick person can restrain the transmission of the virus by restricting the respiratory droplets coughed or sneezed inside the mask. In contrast, a healthy person can safeguard himself from viruses and pollutants present in the air as aerosol or droplets, accidental touch on contaminated surfaces, by covering the face through a mask.

Recently, Eikenberry et al. [29] showed the reduction in mortality and community spread of COVID-19 on basis of data analysis performed for Washington and New York megacities. The cumulative mortality rate due to COVID-19 in these cities was anticipated to reduce to a larger extent on the use of masks by a larger number of citizens (Fig. 3).

Moreover, Leung et al. [10] tested the efficacy of surgical masks to block the release of viruses in exhaled breath of virally infected patients. They observed a substantial descent in SARS (not present) and influenza viruses (present in 1 out of 27) in exhaled breath of patients with the mask on. Similarly, another survey-based study conducted in five hospitals revealed that the healthcare workers working in COVID-19 wards with surgical or N95 masks on were capable of saving most of them from the infection, whereas those using paper masks were infected [30]. Recently, Cheng et al. [31] validated these findings through their study in which they proved that the correct use of face masks effectively controls the outbreak of COVID-19 by reducing the probability of SARS-CoV-2 transmission. These studies indicate the importance of correct usage and choice of type of masks to curtail the risk of COVID-19 infection. Especially in COVID-19 majority of cases are asymptomatic, which acts as silent transmission sources and can be averted by every-one's using FMRs [7].

Moreover, the usage of masks provides physical hindrance, which averts the wearer from contact with the face resulting in better hand hygiene. These outcomes advocate the usage of the appropriate types of masks by infected and healthy people to prevent airborne or direct infectious pathogens. Masks are recommended even after the vaccination for old individuals as well as diabetic persons. Realizing the potential, most countries have mandatory the use of FMRs in public places for their citizens during airborne infectious outbreaks like in COVID-19 scenario. Moreover, the common instruction in the advisory of pollution control boards in highly polluted cities during air contaminant outbreaks suggests the use of FMRs. the global FMR market size of value US-$ 6792.0 million in 2019 is anticipated to grow up to US-$ 9052.1 million by 2027 with a CAGR of −11.1% from 2021 to 2027 [32,33]. It created a global bloom in the FMR market is due to its cost-effectiveness, ease of manufacturing, availability, and usage, and high efficiency. Moreover, the

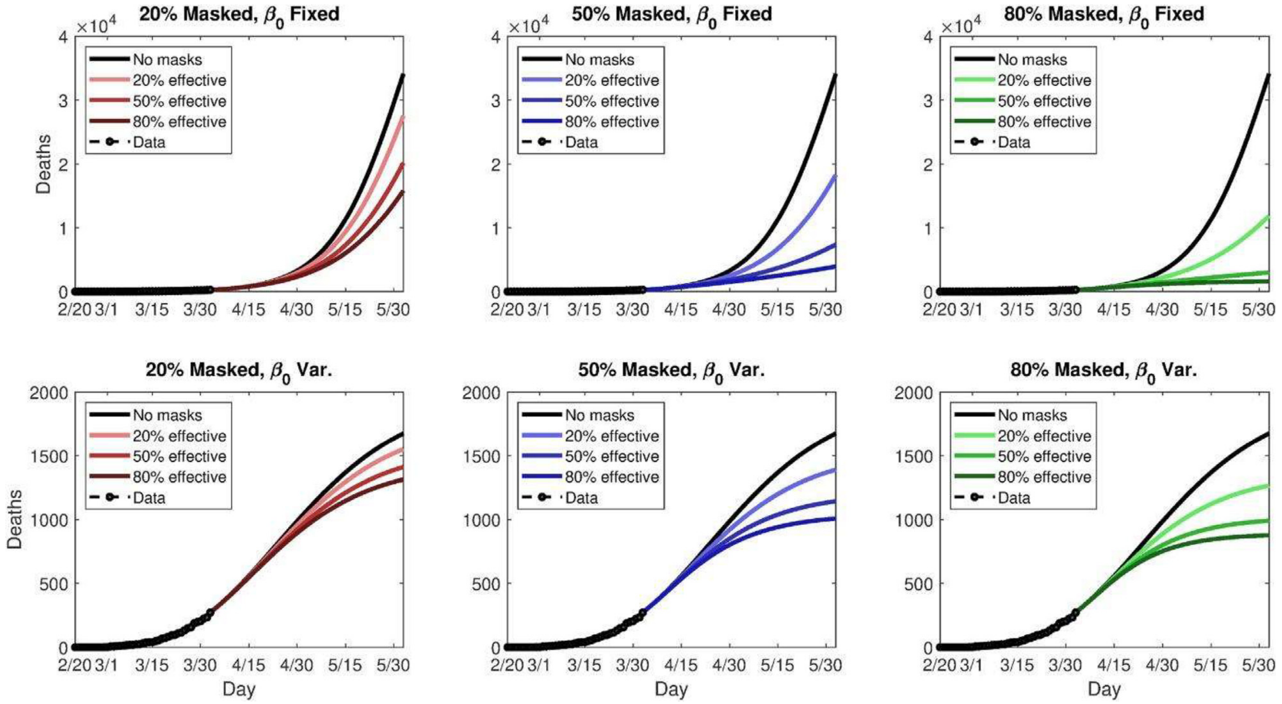

FIGURE 3

Simulated predictions of cumulative mortalities for Washington state due to COVID-19, utilizing either a fixed (top panels) or variable (bottom panels) β, transmission rate, and nine various combinations of general-public mask usage and efficacy; Reproduced with permission from [29] Copyright 2020, Elsevier.

widespread adoption of FMRs possesses enormous potential to combat community transmission of infectious diseases and prevent health hazards due to air contaminant inhalation.

With these recommendations and merits, wearing FMRs has become the "new normal", especially during infectious outbreaks and highly polluted megacities. FMRs have been adopted as a prominent long-term solution in the vicinity of proper and effective solutions. The existing recommendation by the WHO about using FMRs only in certain scenarios (like closed or crowded spaces) was expeditiously protracted to nearly every situation where not cohabitant individuals are involved in public/-mutually shared spaces. Moreover, the use of FMRs is no more restricted to the healthcare fraternity but has been adopted by individuals from every sector, every age, and every area. For instance, especially in the COVID-19 era, they have been used by almost every individual to safeguard themselves from infection. However, this preventive solution possesses many bottlenecks during massive long-term use including breathing issues, skin infection, solid-waste management, communication barrier, safety concerns, and different health distresses. Nanotechnology has been touted as one of the prominent solutions to cater to these challenges by engineering FMRs with nanomaterials. It is attributed to enhanced surface activities of nanomaterials owing to their enhanced properties due to size effects and quantum confinement effects. These remarkable properties including tunable optical and electrical band gap, optimum porosity, selective adsorption, high specific surface area, and biodegradability have shown tremendous potential to fabricate smart FMRs with advanced features of transparency, high breathability, pathogen scavenging, biocompatibility, and self-cleaning. Moreover, the integration of internet-of-things (IoT) and artificial intelligence (AI) in nanomaterials have raised the paradigm of internet-of-nano-things (IoNTs) based on intelligent and smart FMRs (Fig. 4).

This comprehensive review is structured to illustrate state-of-the-art FMR, their associated bottlenecks, and the research and development dedicated to growth in nanomaterials based on smart FMRs. It intends to detail the various nanostructures of different dimensions (including 3D, 2D, 1D, and 0D), and nanocomposites engineered to architect smart FMRs. Besides, the advanced features developed in FMRs due to the use of an optimized nanomaterial, the underlying associated fundamental physical phenomena and performance of smart FMRs are highlighted. Additionally, the challenges due to the use of nanomaterials in FMRs, alternate potential solutions, and the myths and facts related to smart FMRs are discussed. Lastly, the prospect of developing point-of-action intelligent and smart FMR with the integration of IoTs, 5G communication networks, and AI are presented to provide optimal preventive, diagnostic, and solution to airborne health hazards.

Conventional FMRs: Classification and bottlenecks

Conventionally, FMRs are categorized based on their filtering efficiency including respirator masks, surgical masks, single-use layer masks, and cloth masks [34]. The efficiencies, design, and fitting over face of these classes of FMRs are illustrated in Table 2.

Although medical and commercial respirators (generic respirators) possess ultrahigh filtration efficacies, they are specially designed, complex, difficult to carry, cumbersome, heavy, and not advisable to wear for a long time [35]. Contrary, respirator masks are a light weighted, portable, and simple way to cover the face and protect from airborne health hazards. Amongst all,

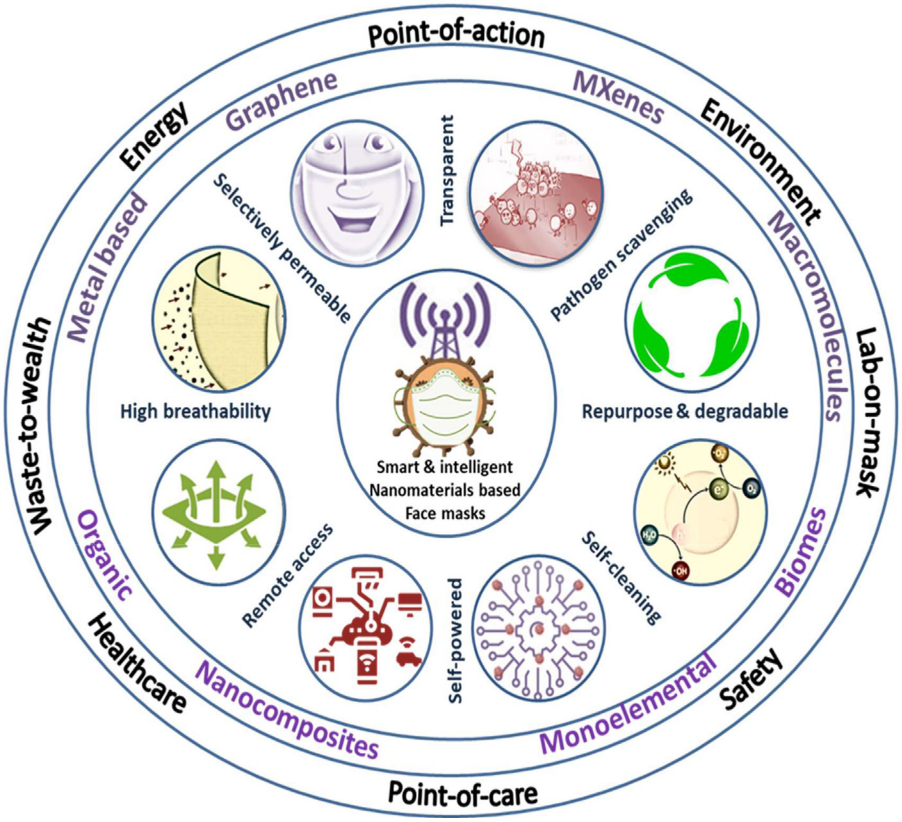

FIGURE 4

Paradigm of smart and intelligent FMRs based on the different types of nanomaterials with the integration of IoT, AI, 5G communication, and data clouding for advanced applications.

TABLE 2

Different classes of face masks and respirators with their characteristics.

Type of mask	Face fitting	Filtering efficiency (for contaminant's size up to 300 nm)	Layers (mouth to outside)
Respirator masks (N-95 and FFP2 masks)	Tight	High (∼95%)	Four (non-woven layer, activated carbon layer, cotton layer, and second non-woven layer with an optional valve)
Surgical masks	Loose	High (∼80%)	Three (non-woven fabric, polypropylene layer, non-woven fabric)
Single-use disposable masks	Loose	Moderate (40–55%)	Single (non-woven, generally folded into 3-ply)
Cloth masks	Moderate	Low (20–40%)	Single (can be folded once or twice depending upon the material of the fabric)
Elastomeric respirators	Tight	High (95% or above)	Two-three filters
Powered air purifying respirators	Loose	Very High (99% or above)	Two-three filters
Atmosphere-supplying respirators	Tight	High (99%)	Cumbersome

respirator masks available in the market including N95 masks (US-based) and FFP2 masks (UK-based), are a popular choice and most commercialized due to their highest filtering efficiency. They are often confused with surgical masks due to their similar design; however, they are engineered for special and different purposes (Fig. 5) [36]. The surgical masks are consists of three layers including a thin middle layer with extra-fine glass fibers covered on both sides with wet-laid non-woven or acrylic bonded parallel-laid material [35,37]. On the other side, respirators are consist of four layers including a non-woven layer (filters contaminants up to 500 nm), an activated carbon layer (filters harmful chemical contaminants), a cotton layer (filters contaminants up to 300 nm), and a second non-woven layer, with an optional valve for regulation of breathing [36,38].

Further, the performance of commercial FMRs is evaluated in terms of various factors and criteria. For instance, the American Society of Testing and Materials (ASTM) F2100 standard authorizes the performance of medical FMRs on basis of five criteria including particulate filtration efficiency, fluid resistance, bacterial filtration efficiency, flammability, and differential pressure

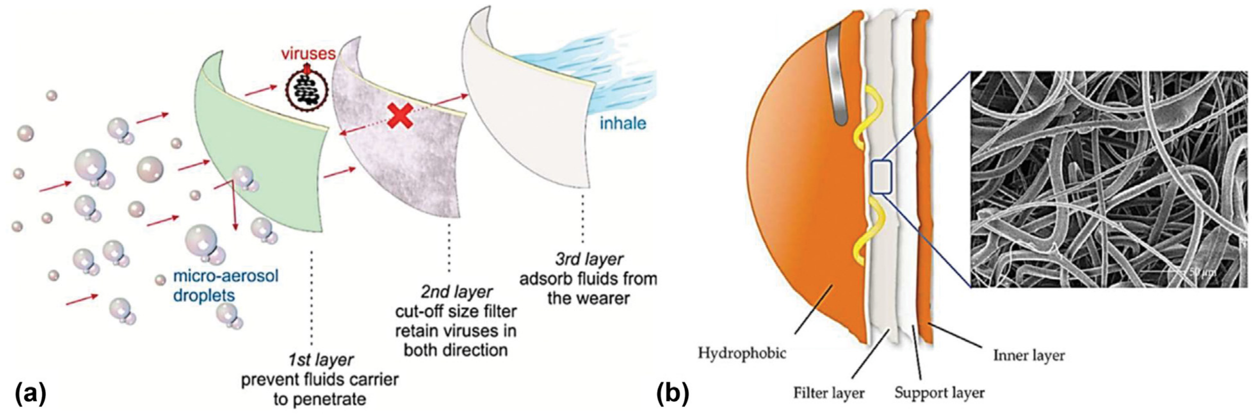

FIGURE 5

Schematic depiction illustrating the difference between the design of (a) Surgical mask; Reprinted with permission of [38] Copyright 2020, MDPI (b) Respirator mask; Reprinted with permission of [37] Copyright 2012, Hindawi.

[39]. This standardization of FMRs is highly required to certify the constancy in mask manufacturing and evaluating validation and helps in the choice of FMR for the intended application.

Though respirator masks have the highest efficiency for filtering contaminants, they possess several disadvantages. These masks must be changed after an encounter with a patient, i.e., these are not reusable, may cause breathing problems on prolonged use due to their four-layered structure, and may cause skin problems as they fit tightly on one's face [34]. Surgical masks possess high filtering capacity due to the presence of a melt-blown polymer (generally polypropylene) as the filter layer sandwiched between two non-woven fabrics. The layer facing the mouth is made up of cotton, which acts as an absorbent, whereas the outermost layer is made up of polyester blend, which acts as a water-repellent layer [36,40]. These masks have proved effective in blocking the transmission of COVID-19 by combined with other preventive measures like social distancing [29]. As these masks fit loose over the user's face, there is a possibility of sideways leakage of infectious content from the masks [41]. Both cloth and single-use masks are unsuitable for COVID-19 health workers due to their low filtering efficiency. However, these are useful when the supply and production of other tiers of masks are limited as they significantly block large respiratory droplets and saliva [9]. Centre for disease control and prevention (CDC), USA, recommends using any of these masks in layer systems, i.e., wearing more than one mask or combination of masks to prevent infection [36]. Recently, the government of India endorsed double masking for better fit and filtering capability after the second wave of COVID-19 in India [26]. The advisory also recommended wearing a face mask even inside the homes and alone driving cars.

However, continuous use of face masks may lead to specific health issues like hypercapnia and hypoxemia [42,43]. Hypercapnia is the accumulation of exhaled carbon dioxide in the bloodstream and can be caused by tight-fitting masks and inadequate ventilation. Similarly, there can be a low level of inhaled oxygen, leading to shortness of breath and chest discomfort or hypoxemia as it is known in medical terms [43]. Both conditions can be hazardous for COVID-19 patients with damaged lungs. Enhanced level of CO_2 over O_2 in the blood is well known to attribute perplexity, reduced cognition, anxiety, hyperthermia, headache, and hand tremors [40,42]. Prolonged use of tight-fitting masks may cause pressure on varicose and cervical nerves leading to physical and general soreness [44]. The pressure due to skin-tight strips may also block facial ducts causing various skin-related problems like acne due to the prolonged use of masks [45].

The recurrent wear of face masks without proper cleaning may lead to a build-up of entrapped pathogens over the mask surface and thus cannot safeguard further from the pathogens [41,46]. Recently, it has been revealed that the SARS-CoV-2 virus persists to be contagious on the outer surface of FMRs even after six days [47]. Additionally, accidental contact with a contaminated surface only for five seconds can results in the transfer of a contagious pathogen to the hands, for instance, 32% of influenza-A virus transfers within 5 s of contact [48]. However, there exist disinfection strategies in the case of reusable FMRs like washing cloth masks with detergent or UV and thermal treatment of N95 respirators [36]. These treatments are discrete, and FMRs get easily re-contaminated on reuse. Moreover, the accumulation of fomite infection on FMR surfaces is anticipated to cause various fungal and microbial diseases. Various pathogen-based infections, including black fungus, yellow fungus, and white fungus, have been recently reported in SARS-CoV-2 infected persons [49]. Moreover, the disposal of contaminated masks acts as a secondary source of further infection and solid waste pollution. The tight-fitting of facemasks also accumulates excessive moisture of breath and humidifies the masks, creating an airtight pocket around the nose and mouth. This situation can be fatal for the wearer doing heavy physical activities like running, exercise, etc. because the air is inhaled and exhaled unfiltered and reduced airflow [46]. Through their guidelines on preventive measures to combat the spread of COVID-19 in gymnasiums and yoga institutes on 3rd August 2020, the Ministry of Health and Family Welfare, Government of India recommended avoiding masks, instead of asking to wear visors as far as possible while exercising [50].

Similar global guidelines to combat COVID-19 and air pollution scenarios have exponentially raised a massive demand for masks [51–53]. A study has suggested a requirement of approximately 89 million masks each month only in the medical sector for treatment and taking care of COVID-19 infected individuals [51]. Moreover, Selvaranjan et al. [53] analyzed that most mask users worldwide are not following the suitable disposal protocols for the used masks. Additionally, a UK-based study revealed that disposing of one mask per individual per day in a year will result in around 124,000 tons of unrecyclable plastic waste, 66,000 tons of contaminated waste and 57,000 tons of plastic packaging [54]. It raises a serious concern about solid-waste management to arise due to the usage of face masks on a massive scale. Lastly, there can be issues related to demand and supply for mass production of surgical masks and respirators in the current pandemic restrictions [46].

Hence, FMRs owing to their economic, easy, and rapid availability are highly desirable preventive measures, which act as efficient potential shields against infectious diseases and air contaminants. However, the associated bottlenecks of massive production, limited filtering capacity, health issues, single-use, and waste production restrict their commercial development and raise secondary concerns of disposing-off and source of contamination. These issues can be addressed by the inclusion of nanomaterials during the fabrication of FMRs. This review comprehensively summarizes the nanomaterials-based FMRs, their smart operation prospects, associated challenges, myths and facts, and advanced prospective applications.

Nanotechnology: An alternate solution to bottlenecks associated with traditional FMRs

After looking at the various limitations of the conventional face-masks, it is necessary to manufacture enhanced facemask fabrics using the available technology with advanced features and lesser costs. Nanotechnology has been touted as a game-changing technology to address these issues and design smart and intelligent FMRs with the integration of the internet-of-things (IoT). It deals with architecting and engineering materials at dimensions between approximately 1 and 100 nm [55]. Owing to surface size effects and quantum confinement effects, nanomaterials possess high specific surface area and excellent physicochemical properties and are applicable in diverse fields. Therefore, nano-engineering functionalization of textiles by adding various nanomaterials into textiles (called nano-textiles) has an immense potential to enhance the durability, filtration efficiency, sustainability, and protective features of FMRs. For instance, the high surface-to-volume ratio in nanomaterials enhances the molecular interactions at their effective surface, including the selective interactions with nano-sized pathogens such as bacteria and viruses [8].

Nanomaterials-based FMRs (NFMRs) can check most of the problems related to conventional masks based on bulk materials and textiles and retains extra advantages [8,46,56]. NFMRs possess great potential and can address every challenge associated with conventional NFMRs. For instance, the central issue of the bulk material-based conventional FMRs is the retention of carbon dioxide, causing hypoxemia, hyperthermia, hypercapnia, and skin-related problems, which can be taken care of by modifying the air permeability of FMRs [42]. Air permeability is defined as the amount of air flux permitted by the mask surface to pass through it. It depends upon the thickness of the mask's layers and the porosity of the material used [34]. The nanoscale fabrication of materials enhances their porosity, and the addition of nanomaterials reduces the thickness of masks. The conventional FMRs possess different layers to acquire different properties and purposes. For instance, a typical surgical mask has three layers: hydrophobic layer, filtering layer and inner layer with different functions. However, with the integration of nanomaterials to fabricate NFMRs, a multifunctional layer can be fabricated, potentially replacing many layers into a single layer. Moreover, the low surface-to-volume ratio and enhanced porosity further contribute to a reduction in net thickness. Both properties together make the NFMRs more permeable than bulk material-based conventional FMRs. Moreover, the high porosity of nanomaterials is also anticipated to improve the FMR’s filtering capacity due to higher effective surface area. More air permeability allows the filtering of a greater number of pathogens through nanomaterials in the FMR's layer (Fig. 6).

The specific functionalization of nanomaterials can provide selectivity in filtering. Such nanomaterial containing FMRs prohibits the entry of specific target particles, including pathogens, but allows other particles to filter-in easily [46,57]. The high effective surface area of nanomaterials further enhances the selective action of these functionalized textiles or layers. Further, NFMRs can be made smart and eco-friendly by utilizing various nanomaterials. For instance, several nanomaterials have been reported to possess antibacterial and antiviral properties. The surface of these nanomaterials either does not allow the pathogens to replicate or destroys the germs/contaminants instantly once in contact. The nanomaterials of carbon [58], inorganic [57], and organic [59] nanomaterials possess anti-pathogenic properties. The presence of nanomaterials with a high effective surface area can augment the bactericidal and virucidal activities in NFMRs and makes them more efficacious in controlling the spread of infection and harmful effects of contaminant inhalation.

Moreover, several nanomaterials possess the ability to annihilate the entrapped pathogens at their surface by photocatalytic or electrocatalytic reactions [57] (Fig. 7). The basic principle of

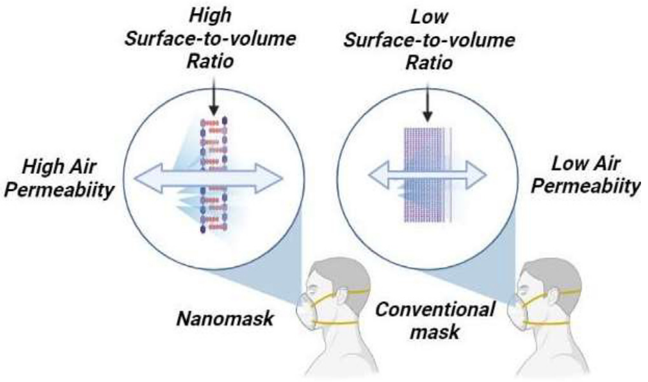

FIGURE 6

Due to the presence of a high surface-to-volume ratio in nanomaterials, there is enhanced porosity in nano masks as compared to the traditional face mask materials.

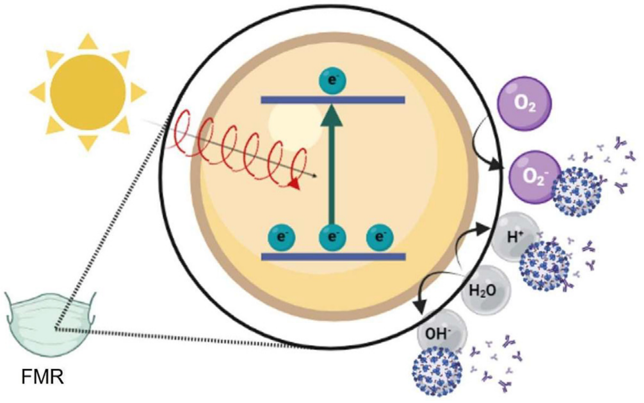

FIGURE 7

Photo and electrocatalytic reactions occur at the surface of diverse nanomaterials, during which the free radicals are generated (using either UV energy or electrostatic charge) and kill the pathogens therein.

photocatalytic-based cleaning of nano-masks is based on the 'Honda-Fujishima effect' [60]. Under this effect, nanomaterials like titanium-oxide produce oxygen radicals from the captured humidity of the atmosphere on irradiation with UV rays (sunlight). These generated radicals can decompose various organic matter, including fat, oils, pathogens, and other contaminants [61]. On the other hand, the electrocatalytic-based cleaning mechanism involves electrostatic charges (instead of UV radiations) to generate the free radicals and extinguish the pathogens. Nanomaterials like magnetite (Fe_3O_4) have the property of induction of static charges by simple rubbing and hence can be used for self-cleaning nano-masks preparation [60]. The self-cleaning property of these masks will be helpful to control the spread of secondary infection, dispose of the utilized masks, reduce solid waste, and clean them easily [60]. Due to their self-cleansing property, NFMRs can be reused multiple times after the cleansing process resolving the problem of disposing-off and secondary contamination [61].

Interestingly, several nanomaterials like Au-citrate and SiO_2 are hydrophobic. This phenomenon of hydrophobicity can be further enhanced at the nanoscale due to the larger effective surface area of nanomaterials [62–64]. This characteristic feature of nanomaterials can be used for designing the NFMRs which are impermeable to aerosols, are dirt-phobic, and can repel the entry of various water or humidity-borne pathogens including coronaviruses. Moreover, synthesizing nanomaterials using green technology involves using plant or animal extracts as the starting material [65,66]. The finally produced fabrics are primarily organic nanomaterials without any toxic by-product chemicals. These are innocuous, economical, compostable, and safe to the user and environment [65,66]. These green nanomaterials with a high surface-to-volume ratio further enhance their degrading action while interacting with specific microbe [67]. Moreover, the mechanical strength of various textiles can be enhanced at the nanoscale due to their high surface-to-volume ratio, which in turn sustains the filtering and anti-pathogenic properties of FMRs even after their repeated usage [8]. Therefore, these NFMRs can be used for a longer time than other "use and throw" masks and help reduce waste production and soil contamination.

A unique con associated with using conventional FMRs is creating barriers to the communication of differently-abled people [68]. Thus, see-through, or transparent masks are essential requirements for persons with hearing and speech disabilities. They require facial expression cues for proper communication with other people. In addition to this, transparent masks will be preferred by organizations and institutions where many people work, study, or live together. Still, the identification of individuals is problematic due to face mask covering. Opaque facemasks are a security concern for different establishments like ATMs, shopping malls, banks, etc. Nanomaterials with a suitably tuned optical band gap can be used to fabricate transparent textiles for NFMR fabrication [68–70]. Thus, nanotechnology can play an essential role in advancing all classes of masks and has been a centric attraction of textile industries to control different infections and prevent adverse impacts of air contamination. Various reports in the literature on nanomaterials based FMRs are summarized in the succeeding section.

Innovations to architect smart FMRs using different dimensional nanomaterials

Nanomaterials are manufactured either by reducing the dimensionality of bulk materials (top-down approaches) or by architecting from molecules (chemical approaches). Depending upon the dimensionality, nanomaterials can be classified into three dimensional (like nanoparticles), two dimensional (like nanosheets), one dimensional (like nanofibers), and zero-dimensional (like quantum dots) materials [55] (Fig. 8). Every class of nanomaterials possess unique merits, which can be utilized to architect desired feature in NFMRs. Most importantly their high specific surface area, optimum porosity, and tunable physicochemical properties make them special to enhance fundamental features (high filtering and breathing capacities) of FMRs, whereas their unique antimicrobial, biodegradable nature and tuneable band gap contribute to achieving smart features (sensing, transparency, biocompatibility, reusability and self-cleaning) of FMRs. This section summarizes reports in the literature on NFMRs fabricated using different low-dimensional materials with superior fundamental features and advanced smart efficacies compared to their bulk counterparts. Moreover, the underlying working mechanisms of NFMRs are explained.

Three-dimensional nanomaterials based FMRs

Three-dimensional (3D) nanomaterials are with one or more dimensions on the nanoscale, for, e.g., nanospheres or nanoparticles (possessing diameter in nanoscale) [55]. Due to the high surface-to-volume ratio, these nanomaterials possess enhanced optical, electrical, thermal, physical, chemical, and anti-pathogen properties [8,71]. Amongst all, metal nanoparticles like copper and silver nanoparticles own anti-pathogen properties and a high surface-to-volume ratio [72–74]. The anti-pathogenicity in metal nanoparticles is due to the generation of metal ions after the adsorption of atmospheric oxygen over the metal surface [75]. Generally, the biocidal action of metal nanoparticles includes two basic steps penetrating nanoparticles causing disruption in cell membrane metabolism by releasing metal ions, and the action of photocatalytic as reactive oxygen

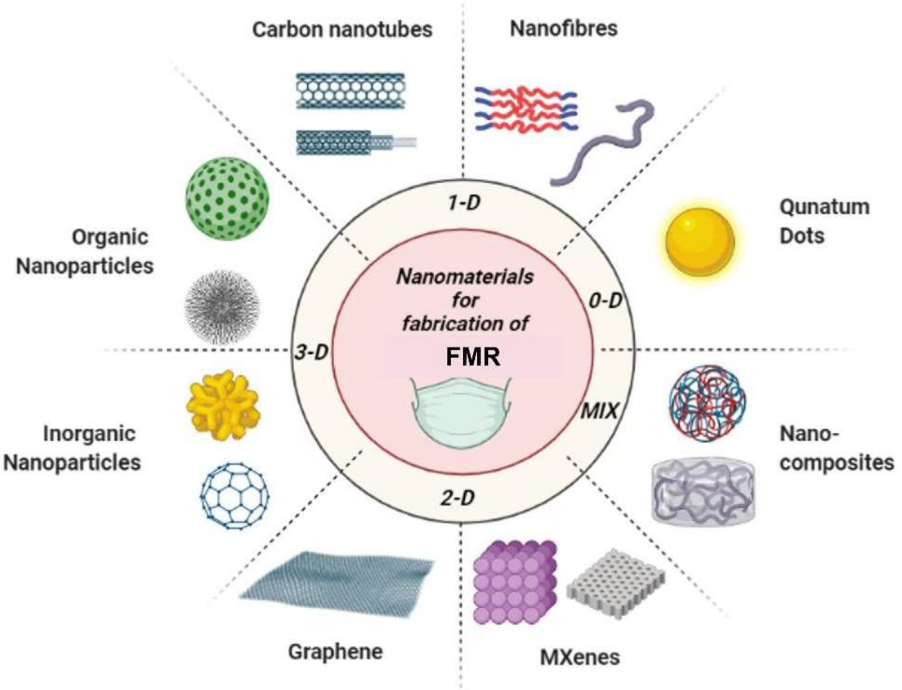

FIGURE 8

Five categories of FMR based on their dimensional nanomaterials.

species (ROS) such as superoxide radicals and hydroxyl, adsorbed on metal nanoparticles. These generated ROSs induce oxidative stress to pathogens and contaminants causing their ultimate inactivation or destruction. In silver nanoparticles (Ag NPs), the generation of warming effect by high infra-red reflectance augments their anti-pathogen effect [74]. A US Patent 6979491 reported the fabrication of antimicrobial yarn for architecting masks by loading glucose-capped Ag NPs on fibrous material [36]. The yarn exhibited excellent antimicrobial activity against various bacteria genus like *Chlamydia*, *Escherichia*, *Bacillus*, *Staphylococcus*, *Pseudomonas*, and fungi like *Candida albicans*, even after 100 times of washing. Hiragond et al. [76] proposed a more facile strategy consisting direct coating of AgNPs onto surgical masks. They evaluated the antimicrobial activity of masks soaked in starch-capped Ag NPs based colloid against both Gram-positive (*Staphylococcus aureus*) and Gram negative (*Escherichia. coli*) (Fig. 9).

Ag NPs are also evaluated for antiviral performance, importantly against SARS-CoV-2. For instance, Aggarwal et al. [8] have reported an antiviral triple-layer-based mask based on N-9 nanosilver coating with high breathing efficiency. Additionally, Anson Biotechnology Co. Ltd. has reported AgNPs based user friendly, reusable, anti-viral, and anti-bacterial masks, which are capable of destroying bacteria and viruses by continuous release of ions due to nanosilver [8,36].

Moreover, copper nanoparticles (CuNPs) owing to their ability to produce ROS during the oxidation of Cu(I) by atmospheric oxygen, have also been reported for antiviral and antibacterial performance by including them into FMRs [75,77–79]. For instance, Copper Clothing Ltd. reported washable and reusable KN99 (FFP3) CuNP-infused masks with 99% bacteriostatic ability to S. Aureus and P. Bacillus even after 50 washes. Moreover, Promethean Particles Ltd. have reported CuNPs coated Nylon prepared by using melt extrusion process for manufacturing FMRs [8]. The FMRs exhibited excellent antiviral efficacy against SARS-CoV-2. Both metal NPs are also reported to blend together to achieve superior FMRs. For instance, Nexera Medical Canada has patented a series of reusable face nano-masks based on a blend of silver and copper nanoparticles with superior antimicrobial activity [71].

Consequently, the use of metal nanoparticles in nano-mask manufacture majorly enhances its anti-pathogen activity, high filtering efficiency, high air permeability, self-cleaning, reusability, and toxicity. The various reports of metal nanoparticles-based nano-masks, including copper, silver, and their blends, have been summarised in Table 3. However, the pristine metals are prone to oxidation in ambient conditions due to high reactivity such as dangling bonds in AgNPs. Alternatively, numerous metal oxides like zinc oxide, copper oxide, and titanium oxide are stable and also possess significant antimicrobial properties [73]. The antimicrobial action of metal oxide NPs is generally photocatalytic or electrocatalytic [80]. Metal oxides NPs form ROSs on exposure to light or subjecting to electric potential, and subsequently kill the trapped pathogen [81]. For instance, FMR fabricated from TiO_2 layer coated nonwoven fabric has exhibited excellent filtration and photocatalytic efficacies. Sonavia Ltd. has manufactured ZnO NPs coated polyester fabric-based washable mask with 5 μm particulate filtration using ultrasonic cavitation technology [8]. The masks exhibited 98% bacteria reduction efficacies against *E. coli* and *S. aureus* after one hour of incubation. Various optical properties, including desired color and transparency in masks, can be achieved using metal oxides-

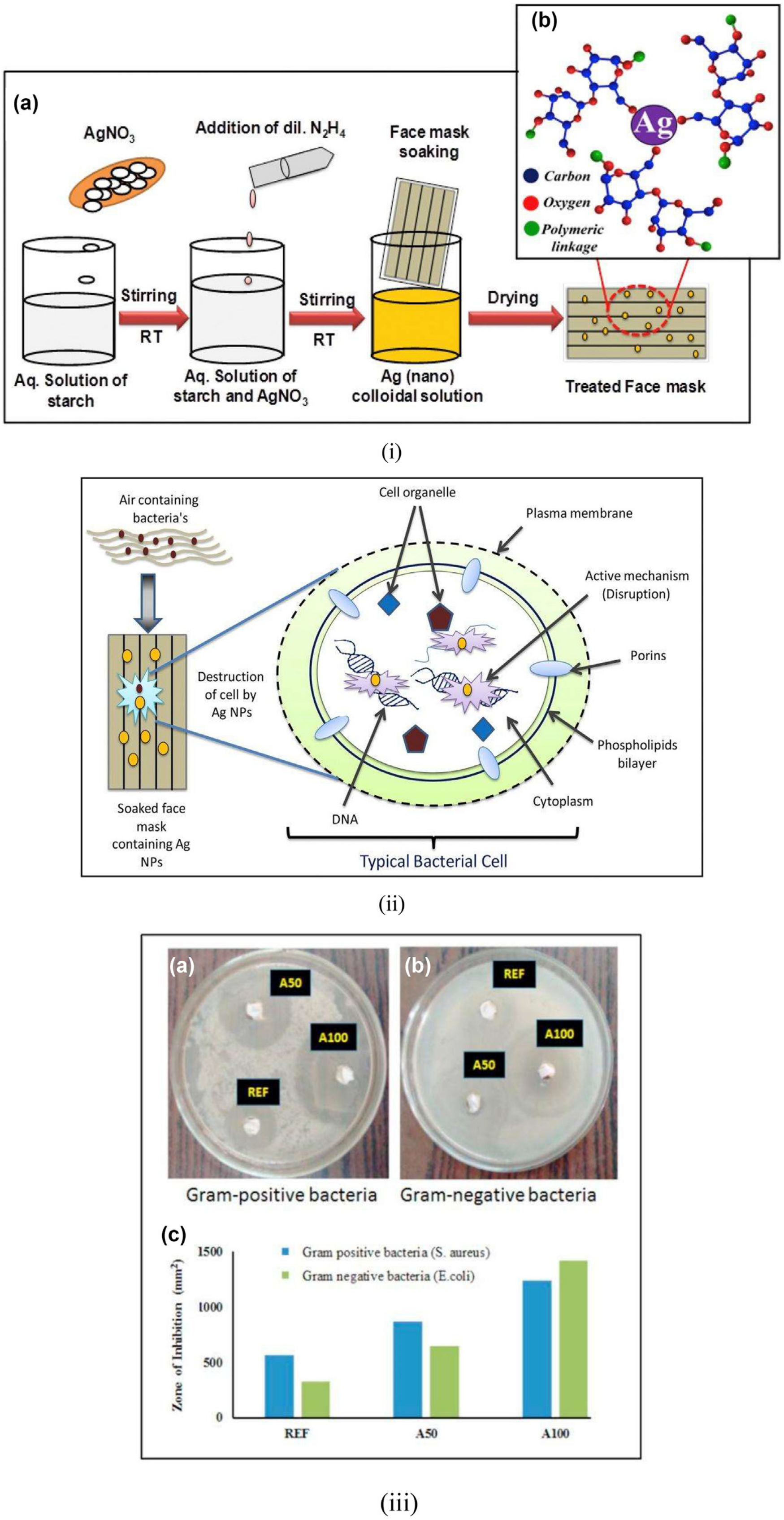

FIGURE 9

(i) (a) Schematic representation of synthesis of colloidal Ag (nano) solution and its treatment with face mask (b) starch capped Ag nanoparticles over the mask, (ii) Representative dual antimicrobial mechanism of Ag nanoparticles embedded face mask, and (iii) Antimicrobial activity with a comparison of the reference sample (untreated face mask cloth), A50 and A100 with the inhibition zone test for (a) Gram-positive bacteria (*S. aureus*) and (b) Gram-negative bacteria (*E. coli*) and (c) Graph of comparison of the zone of inhibition (mm^2) of all samples; Reprinted with permission of [76] Copyright 2018, Elsevier.

TABLE 3

Brief overview of 3-D nanomaterials used for nano-mask fabrication.

Name of mask	Nanomaterial used and size	Characteristic features	Manufacturer/ Innovator	Ref.
Copper nanoparticle in Nylon nano mask	copper nanoparticles in polymer fibers such as Nylon using melt extrusion	Antiviral properties	Promethean Particles Ltd., UK	[8]
3-D printed metal nanoparticle-based mask	spray based coating using silver and copper nanoparticles	Cost-effective and antimicrobial	Indian Institute of Technology-Gandhinagar, India	[8]
N-9 nanosilver mask	triple-layer medical mask based on N-9 nanosilver coating	Antiviral with high breathing efficiency	Resil Chemicals and Nanoclean Global Pvt. Ltd., India	[8]
Nanosilver mask	silver nanoparticles	User friendly, reusable, antiviral, self-cleaning	Anson Biotechnology Co. Ltd., China	[36]
Defensor series mask and The Guardian masks	blend of silver and copper nanoparticles	Reusable, enhanced antimicrobial activity	Nexera Medical, Canada	[71]
Copper and iodide nanoparticle-based mask	monovalent copper compound and iodide nanoparticles	Antimicrobial	Fudzhimori and team	[71]
ReSpimask metal-oxide based nano mask	three-layer nanofibrous membrane, copper oxide (CuO) nanoparticles embedded in the nanofibers	Filtering efficiency ~ 99.9%, kill the trapped pathogens, skin-like color, enhanced optical activity	Respilon Ltd., UK	[8,36]
Sonomasks metal-oxide based nano mask	Zinc oxide (ZnO) nanoparticles	Washable, reusable, design effective, and antiviral	Sonovia Ltd, Israel	[8]
Titanium oxide-based nano-mask	titanium dioxide and silver (TiO_2-Ag) nanoparticles	The outer layer of TiO_2 traps the viruses and kills them in the presence of sunlight, self-cleaning capabilities with such high filtering	X.TiO_2 Inc., USA	[8]
MVX surgical metal-oxide based nano-masks	TiO_2 nanoparticles and silver zeolite	Self-cleaning and antiviral properties with efficiency to kill 99.9% of trapped pathogens	MVX Prime Ltd., UK	[41]
cAgNPs organic nanoparticle-based mask	Curcumin-modified silver nanoparticles	Inhibit cell entry of respiratory viruses by having significant and effective cell levels	Cheng Zhi Huang and colleagues	[87]
Non-metallic nanoparticles-based mask	nano-diamond particles	Antiviral, waterproof, and high-performance coatings with profound breathability	Master Dynamic Ltd., China	[8,41]

based NPs by tuning their optical band gap to intended range [55]. For instance, Repilson Ltd. has fabricated CuO NPs based masks consist of three-layer nanofibrous membrane with high filtering efficiency of almost 99.9% [8]. Additionally, the colour of masks was skin-like due to use of accelerated CuO NPs providing user a civilian appearance rather than a medical appearance. It is attributed to the optimized bandgap of CuO NPs along with superior optical activity. Moreover, metal and metal oxides NPs owing to their photocatalytic nature can be cumulatively used for designing self-cleaning and reusable masks. For instance, X. TiO_2 Inc. reported a novel self-cleaning antimicrobial TiO_2-Ag NPs based facemasks with a high pathogen-killing of 99.999% in perfect dark conditions utilizing active nucleus NP technology. TiO_2 NPs present on the outer layer of these masks traps the pathogen on filtration and destroys them with the assistance of sunlight. It creates self-cleaning capabilities in masks with high filtering and germs-killing efficiency. Such FMRs possess potential to be utilized first hand in healthcare centres and are an effective weapon to combat COVID-19 [8]. Various reports on metal oxide nanoparticles-based masks or layers with different enhanced characteristics like colour alteration, anti-pathogen property, reusability, transparency, washable and self-cleaning action have been summarised in Table 3.

Moreover, the inclusion of organic materials in masks fabrication has the potential to achieve biocompatibility. Recently, nanoformulations of riboflavin and curcumin compounds have been used to fabricate nano-masks due to their anti-pathogen properties [82]. These organic nanoparticles are photocatalytic due to their inherent chemical composition and produce radical oxygen ions on exposure to light to kill trapped pathogens by destroying their proteins and nucleic acid. Tea polyphenols contain theaflavin and catechin in native and derivate form which binds to viral nucleic acids like influenza A (H1N1 and H3N2) and B viruses, and inhibits their replication, damage their membranes, and ultimately destroy them [83,84]. Catel-Ferreira et al. [85] grafted catechin on nonwoven cellulose by utilizing laccase and reported the inhibition and reduction of surface virus titer of T4D bacteriophage over mask surface. Tiliket et al. [86] used a coating of poly(ethyleneimine) in filter layer of mask and achieved, 99.999% filtration of T4D bacteriophage within an hour. Various reports in the literature on the use of organic three-dimensional nanomaterials have been summarised in Table 3.

Two-dimensional nanomaterials based FMRs

Two-dimensional nanomaterials possess one nanoscale dimension and are comprised of various shapes, such as sheet-like or flake-like morphology [88]. These possess remarkable properties such as the high surface area to volume ratio, anti-pathogen action, enhanced electrical, optical, chemical functionality, and excellent photocatalytic properties. Their unique physicochemical and biological properties are attributed to high specific surface area and abundant surface functionalities. Amongst all, popular classes of two-dimensional nanomaterials include graphene [89], metal–organic frameworks (MOFs) [72] and Metal carbides/nitrides (MXenes) [13,90,91]. A new class of ultrathin 2-D material named borophene has recently been synthesized from the monolayer of boron and is anticipated to have improved characteristics compared to the other 2-D materials [92]. Therefore, borophene can also be an excellent material in nano-mask fabrication.

Graphene is the most promising class of two-dimensional nanomaterial, along with its oxidized form (graphene oxide, GO). It is composed of hexagonally arranged single carbon atoms in two-dimension [93]. GO can be reduced to rGO (reduced graphene oxide) by removing oxygen groups with the action of reducing agents [93]. rGO is single-layer material with a high surface area to volume ratio, immense absorbing capabilities, and hydrophobicity. Recently, Goswami et al. [94] reported graphene air filter containing a face mask fabricated by a fused deposition modelling strategy with 8.2% of bacterial filtration efficiency with 1.10 mbar of breathing resistance. The reported mask also exhibited efficient capture of SARS-CoV-2. Recently, graphene owing to its excellent photothermal characteristics in the near-infrared regions is applied to inactive pathogens by increasing its surface temperature. Due to these features, rGO has been efficiently used for sterilization, heat production, and anti-pathogen action [93]. Lin et al. [95] reported graphene-based masks with advanced features of superhydrophobicity and photothermal activity turning them into reusable and recyclable masks. They deposited graphene on a commercial surgical mask utilizing laser ablation, which improved its photothermal, superhydrophobic and self-cleaning capabilities with a static contact angle of 140°. Moreover, Zhong et al. [96] reported few-layer graphene-based non-woven masks fabricated using a dual-mode laser-induced forward transfer strategy with excellent photothermal and superhydrophobic efficacies (Fig. 10).

Owing to superhydrophobicity from deposited graphene, the mask is reported to effectively repel falling aqueous droplets, whereas the mask surface temperature can be raised up to 80 °C to achieve self-cleaning. Interestingly, both the roll-to-roll surgical mask manufacturing and laser production can be integrated, which together with the cost-effectiveness of raw materials makes the technology promising for commercial prospects and advanced applications like solar-driven desalination.

Additionally, numerous companies such as Bonbouton, ZEN Graphene Solution Ltd., Graphene Composite Ltd., Planar TECH & IDEATI's 2AM, LIGC Applications, and Directa Plus PLC have developed antiviral graphene and its derivatives based FMRs with advanced smart features of self-cleaning, reusability, high filtration efficiency, superhydrophobicity and antiviral activities

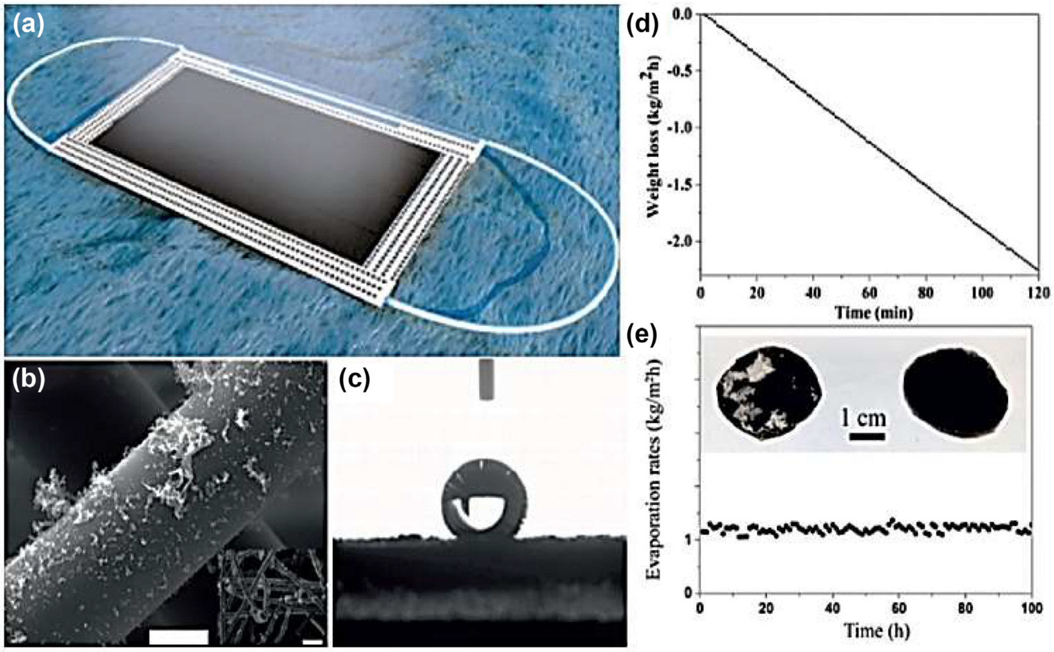

FIGURE 10

(a–e) Graphene-coated nonwoven fiber surgical mask. (a) Illustration, (b) SEM studies, scale bar is 10 mm. (c) Water contact angle, (c) weight loss of 10% saltwater under 1 sun intensity. (e) Top: Salt rejection performance capture photos of the polyimide after laser scribing after 24 h of desalination (left) and graphene-coated mask after 100 h of destination (right). While the evaporation rate of the graphene-coated mask under 1 sun intensity is at the bottom. Reprinted with permission of [96] Copyright 2020, American Chemical Society.

[8,36]. For instance, LIGC Applications fabricated “Guardian G-Volt”-FMRs using laser-driven microporous graphene with advanced features of self-cleaning, anti-static, anti-dust, and effectiveness against particulate matter [8,36]. Owing to their high porosity, these FMRs possess high air permeability and significant filtration capacity. The FMRs exhibited 99% trapping efficacy towards contaminants with sizes around and beyond 300 nm. Moreover, the FMRs possess a self-cleaning feature through static charge electrolytic activity aided by power supplied from portable batteries. They also possess an LED light-based alarming system, which alerts the user for the replacement of FMR [8,41,89]. On other hand, ZEN Graphene Solution Ltd. and Graphene Composite Ltd. have fabricated FMRs and PPE kits using functionalized graphene with silver nanoparticles and reported it for inhibition of human coronavirus, and influenza A and B viruses [97].

MXenes, on the other hand, are two-dimensional hydrophilic inorganic compounds made up of transition metal carbides, nitrides, or carbonitrides with enhanced effective surface area, tuneable interlayer distance, excellent physicochemical properties, and rich surface chemistries [13,98]. For the first time, Unal et al. [99] demonstrated the antiviral and immunomodulatory properties of 2D MXenes against SARS-CoV-2 (Fig. 11).

Due to their enhanced antimicrobial and hydrophilic properties, MXenes and their composites are prospective candidates in the fabrication of FMRs. For instance, Rasool et al. [100] reported antibacterial efficacy of single-layered, unexfoliated, and exfoliated MXenes to constrain Gram-negative *E. coli* and Gram-positive *B. subtilis* bacteria. The antibacterial efficacy of MXene was superior compared to that of graphene. Moreover, Dwivedi et al. [88] reported the latent of MXene based foams and MXene-graphene composites for FMR’s manufacture owing to their high specific surface area, optimum porosity, abundant surface terminals, and anti-pathogen activities.

MOFs are a class of crystalline 2D materials consisting of transition metal cations coordinately bonded with multidentate organic linkers [101]. Owing to high porosity, rich surface chemistries, and optimum thermal stability, MOFs are largely explored as filtration materials. Generally, MOFs are either embedded in polymer fiber-based membranes or grown over porous substrates to fabricate FMRs [102]. For instance, Li et al. [103] were the first to report the interaction of MOF incorporated ZIF-8 nanocrystals in electrospun PAN membranes and particulate matter (PM). They proposed three mechanisms of trapping PM using MOF-based FMRs including binding of PM to open metal sites over MOF surface, the interaction of PM with surface functional terminals of MOFs, and electrostatic interaction of PM

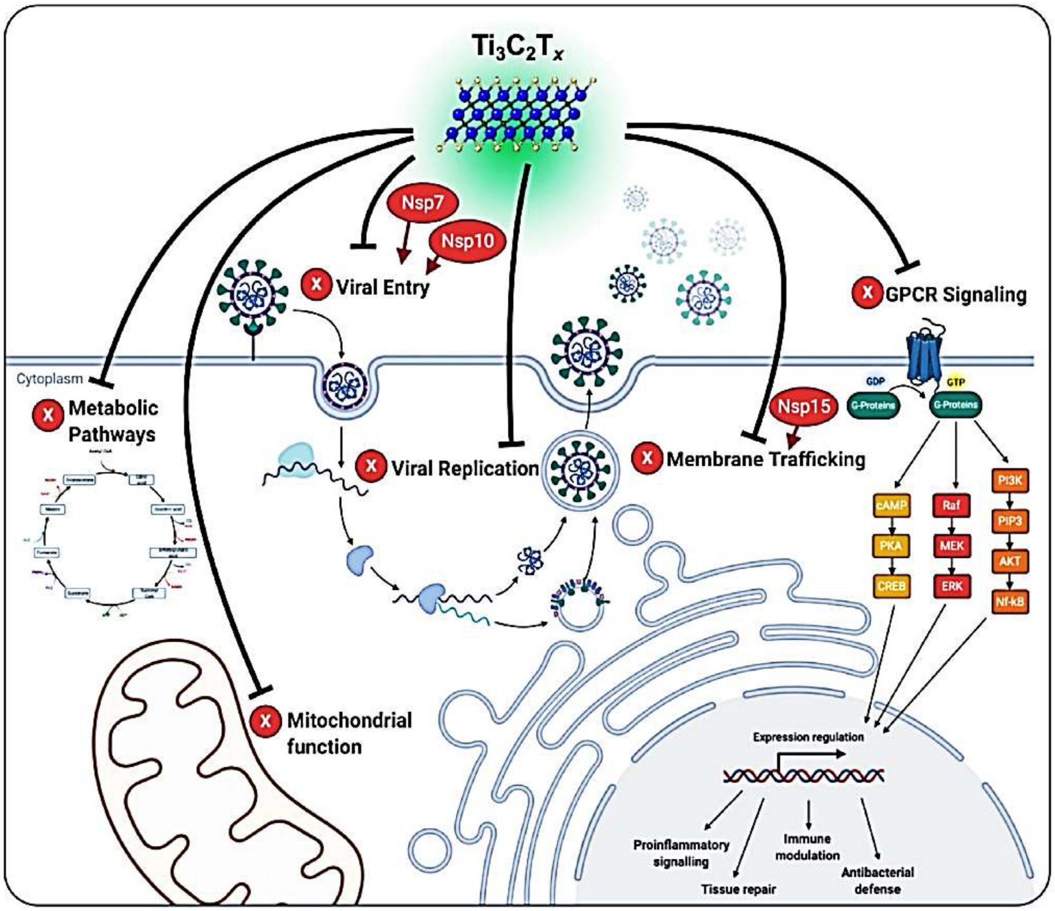

FIGURE 11

Mechanism of virus inhibition by 2D MXenes by various signalling processes such as membrane trafficking, surface interaction, GPCR signalling, metabolic pathways, mitochondrial function, and viral replication; Reprinted with permission of [99] Copyright, 2021, Elsevier.

with MOFs. The unbalanced metal ions and defects on the MOF surface offer a positive charge to polarize the surface of PM, which results in enhanced electrostatic adsorption of PM molecules. Moreover, the incorporation of 60 wt% of MOF into the PAN filter was observed to enhance its specific surface area from 115 to 1024 m^2/g. The fabricated FMR exhibited high PM removal efficacies of 88.33% and 89.67% for $PM_{2.5}$ and PM_{10}, respectively, along with a minimal pressure drop of less than 20 Pa. They are also reported to selectively trap SO_2 from a stream of SO_2/N_2 mixture, which further suggests its smart utilization in selective adsorption of contaminants. In another study, they reported scalable production of MOF-based filters on numerous commercial and flexible substrates like metal mesh, plastic mesh, nonwoven fabric, and glass cloth [104]. These MOF-filters exhibited outstanding PM removal efficacy in a wide range of operational temperature ranges of 80–300 °C. Notably, the ZIF-8/plastic mesh-based filter retained PM removal efficiency to be more than 905 even after 30 consecutive days.

Moreover, Koo et al. [105] showed flower-like hierarchical 2D assembled MOF/polypropylene hybrids based filters with excellent PM removal efficacies of 92.5% for PM2.5 and 99.5% for PM_{10}, respectively, with enhanced stability for 12 cycles of reuse. Recently, MOFs have also been explored for biocidal activities owing to their tuneable and enhanced photocatalytic activities. For instance, Li et al. [106] reported light-assisted biocidal performance of MOF-based air filters prepared by integrating ZIF-8 nanocrystals into nonwoven fabrics through hot pressing. The filter exhibited $PM_{2.5}$ removal efficacy of 96.8% with a low-pressure drop of 64 Pa and antibacterial efficacy of 99.99% for 30 min against *E. coli* containing aerosols. The dominant biocidal mechanism was due to the production of ROS from trapped photoelectrons at Zn+ centers within ZIF-18 through ligand to metal charge transfer. This work anticipates the potential of MOFs to combat pathogens and air pollutants.

Thus, 2D materials with high specific surface area, optimum porosity, excellent physicochemical properties, and rich surface terminals possess antimicrobial, self-cleaning, selectivity, reusability, and high air filtration efficacies for designing smart FMRs as illustrated in Table 4.

One dimensional nanomaterial based FMRs

One dimensional nanomaterial is with two dimensions in nanoscale and one dimension outside the nanoscale [55,108]. Nanofibers are a typical example of a one-dimensional nanomaterial, which are extensively used for textile and FMR fabrication. The addition of dimensional energy to the bulk dimension in nanofibers produces quantum size effects. These quantum size effects are responsible for high surface area and can be used in various applications in combating pathogens [109].

Nanofibers (NFs) can be converted into a dense web-like network with a high effective surface area and numerous tiny pores known as the nanofibrous membrane [55,109]. This nanofibrous membrane efficiently restricts the entry of microbes with high filtering and breathing efficiency [70]. Liu et al. [110] were the first to report the efficacy of NFs in trapping air contaminants. They reported an electrospun transparent membrane based on polyacrylonitrile NFs (with an average fiber diameter of 200 nm) to trap $PM_{2.5}$ particles. The membrane exhibited optimal optical transparency (∼90%), low-pressure drop (∼132 Pa), lightweight, and higher filtration efficiency (∼95%), which inspired the inclusion of NFs to make protective equipment such as FMRs from airborne health hazards. Further, the utilization of PP or polyester filter layer with S-type polymer coatings exhibited 99.1% viral reduction efficacy against influenza A (H5N1) virus titer on one minute of incubation [36]. However, the content of non-skin friendly constituents like PP was reduced during fabrication by the utilization of bio-products. For instance, Sundhari et al. [87] fabricated anti-allergic, biodegradable, cost-effective, and antiviral NMRs using curcumin and *Moringa oleifera* loaded NFs. The use of anti-allergic and anti-inflammatory curcumin in FMR fabrication prevents any probable skin infection from the persistent use of FMRs. Moreover, these nanoscale bio-

TABLE 4

Brief overview of 2-D nanomaterials used for nano-mask fabrication.

Name of mask	Nanomaterial used	Characteristic features	Manufacturer/Innovator	Ref.
Graphene-based nano mask	graphene and its derivatives	Microbe-static, anti-pathogen, and non-toxic nano-mask	Directa Plus PLC, UK	[8]
Guardian G-Volt	laser-driven microporous graphene	Large porosity, high permeability, enhanced filtration, and self-cleaning due to electrostatic charges trap 99% contaminants of size ∼300 nm and kill trapped pathogens through an electric charge.	LIGC Applications, USA	[8]
Surgical nano-mask	graphene coating	Superhydrophobic, gets sterilized when exposed to sunlight due to the high light-absorption property of graphene	Hong Kong Polytechnic University	[41]
2AM antibacterial nano mask	graphene and other carbon nanomaterials	Antimicrobial capacity up to 99.95%., filter contaminants of size < 2.5 μ, dust repellent and washable up to 10 times	planarTECH & IDEATI	[107]
MXene sheet based nano mask	single layered unexfoliated and exfoliated MXene sheets	Antibacterial	Yury Gogotsi, Khaled A Mahmoud, and their team	[100]

components are antiviral, highly porous, and possess a high specific area. Nevertheless, these NFs are non-biodegradable and can be a nuisance to the environment [70]. There are reports of the synthesis of organic-NFs based FMRs, which are biodegradable with a high surface area to volume ratio [57]. For instance, Rainey et al. fabricated nanocellulose NFs based biodegradable FMRs with high filtering capacities towards contaminants/pathogens of size up to 100 nm. Fascinatingly, nanocellulose NFs were manufactured by utilizing agricultural plant waste like sugar cane bagasse, which serves as dual-functional advanced smart technology to reduce solid waste and generate an efficient biodegradable product using it [36]. Zhang et al. reported reusable and biodegradable FMR filters using electrospun PVA NFs and cellulose nanocrystals [70]. The filter exhibited stability in a high filtering capacity of 95% towards particulate contaminants even after five times of washings and high breathing efficacies with low-pressure drop below 100 Pa (Fig. 12). Interestingly, Das et al. [111] fabricated a biocompatible FMR by electrospinning the gluten biopolymer onto NFs based membrane (Fig. 12). The FMR exhibited significant effectiveness in barring transmission of contagious pathogens and prompt degradation in ambient surroundings to harmless and non-toxic by-products.

By tuning the optical band gap, FMRs can be made transparent or of a particular choice [68]. For instance, a study reported fabrication of ‘Hello mask’-FMR with transparent and biodegradable features by electrospinning of organic NFs [70]. The masks are consisting of very fine membranes of pore size 100 nm providing significant protection from viruses. Fascinatingly, the transparency of masks eliminates the security concerns with visible identification of wearer and addresses problem of communication barriers for deaf-mute differently-abled persons while using opaque FMRs. Similarly, He et al. reported fabrication of biodegradable transparent FMR using a 3D printing strategy including printing of polylactic acid (PLA) struts on electrospunned PLA nanofibers [68]. Further, their efficiencies can be enhanced by the use of high dielectric materials like carbon nanomaterials, polytetrafluoroethylene nanoparticles, and metal–organic frameworks for the manufacture of FMRs or their filters/layers [46,113]. For instance, Bai et al. [114] reported graphene-quaternized chitosan NFs possessing antiviral efficacy owing to the generation of static positive charge and excellent hydrophobicity. Moreover, Kim et al. [115] reported nanofibrous mats based on poly (butylene succinate) integrated with Janus membrane filter and are coated with chitosan nanowhiskers. The FMR exhibited high filtering capacity (98.3% for contaminants of size up to 250 nm), high breathability, and water-resistant features. Additionally, the FMR filter is biodegradable with complete decomposition in soil within 4 weeks of composting (Fig. 13).

On other hand, various FMR manufacturing companies including Metamasks, YAMASHIN Filter CROP., and Nanopoli have fabricated commercial FMRs based on NFs with advanced features [8,36]. For instance, Metamasks Ltd. fabricated FMRs using NFs extracted from coconut shells and carbon (nano-coco-carbon) with a thin membrane of less than 1 nm, which can restrict 99.99% of air contaminants from entering to the human body [97]. Various nano-masks based on NFs, which are user and environment-friendly, cost-effective, and non-toxic, are reported in Table 5.

The various working mechanism for nanofiber-based masks involves interception, inertial impaction, diffusion, gravitational settling, and electrostatic attraction phenomenon [113] (Fig. 14).

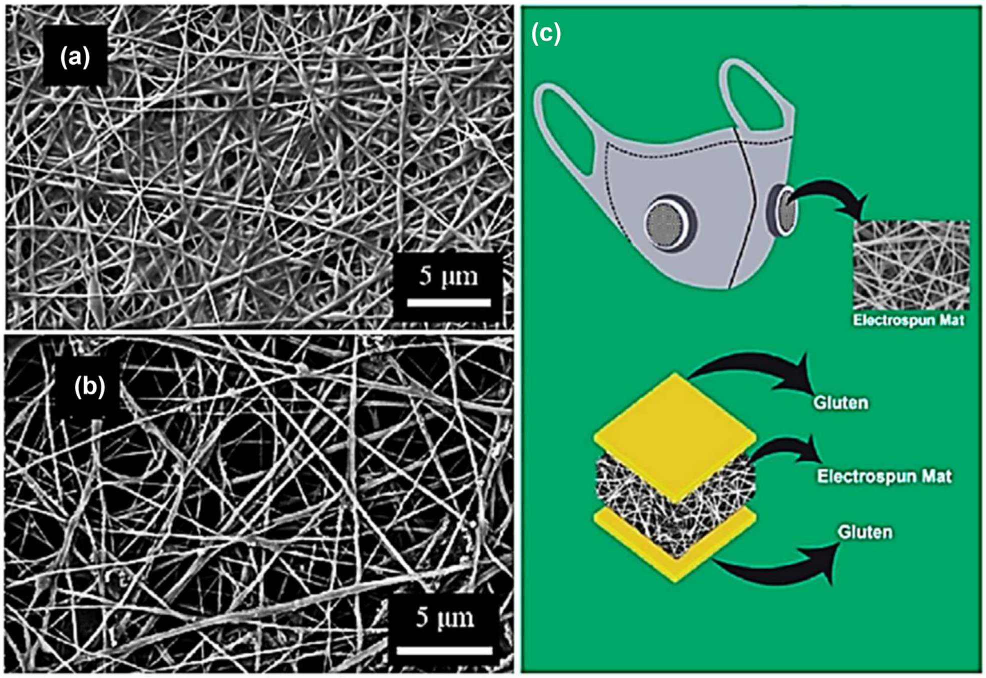

FIGURE 12

SEM micrographs of fouled-PVA/CNCs FMR’s filters (a) prior to (b) afterward washing with water; Reproduced with permission of [112] Copyright 2020, Elsevier. (c) Schematic depiction of bio-based FMR’s internal structure and outer design; Reproduced with permission of [111] Copyright 2020, Elsevier.

The blocking of large particles (usually >600 nm) by nanopores is known as an interception. The contaminants with lesser sizes up to 300 nm may enter through the pores, but they drop down after colliding with fiber walls (like a non-straight path of particles with high speed). This is the second step of the filtration process and is known as the impact or collision mechanism. Then, the particles less than 300 nm in size are captured by ultrathin NFs with diffused branched and web-like entanglement, and this process is known as diffusion-based capturing [113]. In the gravitational settling mechanism, the large-sized particles get settled due to gravity in the slowly moving air stream. Finally, electrically charged mats or fibers in FMRs attract oppositely charged contaminants through the Columbic attraction. This is called the electrostatic filtering mechanism [70,113]. All the phenomena together contribute to the filtering action of nanofibers-based FMRs.

Zero-dimensional nanomaterials based FMRs

Zero dimensional nanomaterials have all their dimensions in nano-range (i.e., below 10 nm) [65,66]. Quantum dots are the most studied zero-dimensional nanomaterial and have been used in various applications. These were the earliest nanotechnological advancements used in medical and biological sciences [65,66]. The most common quantum dots are graphene quantum dots, polymer quantum dots, carbon quantum dots, and metal quantum dots. These are also known as ‘artificial atoms’ with discrete energy levels due to which their bandgap can be tuned by regulating their size. Due to their quantum size and effective surface area, they possess improved optical, electrical, and chemical properties, making them a prospective material for the fabrication of nano-masks [65,66]. For instance, Harris et al. [116] have patented the phototherapy-based FMR made up of Phosphor quantum dots. The fabricated FMR is consists of a rigid outer shell with a LED affix at the inner surface with quantum dot-based film. However, the use of quantum dots for general face masks is limited and is being a matter of controversy due to their high toxicity.

Hybrid nanocomposites based FMRs

Till now, we have discussed the individual properties of the nanomaterials, which can be used for the fabrication of nano masks. A combination of two or more nanomaterials for fabrication purposes can synergistically enhance the characteristics of nanomaterials. This type of material which comprises more than one type of material is known as a composite. The nanocomposite is a composite material possessing at least one of its constituent materials in the nano-range (less than 100 nm) [13,20,55,108,117,118]. Depending on their synthesis process, nanocomposites are classified into three: phase-separated system, exfoliated system, and intercalated system [13,20,55,108,117]. Nanocomposites comprise the merits of all the precursors with enhanced physicochemical properties, which can be further used to improve FMR's performance and quality. For instance, Nazek et al. [119] reported the fabrication of hard masks consisting of nanoporous flexible silica templates on a silicon-on-insulator wafer by reactive ion etching strategy. The flexible and reusable membrane exhibited high filtration efficacy for contaminants of size up to 300 nm with potential

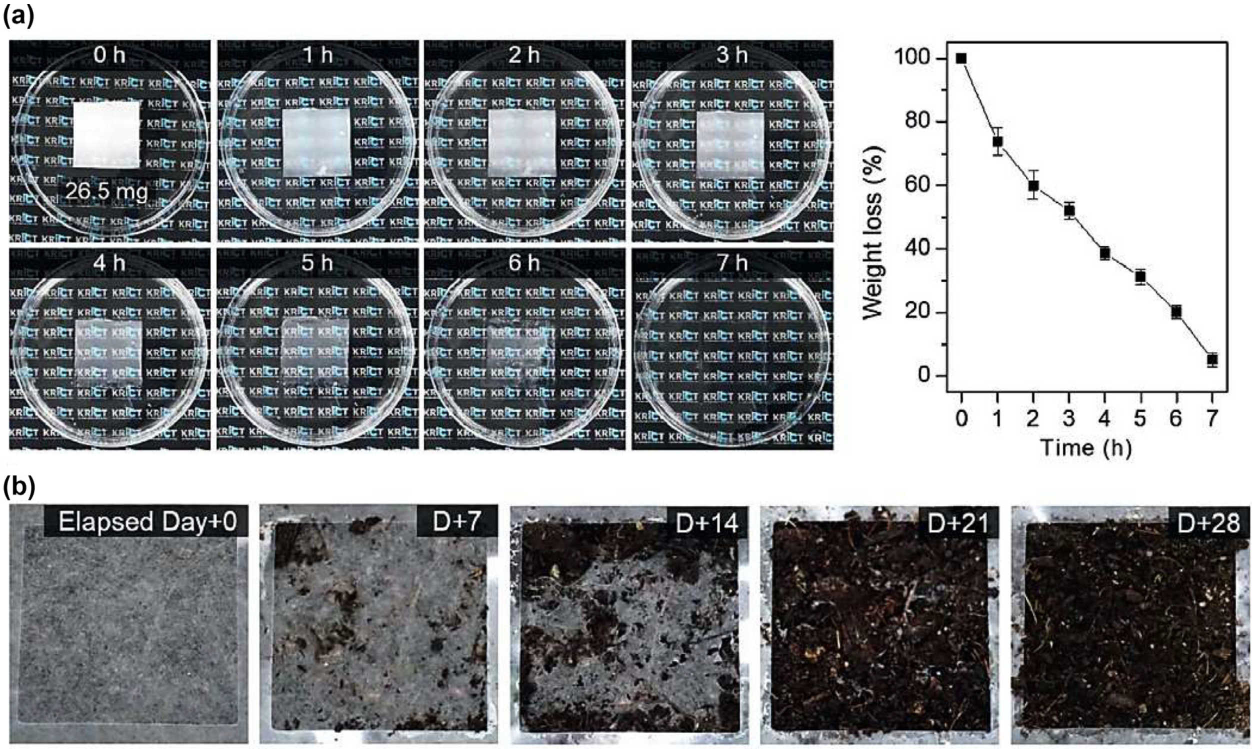

FIGURE 13

Study illustrating the biodegradability of the developed FMR’s filter. (a) Time-dependent enzymatic degradation of CsW-coated PBS filter and the corresponding weight loss as a function of time (b) Images showing the degradation of the CsW-coated PBS filter in the composting soil over time; Reprinted with permission of [115] Copyright 2021, Wiley.

TABLE 5

Brief overview of 1-D and 0-D nanomaterials used for nano-mask fabrication.

Type of nanomaterial	Name of mask	Nanomaterial used	Characteristic features	Manufacturer/Innovator	Ref.
Zero-dimensional	Phytotherapy mask	Quantum dot phosphors	A semi-rigid shell with LEDs affixed at the inner surface (towards the face) with quantum dot-based film for the treatment of pathogens and self-cleaning	Nanoco Technologies ltd./ Torsten Schanze	[116]
One-dimensional	Nano-cellulose mask	Nano-cellulose derived from the extract of agricultural waste such as sugar cane bagasse	Bio-degradable nano-masks, filter contaminants of sizes up to 100 nm	TJ Rainey and colleagues	[36]
	Nano-coco-carbon mask	Nanofibers derived from coconut shells and carbon	Can resist up to 99.99% of air contaminants	Metamasks	[97]
	3-D nanofiber mask	nano resin and synthetic polymer-based nanofibrous nano-mask	High effective surface area, high polarity, self-extinguishing, and sound/heat-insulating properties	Yamashin Filter Co., Japan	[8]
	Silk nanofiber mask	hydrophobic non-woven fabric and skin-friendly silk layer	Air filtration efficiency up to 98.75%	Nanopoly Co. Ltd., South Korea	[8]
	Textile based nanofibers mask	two biocompatible and biodegradable layers of textiles	Biodegradable and disposable	Amrita Centre for Nanosciences and Molecular Medicine	[8]
	Chitosan-based nano masks	Quaternized chitosan nanofibers with graphene	Antiviral due to static positive charge and hydrophobicity	Caryn L. Heldt and group	[41]
	Janus membrane-based nano-masks	Janus membrane filter integrated with PBS (polybutylene succinate) based nanofibrous mats and with chitosan nanowhiskers	Biodegradable, highly breathable, and water-resistant with 98.3% filtering capacity for contaminants of size up to 250 nm	Team of Shin Dongyeop X Oh, Sung Yeon Hwang, Jeyoung Park, and associates	[115]
	Herbal nano-mask	Curcumin and *Moringa oleifera* loaded nanofibers	Anti-allergic, biodegradable, cost-effective, and antiviral nano-masks	Curcumin: S Hajir Bahrami and group, Moringa oleifera: Norziah M Hani and colleagues	[87]
	Polylactic acid-based nano mask	polylactic acid (PLA) struts on electrospunned PLA nanofibres	Biodegradable and transparent nano mask	Kolos Molnar and colleagues	[68]
	Hello mask	Electrospunned organic nanofibres	Biodegradable membranes with pore size around 100 nm and transparent	Empa and EPFL, Switzerland	[70]
	Gluten polymer-based nano mask	electrospun gluten biopolymer into the nanofibrous membrane	Anti-pathogenic, self-cleaning, and biodegradable	Elham Arkan and group	[111]
	PVA nano mask	electrospun poly(vinyl alcohol) nanofibers and cellulose nanocrystals	Biodegradable and reusable filter, washable up to 5 times, filtering efficiency up to 95% for PM 2.5 and other contaminants	Nouha Ghorbel and colleagues	[70]

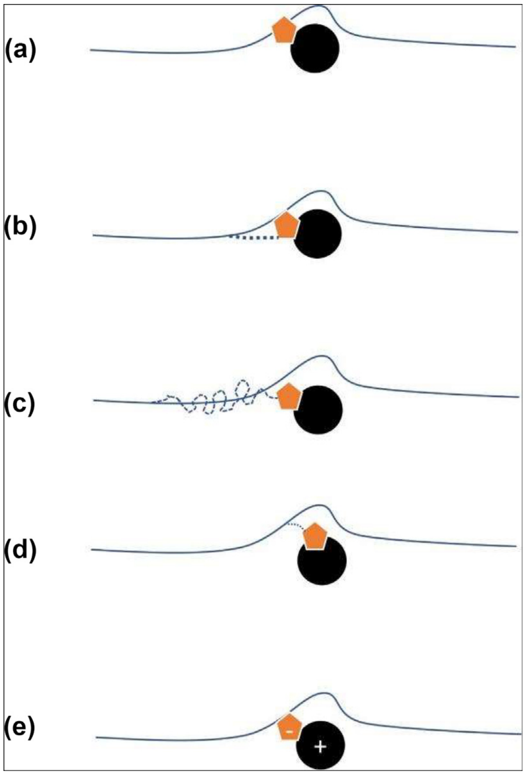

FIGURE 14

Filtration mechanism of a nano mask. The black dot represents the nanofiber, whereas the orange pentagon represents the viral particle or contaminate, which travels through the straight-line path depicted by the blue line. (a) Interception, (b) inertial impaction, (c) diffusion, (d) gravitational settling, and (e) electrostatic attraction.

use in N-95 type nano-masks. Park et al. [64] reported the fabrication of an anti-viral membrane based on silver nanoparticle/ silica hybrid nanocomposite with the potential to inhibit influenza virus and other similar viruses. Moreover, Jahangiri et al. [35] reported the fabrication of an activated carbon/carbon NF hybrid for developing an FMR cartridge using its lightweight and enhanced absorption capabilities. Dhineshbabu et al. [120] reported magnesium oxide /Nylon 6 hybrid-based NF with high fire retardancy and anti-bacterial properties, which possess the potential to be utilized in FMR fabrication. On the other hand, Tremiliosi et al. [70] reported anti-viral Ag NFs based poly-cotton fabrics with high inhibition capability of 99.99% on incubation for two minutes. It exhibited inhibition of numerous pathogens like *E. coli*, *S. aureus*, and *C. albicans* up to 99.99%. Galliani et al. [121] reported the fabrication of conducting polymer based organic sensor FMRs interdigitated though inkjet printing technique which are effectively low cost with rapid reproducibility at commercial level. These eco-friendly disposable, e-masks developed through integration of polymers and inkjet printing system ensures not only the low infection health risk in an individual user perhaps these masks can also serve for domestic utility along with the advanced option in form of protective equipment for professionals in healthcare industry.

Additionally, Wang et al. [122] reported an electret NF-based filtering membrane made of nano-barium titanate with long-term charge storage capability. The fabricated membranes on different hybrid nanocomposites possess tremendous potential for the fabrication of advanced FMRs. Moreover, a US patent application US20110114095A1 reports the Ag NPs impregnated activated carbon cloth-based filtration layer for fabrication of face masks [36]. The layer based on pristine activated carbon cloth exhibited enhanced antiviral efficacy of 93% against MS-2 coliphage on incubation of 6 h, which can be enhanced up to 98% by impregnation of Ag NPs. Additionally, the use of this membrane in masks resulted in superior air permeability and high viral filtration efficacy of 99.88% compared to the FFFP3 type masks. Moreover, various commercial manufacturers including Copper3D, Replison Group, and ZEN Graphene Solutions Ltd. have utilized nanocomposites to fabricate FMRs [8,36]. Copper3D Ltd. has reported an anti-viral and anti-microbial face mask called 'NanoHack', consisting of three sterilizing and filtration layers made up of non-woven polypropylene impregnated with 5% of CuO (copper oxide) nanoparticles [8,36]. The inclusion of CuO offers anti-viral and anti-microbial properties, whereas polypropylene renders high effective surface area and hydrophobicity in designed FMR. Various reports on nanocomposites-based nano masks have been summarised in Table 6.

Architecting innovative and intelligent FMRs for a single solution for multiple concerns

The inclusion of nanomaterials in FMR fabrication has evidently contributed to the smart function of FMRs, especially in terms of anti-contaminant, anti-moisture, anti-allergic, transparency, desired colors, biodegradability, biocompatibility, fire retardancy, and self-cleaning, with addressing the fundamental bottlenecks of conventional FMRs like low breathability, secondary infection, limited filtration and anti-contaminant efficacies [36,113]. However, the potential of FMR is not saturated with these features and is further expandable by designing intelligent features like pathogen detection, self-powered and automatic response. They can be achieved with the integration of modern-day technologies including internet-of-things, artificial intelligence, machine learning, sensors, nano-triboelectric generators, and advanced communication strategies [90,124–128]. There are some reports in the literature on designing intelligent FMRs with these advanced features with the utilization of internet-of-nano-things (IoNTs). For instance, Ghatak et al. [129] reported the self-powered three-layered smart mask-based simple textile triboelectric nanogenerators to filter SARS-CoV-2. The contact electrification and electrostatic induction act together to inactivate the virus in a bidirectional manner. This intelligent FMR can be utilized by numerous people due to its modest mechanism, self-driven efficacy by harvesting energy from fundamental movements including e.g. breathing, talking, or other facial movements, and excellent viral filtration efficacy [129,130]. Fois et al. [131] reported AG47-SmartMask for efficient filtering of SARS-CoV-2 along with incessant monitoring of several cardio-pulmonary variables. They integrated various specific sensors FMR for its intelligent operation to detect temperature, air pressure, and relative humidity inside the mask, along with body temperature, percentage of oxygen saturation of hemoglobin, and heart rate. Additionally, the sensors-based intelligent

TABLE 6

List of generally used nanocomposite-based face masks and their characteristic features.

Name of mask	Nanomaterial	Features	Manufacturer/Innovator	Ref.
Graphene oxide and silver nanoparticle-based mask	graphene oxide ink functionalized with silver nanoparticles	high effective surface area, enhanced thermal properties, anti-pathogenic due to high reflectivity of silver	ZEN Graphene Solutions ltd, Canada	[123]
NanoHack	three disinfecting and filtration layers of non-woven polypropylene impregnated with 5% of CuO nanoparticles	antimicrobial and antiviral due to CuO, the inclusion of polypropylene renders high effective surface area and hydrophobicity	Copper3D, Chile	[8]
Copper oxide with organic nanofiber-based mask	three layers with copper oxide nanoparticles suspended into the organic nanofibrous matrix	99.9% filtering capability	Respilon Group, Czech Republic	[8]
Barium titanate membrane-based nano mask	electret nanofibrous filtering membrane based on barium titanate ($BaTiO_3$) nanomaterials	the fabricated membrane has long term charge storage capability	Na Wang and colleagues	[122]
Silver and silica-based nano mask	silver nanoparticle and silica hybrid composite	Antiviral	GwangPyo Ko and colleagues	[64]
AC/CNF nano mask	composite of activated carbon and carbon nanofiber	Air-permeable, lightweight, and significant absorption capabilities	Javad Adl and group	[35]
Nanoporous hard mask	flexible silica template on a silicon-on-insulator wafer fabricated by the reactive ion etching process	reusable and possesses high filtration efficiency for particles of size up to 300 nm	Dr. Mustafa Hussain and the group	[119]
nanofibrous mat-based nano mask	magnesium oxide – Nylon 6 hybrid nanofibrous mat	high fire retardancy and antibacterial properties	Venkatachalam Rajendran and colleagues	[120]
Silver and poly cotton-based nano mask	nanofibrous silver-based poly-cotton fabrics	antiviral, inhibit the replication by 99.99% after the incubation period of two minutes	Nanox Tecnologia SA, Brazil	[113]
MXene and graphene composite nano mask	MXene foams and MXene-graphene composites	high surface to volume ratio, tunable porosity, and anti-pathogen activities	Hao-Bin Zhang and colleagues	[88]

FMR works in cooperation with an innovative telemedicine platform. They evaluated the performance of AG47-SmartMask on twenty people engaged in the vegetable packaging chain and quantified the simulated dyspnoic events of coughing and sneezing with high accuracy. In another study [132], they reported an anti-COVID mechatronic smart and intelligent face mask to remotely monitor cardiorespiratory variables in farm labors involved in jobs at high threat of contagion with the integration of sensors.

Moreover, Pan et al. [133] reported a “Lab-on-mask” intelligent FMR with an integrated remote, noncontact multiplexed sensor system to monitor respiratory diseases like COVID-19. It exhibited efficient monitoring of the blood oxygen saturation, blood pressure, heart rate, and body temperature allied with indications of pneumonia caused by SARS-CoV-2 in real-time. The remote monitoring feature of this FMR minimizes the risk of healthcare workers being infected by reducing their direct exposure to patients. Yang et al. [134] reported NFs-FMR based on electroless-plating of Ag NFs with intelligent feature of weather adaption for the user. The FMR exhibited excellent radiative cooling features in hot weather by reflecting most of the human body radiation. Moreover, advanced 3D printing technology have also been adopted to design customized FMRs. Ishack et al. [135] described the implementation of 3D laser scanning to evaluate exact facial parameters to design customized N95 masks. The reported technology was feasible for scalable production of customized FMRs for fulfilling their expanding demand. Recently, Xue et al. [136] reported an intelligent FMR comprised of a flexible immunosensor based on array of high-density conductive nanowires, wireless communication units, and a compact impedance circuit to detect COVID-19. The small gap and size between nanowires ($\sim$100 nm) provide the locking of virus particles and enhance the diagnosis efficacies. The FMR was demonstrated as a point-of-care strategy to detect coronavirus ‘spike’ protein and virus-aerosol in stimulated human breath. The FMR exhibited low viral detection limit of 7 pfu/mL using an atomized sample of coronavirus aerosol mimic within five minutes. The FMR has the potential for on-site preliminary screening of COVID-19 (Fig. 15).

AI and ML techniques can also be used to design intelligent FMRs. For instance, Kong et al. [137] reported an edge computing-based mask (ECMask) identification strategy to aid public health safeguards by ensuring real-time monitoring of the energy-efficient camera devices of buses. They used deep learning techniques to train and evaluate real video datasets and explored their potential for COVID-19 prevention. Moreover, the integration of IoTs amplifies the real-time monitoring efficacies of FMRs with intelligent features [138–141]. For

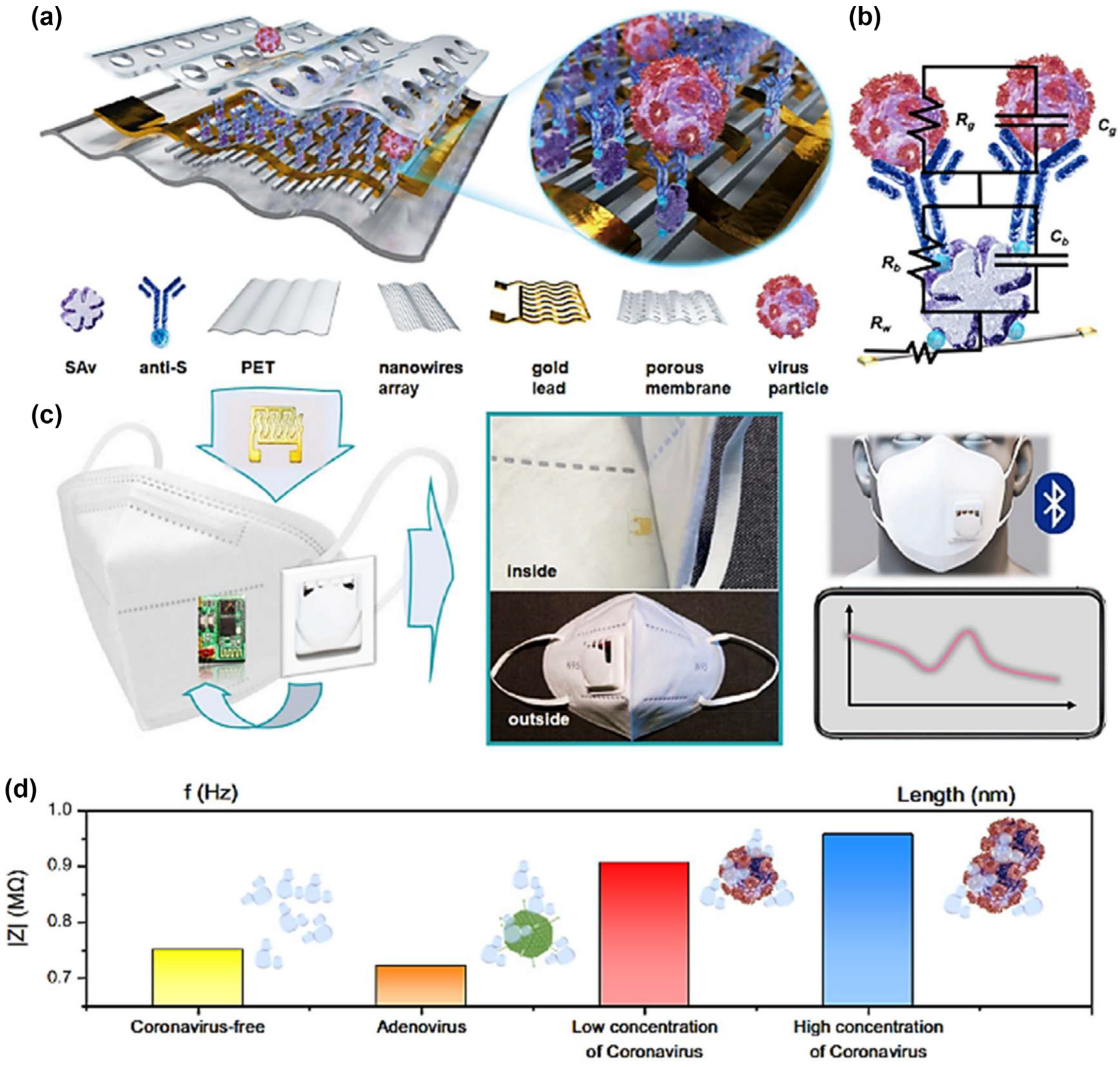

FIGURE 15

Schematic illustration of the nanoscale sensor design, includes PET, nanowires array, gold lead, Sav, anti-S, porous membrane, and virus particle (a), virus sensing mechanism (Rb: the equivalent resistance of surface binding antibody; Rc: the equivalent capacitance of surface binding antibody; Rg: the equivalent resistance of surface binding antigen; Rg: the equivalent capacitance of surface binding antigen; Rw: the equivalent resistance of nanowires) (b), the images of the constituted intelligent face mask (c); Reprinted with permission of [136] Copyright 2021, Elsevier.

instance, Sarkar et al. [142] reported an intelligent mask (Sense mask) comprised of an infra-red proximity sensor, GPS, FS5 sensor, and walk sensor. The masks were reported to monitor the health condition of patients and transfer the collected data to the cloud by the home/hospital-based local cloudlet, which is further forwarded to physicians for diagnosis of patients.

Fascinatingly, Kalavakonda et al. [143] reported an intelligent IoT-enable active mask as an efficient defense against airborne contaminants. It is comprised of a real-time closed-loop control system with detection capabilities towards airborne contaminants of various sizes through utilizing an onboard PM sensor. Subsequently, it intelligently alleviates the contaminant by utilizing mist spray, produced through a piezoelectric actuator, to load proximate aerosol particles like they promptly fall on the ground. An on-board microcontroller unit controls the whole system, which collects the data, analyses it, and responds by generating mist if necessary. Additionally, the user can remotely control the system and receives real-time alerts related to recharging/refilling/decontamination of the mask before use through a customized smartphone application.

Facts, challenges, and alternate potential solutions related to NFMRs: Sustainable aspects

Various antiviral drugs are still in the trial phase to combat the current COVID-19 scenario [144–147]. However, many preventive measures are in place to control the pandemic. These include the use of hand sanitizers, hand washing, installation of air purifiers, vaccinations, lockdowns of affected areas, social distancing, etc. Most of these preventive measures are challenging to implement in the long run and in an effective manner. For instance, sanitizers disinfect the infected surface momentarily as the surface can be contaminated again by an infectious pathogen [8].

Moreover, the continuous use of chemical-based sanitizers and disinfectants is toxic to human health and the environment [148]. Similarly, air purifiers with high filtering efficiency cannot be installed in every place due to space and economic constraints [149]. Vaccination is the safest and best measure to prevent the spread of SARS-CoV-2. Still, the vaccination is inadequate due to factors like the constraint of mass production of vaccines, the reach of vaccines to every individual, and the mutating nature of the virus [150]. The SARS-CoV-2 has been reported with various strains in different countries, raising the challenges to current vaccines day by day [150]. Additional preventive actions, including lockdown and social distancing, are ineffective in a lone way and may lead to social, mental, and economic crises [23,151,152]. Until the vaccines and curing drugs are in their development and production phase, it is crucial to break the pandemic chain to save human lives. This can be efficiently achieved by using NFMRs in combination with other precautionary protocols. Therefore, NFMRs is indeed required as anti-infective therapy in the current situation due to COVID-19. However, the utilization of NFMRs also possess certain threats to environment and user, which can also be catered by different strategies such as strategic disposal, repurpose, recycle, reuse, and appropriate choice of precursors. Thus, the utilization of NFMRs possess both merits and demerits as illustrated in Fig. 16.

Toxicity of nanomaterials

Despite so many beneficial features of NFMRs, the imminent use of nanomaterials embedded in textiles is doubtful. The limitations of NMFRs are the potential leaching of nanomaterials from the mask into the environment resulting in secondary environmental contamination and health hazards, limited solid-waste production, and scalable manufacturing to meet massive demand.

For instance, the generation of "nano-waste" after disposing or washing such textiles is a menace to our health and ecosystem [41,153,154]. The high surface-to-volume ratio of nanomaterials augments their toxicology, which risks human health and the environment [153,155]. The leached nanomaterials into the water and the environment have been reported to have toxic effects. For example, silver and copper nanoparticles bring lethal effects, including immunotoxicity in marine organisms [156]. Luo et al. [157] have also reported the toxic effects of nano-TiO_2 on human health and other living species. Moreover, loosely embedded nanoparticles of NFMRs can cause respiratory disabilities via inhaling through the lungs. Similarly, the inhaled silver nanoparticles can cause lung failure, tachycardia, and hypoxemia [158,159].

Additionally, there are significant toxicity issues related to using 2D materials like MXenes and graphene for manufacturing NFMRs [160–163]. Although MXenes are demonstrated to be safe bioagents, several reports have indicated that they can result in respiratory issues/disorders by affecting the regular functioning of some internal organs [160]. For instance, they can result in enhanced airway confrontation in pulmonary parts by accruing in the cytoplasm of alveolar endothelial and epithelial cells, leading to respiratory issues/disorders [160]. It raises the requirement of careful administration of MXenes for devising NFMRs and reducing their cytotoxicity by adopting green precursors and strategies [147,164]. Moreover, scalability and stability in an

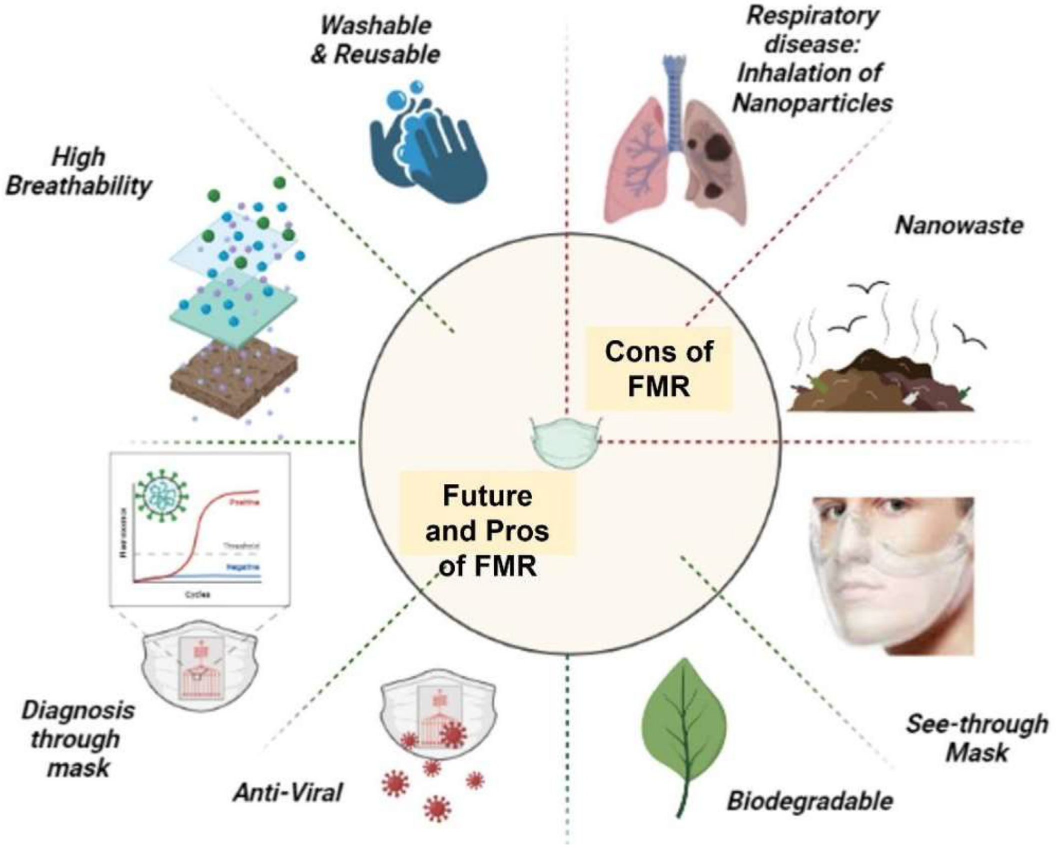

FIGURE 16

Advantages and disadvantages of using nanomaterials based FMR for airborne health hazards.

oxygen environment are other prominent issues related to MXenes, which can be addressed by functionalization strategies, including hybridization, intercalation, doping and surface functionalization [13,90,91,165]. On the other hand, graphene and its derivatives have also been found to possess several side effects on the normal functioning of animal cells [161–163]. They can easily cross the animal cell's physiological barriers/cellular membranes through diverse contact ways or administration routes, ultimately ensuing in toxicity *in vivo* and *in vitro*. However, it is evident from the literature that their toxicity can be reduced by modifying graphene and its derivatives with non-toxic, eco-friendly, green and biocompatible materials [166]. For instance, Yang et al. [167] reduced the toxicity of reduced graphene oxide (rGO) by coating it with PEG, which is a non-immunogenic and non-toxic material approved by the United States Food and Drug Administration (FDA) for internal use in animals [168]. On administering the PVA coated into mice at a dose of 20 mg kg^{-1}, no subsequent organ failure or side effects were observed, evidencing its reduced toxicity [167]. It implies there is a future requirement to dedicate the research towards the control of toxicity of nanomaterials using functionalization/hybridization with biocompatible materials, adopting green precursors and strategies and developing specifically dedicated protocols for their administration and utilization.

Therefore, some stipulated guidelines must be set up by administrative authorities for testing, trial, production, and use of nanomaterials in any application. Moreover, adopting smart degradable FMRs fabricated from green or biodegradable materials can cater to the problem of solid-waste management anticipated due to the large-scale usage of FMRs.

Solid-waste and electronic-waste management

It is also evident in literature that conventional FMRs based on metallic nanoparticles and 2D materials (like graphene) upon use are a potential global hazard in light of solid-waste management [36,52,70,169]. Thus, they must be adequately disposed of and treated before disposing of off using various strategies such as UV treatment, photocatalytic degradation, intelligent segregation, controlled heat treatment etc. [52,70,96]. However, these strategies require extensive human care and resources with strict public policies. However, the architect of smart NFMRs addresses these problems with recyclable, reusable, degradable, compostable and repurposes modules.

Recently, Talukder et al. [170] reported a new generation of washable FMR based on polyethersulfone membranes fabricated from green solvent. The reported mask has shown excellent nanofiltration efficiency of 99.9% towards bacteria and aerosol found to restrict SARS-CoV-2. Moreover, using green solvent and washable features reduces the challenge of solid waste generation upon disposal of FMRs. However, most FMRs are made from PP, which must be recollected and re-evaluated upon use in a controlled manner so that it does not pose a risk of secondary contamination to other individuals and the environment. It requires proper framing and enforcing specific waste management guidelines from policymakers and policy enforcers.

Moreover, sustainable strategies are required from researchers and environmentalists to repurpose used FMRs. Several recent reports have demonstrated the repurposing of used FMRs for various purposes under the waste-to-wealth model. Recently, Guo et al. [169] architect a photothermal evaporator by utilizing the interwind structure of used FMRs. The collected used FMRs were initially disinfected using UV light and ethanol, followed by PVA treatment to convert DMR hydrophobic surface to hydrophilic. The fabricated PVA-FMR exhibited enhanced wettability, high solar adsorption (97%), long-term salt rejection capability, and excellent solar efficiency (91.5%). The prototype of a floating photothermal evaporator is further shown to perform autonomous solar ocean farming, which provides an ecologically sustainable solution to FMR disposal. Muhyuddin et al. [171] demonstrated the conversion of surgical masks into crude oil and nanostructured platinum-free electrocatalysts for fuel cells through pyrolysis, which is a sustainable approach to addressing the FMR disposal problem and supporting the circular economy. Moreover, Mendoza et al. [172] reported the utilization of used FMRs and paracetamol packaging in fabricating highly efficient textile supercapacitors. The best-optimized supercapacitor made with $Ca_3Co_4O_{9-\delta}$ exhibited significant capacitance retention of around 82.1% after 1500 cycles of charge/discharge. Alternatively, Irez et al. [173] and Battegazzore et al. [174] showed the fabrication of disposable FMR recycled materials with different materials in the form of nanocomposites, which is another potential solution to cater to the issue of FMR disposal.

Moreover, due to integrating IoTs, electronic components and sensors into NFMR, the architect raises concerns about managing the potential production of electronic waste (e-waste) [90,175–178]. It indicates the requirement of smart and sustainable strategies to incorporate 5th generation IoNTs into FMRs, including utilization of green materials and strategies to fabricate its components, strategic and intelligent segregation methods for their disposal, adoption of recyclable, reusable, repurpose and degradable materials for component fabrication, and designing and strategically employing strict e-waste monitoring guidelines.

Hence, adopting proper guidelines for used FMR collection and repurposing them with suitable technology can address the solid-waste and e-waste generation due to the massive usage of FMRs. It also provides prospects of utilizing FMR waste for other applications and contributing to a circular and sustainable economy.

Conclusion, prospect, and vision

Despite of numerous myths associated with the use of face masks to combat airborne hazards, wearing FMRs is currently new normal for humans worldwide due to the current COVID-19 pandemic scenario. More than 50 countries have already made wearing FMR mandatory in public spaces to curb the virus spread, and in other places, public health experts are highly encouraging the utilization of FMRs to break the chain of viral spread and protect the community from infection. The causable SARS-CoV-2 virus has been anticipated to possess a correlation with microbial and fungal infection. It is evident from the spread of mucormycosis in numerous countries as an epidemic as a secondary effect of COVID-19. The new variants of SARS-CoV-2 like Omicron possess a superior spread rate, which is anticipated to challenge state-of-the-art preventives, diagnosis, and therapeutics for COVID-19. The reach of virus transmission is too large as it has been identified in almost every part of the world. It raises the requirement for more innovations in architecting preventive measures such as FMRs with smart and intelligent features. It is only achievable with the inclusion of modern era technologies of internet-of-things (IoT), nanotechnology, machine learning, data analytics, and artificial intelligence (AI). The utilization of IoTs with the integration of nanomaterials has created an era of internet-of-nano-things (IoNT), which possesses the immense potential to design next-generation smart and intelligent FMRs with the integration of modern AI techniques. Moreover, the incorporation of sensors in FMRs to monitor human physiological and behavioural signals possesses latent to revolutionize the field of e-healthcare. For instance, the integration of nanomaterial-based biosensors on FMR with minute radio antennas can be used for point-of-care diagnosis of COVID-19, even in the remotest part of the world. The inclusion of a radio antenna or any modern generation communication chip on the same FMRs will enable to reporting and recording of diagnosed COVID-19 cases at any place.

Moreover, the integration of AI and pattern recognition-based strategies will help to respond to the reported cases on basis of pre-trained protocols. Additionally, the integration of IoNTs and AI allows the use of any smart device as the distant reader instead of an ad-hoc reader, turning the technology virtually accessible to any user, which enables self-health monitoring and management even in the remotest part of the world. The problem of massive diagnosis due to large spread, unavailability of sufficient medical support and equipment, and designing proper monitoring strategies can be achieved by making FMRs smarter and more intelligent. Additionally, the recorded data processing through advanced ML strategies can be encompassed to accommodate the cautionary levels to various circumstances depending upon the individual user's necessities or application. Moreover, the advanced Global positioning system (GPS) location feature can also be integrated to monitor the individual's routine and probably establish precise and prompt early advice and warnings. A feature for automatic or scheduled sharing of data and reports to a remote healthcare staff or e-monitoring station can be implemented.

All these advanced features, integrated with the wireless and wearable system, can make smart and intelligent FMRs, a potential technology for implementation in various sectors like non-invasive healthcare and physiological monitoring, preclinical research, diagnostics, and prognostics of diseases. Recently, Escobedo et al. [179] reported an Opto-chemical sensor integrated with a smart FFP2 mask driven through a smartphone for real-time monitoring of airborne CO_2 inside it. It has been designed to tackle the health issues that arise due to CO_2 rebreathing on prolonged use of FFP2 masks (Fig. 17).

Additionally, the smart and intelligent mask possesses advanced features of battery-less, flexible, near-field-enabled tag, and field-deployable, with the lowest limit of detection of 140 ppm CO_2 and a lifetime of 8 h. The fabricated FMR caters to several issues associated with conventional devices including dead-space volume of FMRs, low detection range, and manual monitoring. Similarly, Cheng et al. [180] reported the self-powered smart FMR based on electrospun polyetherimide (PEI) electret nonwoven. The fabricated smart mask is bi-functional as it generates electricity for its own operation and removes the PM. Moreover, the other smart features in IoNT-FMRs include

FIGURE 17

Schematic depiction of smart and intelligent FMR integrated with Opto-chemical sensor-driven through a smartphone for monitoring of low-trace airborne CO_2 as low as 140 ppm with a lifetime of 8 h; Reprinted with permission of [179] Copyright 2022, Nature.

anti-contaminant, self-sterilization, hydrophobicity, biocompatibility, biodegradability, transparency, high breathability, skin-friendly, and desired colour are required to make FMRs a new normal to every human. Additionally, the intelligent features of FMRs are highly required to tackle the issues related to the shortage of medical infrastructure, correct reporting, power consumption, responding, and saving human resources. NFMRs with the integration of IoNT, AI, machine learning, and advanced communication technology is the future strategy to combat COVID-19, similar infectious diseases, and other air-borne health hazards. They can be designed on the theme of hospital-on-chip strategies to benefit every infected individual with any barrier. Until the design of a complete medical protocol for vaccine and antiviral drugs, and a long-term solution to air contamination and COVID-19 (and similar airborne hazards), smart NFMRs with intelligent features have become a mandatory part of life as a new normal.

Declaration of Competing Interest

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

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