Smart Face Masks for COVID-19 Pandemic Management: A Concise Review of Emerging Architectures, Challenges and Future Research Directions

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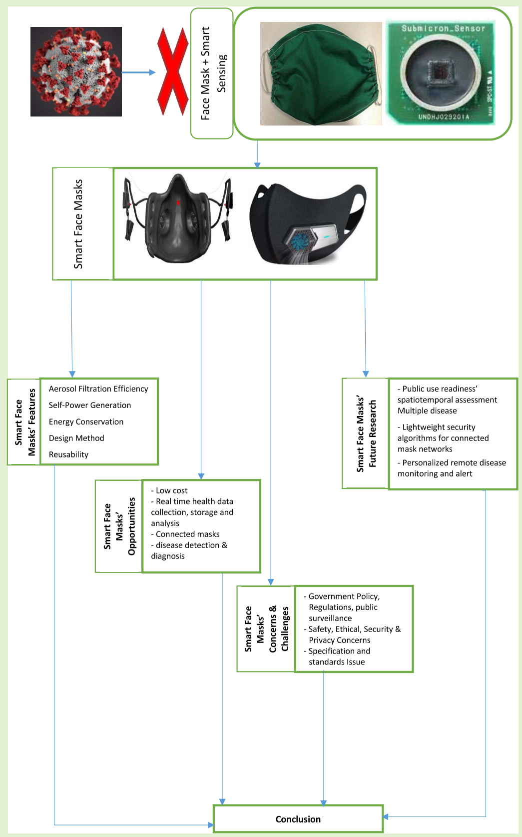
***Abstract*—Smart sensing technology has been playing tremendous roles in digital healthcare management over time with great impacts. Lately, smart sensing has awoken the world by the advent of smart face masks (SFMs) in the global fight against the deadly Coronavirus (Covid-19) pandemic. In turn, a number of research studies on innovative SFM architectures and designs are emerging. However, there is currently no study that has systematically been conducted to identify and comparatively analyze the emerging architectures and designs of SFMs, their contributions, socio-technological implications, and current challenges. In this article, we investigate the emerging SFMs in response to Covid-19 pandemic and provide a concise review of their key features and characteristics, design, smart technologies, and architectures. We also highlight and discuss the socio-technological opportunities posed by the use of SFMs and finally present directions for future research. Our findings reveal four key features that can be used to evaluate SFMs to include reusability, self-power generation ability, energy awareness and aerosol filtration efficiency. We discover that SFM has potential for effective use in human tracking, contact tracing, disease detection and diagnosis or in monitoring asymptotic populations in future pandemics. Some SFMs have also been carefully designed to provide comfort and safety when used by patients with other respiratory diseases or comorbidities. However, some identified challenges include standards and quality control, ethical, security and privacy concerns.**

***Index Terms*—Aerosol, Coronavirus, COVID-19, mask technology, material science, nanotechnology, pandemic management, smart face mask (SFM), smart sensing.**



I. Introduction

CORONAVIRUS is a deadly infectious disease of huge public health concern globally. It has accounted for over 442 million infected cases and over 5.98 million deaths around the globe since the year 2020 when it emerged[1]. Among several strategic control measures applied by the World Health Organization (WHO) and the governments of the world in the fight against this ravaging pandemic is the introduction of face masks (FMs) [1], [2], [3], [4]. FM can be described as a form of protective fabric of the face, which, when worn correctly, may safeguard the wearer from direct exposure to the virus [4].

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Please see the Acknowledgment section of this article for the author affiliations.

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[1]https://www.statista.com/statistics/1093256/novel-coronavirus-2019ncov-deaths-worldwide-by-country/

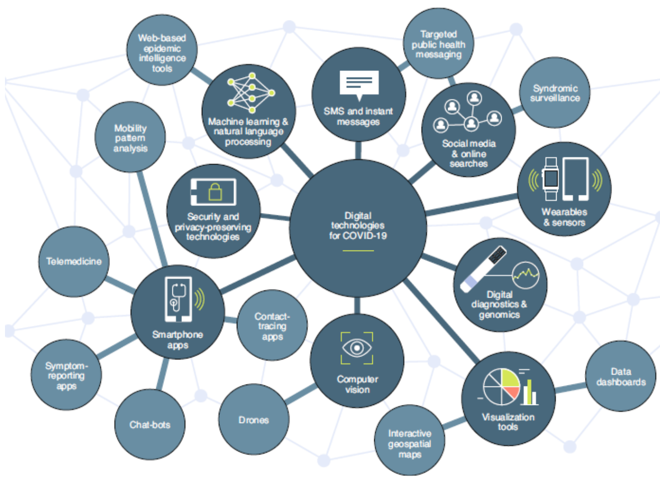

Fig. 1. Digital technologies applications in public health for pandemic management [13].

The use of FM as a means of public health outbreak management has been reported to have greatly reduced the burden of COVID-19 attacks and associated mortality cases [5].

The traditional FM is, however, highly prone to retaining infected aerosols or loads of viral antigen on its vulnerable surface [6], [7], which may pose huge infection or reinfection risks to the wearer. This may likewise lead to the increased public spread of the virus if the FM is not hygienically used or not properly disposed of after use. Although Gómez-Ochoa and Franco [8] reported that using a FM in a community has no effect in curtailing the spread of COVID-19; however, emerging evidence from some recent country-wide evaluation studies has revealed that the proper use of FMs can assist greatly in mitigating the risk of contracting COVID-19 disease or its spread [6], [9], [10]. Generally, some health-related risks and sociocultural challenges associated with the use of FM have limited its wide adoption and the compliance level of its use by the public [11]. Such risks, which may be heightened by the use of FM, have been identified to include airflow obstructions in its different forms [4], which can lead to suffocation or prolonged breath seizure in patients suffering from lung problems, severe obstructive pulmonary diseases, or any other respiratory diseases [1], [2] and eventually cause death. Other social-related challenges associated with the use of FMs include cultural misunderstandings, stigmatization [9], [12], limited social interactions and communications [2], [5], quality, and cost issues [3], [12]. This set of risks and challenges may have overridden the actual purpose and effectiveness of most FMs.

Lately, the world has witnessed accelerated development and innovative use of digital technologies in the fight against disease pandemics [11], [13]. The COVID-19 pandemic has equally provided evidence that the future of public health is tending toward integrated digital innovations. In Fig. 1, a conceptual summary of several disparate digital technologies, social computing, and data processing approaches that have played prominent roles in enabling easy and effective management of the global COVID-19 pandemic is presented [14]. Such techno-driven systems and approaches include but are not limited to global positioning system (GPS)-enabled drones for screening, surveillance, disinfection, and delivery of medical supplies, computer vision, automated contact tracing apps, security and privacy-preserving technologies, telemedicine, disease detection wearables and sensors, live casualties reporting apps, and user-support mobile applications among others [13], [15], [16].

In an attempt to address the challenges of the traditional FMs, the wearables and smart sensing domain have amazingly awakened the world with the evolution of smart FMs (SFMs). SFM is a product of an integration of smart sensors and the traditional FMs thereby translating the latter to a multifunctional wearable healthcare device. Although the development of SFMs is at its infant stage; however, a number of promising solutions are currently emerging [17], [18], [19], [20]. Some SFMs are now capable of providing early warnings and alerts of electronically or remotely sensed diseases in the body of the wearer for immediate care [21].

Most importantly, in preparation for the next-generation innovative SFM solutions, it is imperative to investigate the state-of-the-art FM designs and architectures, their specifications, features and their limitations. This attempt will further help to gain insights into the social and technological challenges of the development and use of SFMs, as well as identify new areas for future research; however, no previous study has been conducted in this direction. In this article, we provide a concise systematic review of the features, architecture and design, opportunities, challenges, and future research directions for the emerging SFMs. In turn, five research questions (RQs) have been identified, investigated, and analyzed as presented in Table I.

Main contributions of this article are as follows.

1) This research discovers that smart sensing has inspired the current innovations in FM design in the COVID-19 era by introducing new features and capabilities, which are location-aware technologies and flexible architectures, energy conservation and awareness, self-power generation potential, aerosol filtration efficiency, safety awareness, reusability and cost-effectiveness. These newly integrated features can help to gain deeper insight into understanding and evaluating the quality, user acceptability, government policies and socioeconomic relevance of the emerging SFMs. This is in response to RQ1 (see Section III-B).
2) The traditional FM is limited in its sole function as a protective covering. This research finds that a number of emerging architectural designs and/or smart technologies have functionally aided and extended the capabilities of FMs beyond just being a protective covering by making it smart. Most of the emerging architectures and smart technologies employed are based on ultrathin Au/parylene/Teflon amorphous fluoropolymer (AF) films pressure sensors, NRF2832 SoC board with a chip antenna on the BMD-350 BLE Module, Copper3D technology and Ultimaker Cura, STM32L4R5AI ARM-M4 Ultralow Power microcontroller, laser scattering-based Sensirion SPS30, polydimethylsiloxane board, triboelectric filters,

TABLE I
RQs FOR SFMs DESIGN AND USE

Research Question	Motivation
RQ1: What features do the smart face masks possess to more effectively reduce the risk of contracting Coronavirus or support ease of use among some people in defined health risk groups like those with respiratory or pulmonary problems?	This information will help to identify the key characteristic features of smart face masks that are evident and which can be used to comparatively evaluate them. With this information, it becomes possible to determine how flexible, scalable, effective, and efficient each emerging smart face mask is.
RQ2: What are the different architectural designs and/or smart technologies that have functionally-aided the emerging smart face masks? What areas of the current smart face masks technology can be scaled up or extended to increase the capabilities of SFM beyond the state-of-the-art applications?	The purpose is to highlight the disparate innovations and smart technological advancements surrounding the architectural design of smart face masks. These set of SFM information can be further studied for extensibility, scalability, efficiency, and general improvement purposes.
RQ3: What extensions of smart face masks exist beyond being a protective covering only?	The purpose is to identify other public health applications and capabilities of the emerging state-of-the-art smart face masks beyond their use as protective covering. What technologies and models among other approaches have been adopted or developed to initiate the design of smart face masks? This knowledge can help researchers and smart face mask engineers to be in tandem with current SFM trends and identify other possible extensions beyond the current technological solutions and design mechanisms of smart face masks.
RQ4: What are the challenges and notional public concerns regarding their readiness to adopt or use smart face masks?	The purpose is to identify the reactions of the end-users of smart face mask solutions and know if there exists any concern arising or that may arise relating to the use. This information can assist the public health service providers, regulators, and the government to devise sustainable and strategic approaches to increase the readiness, acceptability and adoption of smart face masks to gain high compliance use of the smart face masks towards effective pandemic disease transmission and control.
RQ5: What future research can emanate from the current SFM technology to extend its contributions towards pandemic management in the future?	This information will assist to identify areas of the emerging smart face mask designs that require further investigation to be more effective as a protective covering or beyond. It will also assist to bring together multidisciplinary researchers that may be interested in improving or extending the emerging state-of-the-art smart face mask solutions from a number of perspectives.

polytetrafluoroethylene and electrospun polyetherimide (PEI) among others. In turn, the capabilities of SFMs have become extended to include but not limited to the automatic detection of microbes and aerosols, wireless CO_2 monitoring, remote health-metrics sensing and monitoring, disease screening and diagnosis, air quality sensing, mask usage time sensing, mask fitness sensing, head and body motion sensing. These extended capabilities have eliminated the challenges of the traditional FMs. This is in response to RQ2 (see Sections IV-A and IV-B) and RQ3 (see Section V-A). We further identify the challenges and notional public concerns regarding their readiness to adopt and use SFMs. This is in response to RQ4 as discussed in Section V-B.

3) From our findings, the emerging SFMs have potential to provide opportunities for researchers, network engineers, and data engineers to collect data from SFMs in the edge and/or their network. As a potential edge device in a connected mask network scenario, SFMs would be able to rapidly collect, aggregate, and process data. This data can be used to more efficiently derive relevant insights that can aid better use and effective societal impact. In this direction, we have presented a number of research gaps that can leverage such data for key technological, security, and societal insights. We have also provided suggestions on possible extensions and scalability options in SFMs in a bid to increase their capabilities with wider public acceptance gain. This is in response to RQ5 (see Section V-C).

The rest of the sections are as follows: in Section II, review of related works on smart sensing in pandemic and healthcare management is presented; Section III presents the method; Section IV presents the review of literatures on the characteristics, design methods, technologies, and architectures of some emerging SFMs toward COVID-19 pandemic management. In Section V, the direction for future research is presented, while Section VI concludes the article by summarizing its key contributions.

II. Related Work

The role of smart sensing in healthcare disease management cannot be overemphasized. In this era of the COVID-19 pandemic, a number of studies are being carried out to report several innovative smart applications or the use of smart sensing technology in pandemic disease management. Regarding works that establish strong connections between humans and the use of technology in critical events, Kummitha [5] performed a comparative study of governments' perspectives on the use of technology in COVID-19 management in some settings. The author investigated technology-based and human-based approaches that dominate China and western democracies, respectively, as case studies. The study mentioned that a tech-driven approach might be more effective in fighting COVID-19. While this is a welcoming development, tech-driven COVID-19 management may pose some privacy concerns to the public [15]. In another study, Khan et al. [22] reviewed existing smart innovations (mainly sensor technology, mask, robotics, drone, artificial intelligence) and their associated frameworks that have recently emerged to tackle the global emergence of the COVID-19 pandemic [23]. The authors identified the disparate smart devices and smartphone applications used in a number of geographical distributions to manage the COVID-19 pandemic. The societal changes and health intervention impacts that these smart technologies have brought to the limelight in counter-responses to emergency situations are also presented.

In an attempt to understand the capabilities of wearable technologies, including FMs, Ivanoska-Dacikj and Stachewicz [24] performed a systematic review and critical analysis of the capabilities offered by the use of wearable technologies and smart textiles in the face of the COVID-19 pandemics via a comparative study of the roles of FMs in the management of past and present pandemics. In the work of [25], several raw materials and testing approaches that have been used in the production of FMs were reported. The authors also reviewed the varying perspectives of the public and sustainability concerns regarding the production and wearing of FMs. Dalia and Khaled [26] conducted a review of the properties of advanced materials being used for the manufacturing of medical coverings and wearable healthcare devices. They reported the role of design in textile rendering and associated challenges with smart wearable device technologies and applications. In another study conducted by Farzaneh and Shirinbayan [27], the authors presented a review of the production process and quality control approaches for the traditional FMs. Further, they argued the need for thorough quality assurance tests, including dynamic respiratory resistance, to ascertain that the masks being produced meet minimum acceptable quality specifications. As evident, none of these existing works has considered a systematic review of the emerging SFM architectures, the socioeconomic and technical opportunities they may present, their potential challenges, and future research opportunities. As a result, this study presents a concise review of the emerging architectures of SFMs for use in COVID-19 pandemic management, the opportunities they present, and the associated challenges and concludes by suggesting areas for potential future research.

III. Method

In this section, we highlight the method used for the selection of articles and the analysis conducted in this study.

A. Data Selection

For the purpose of the review that was conducted in this study, the "search" tool of the Scopus database engine was used to fetch and obtain articles relating to SFMs and COVID-19 pandemic. Scopus database was considered because it accommodates a large article base with over 4600 health science titles, and has a hundred percent MEDLINE, EMBASE, and Compendex coverage, which are most relevant to this study [28]. An advanced search was conducted on February 2, 2022, using search key phrases like "Smart Mask," "SFM," "Biosensor FM," "Face centric biosensing," "Digitized Mask," "COVID-19," and "Coronavirus." The search produced a total of 59 articles, from which 12 articles were excluded. The exclusion criteria of articles for this study include the scope of an article if it is outside of SFMs technology or if it is a book. About 15 duplicate articles were found and removed. In all, 32 articles were found very relevant to the current study and analyzed; however, some relevant articles within our inclusion criteria from major newspaper companies that mentioned "smart mask" or "SFM" in their headlines were also reviewed.

B. Data Analysis

We analyzed the literature and identified key features of most emerging SFMs, which can be used for their evaluation. These include technologies and architectures, energy conservation and awareness, self-power generation potential, aerosol filtration efficiency, safety, reusability, and cost. These features will help to gain deeper insight into understanding and evaluating the emerging SFMs. The basic findings are presented in Section IV of this article. This attempt will also assist in understanding better the social relevance and implications surrounding the development of SFM, as well as the key drivers for its anticipated public acceptance. For clarity purposes, some key features mentioned above are contextually defined as follows.

1) SFM Architecture: The architecture refers to the structural makeup and design specifications of an SFM and the associated hardware. For instance, this definition attempts to determine the components of an SFM and its design approach.

2) SFM Technology: This explains the smart technological innovations, processes, systems, procedures, or approaches that have been integrated into the structural architecture of an FM. This may account for the level of efficiency or effectiveness of some features like self-power generation capability and energy conservation.

3) Energy Awareness: This explains whether an SFM is able to efficiently and effectively sustain and conserve device energy over a sufficient period of time.

4) Self-Power Generation Capability: This indicates the energy options available to power up an SFM. We discovered that the majority of the SFMs leverage on battery, which is the size of a small coin, to power the FM and so are unable to self-generate a power of their own. Few emerging SFMs have, however, shown potential to harvest energy (both in kinetic and thermal form) from the sun and wearer's breathing activities to power themselves.

IV. SFMs in COVID19 Pandemic Management

In this section, the design methods, technologies, and architectures of the emerging SFMs are presented.

A. SFMs

The smart mask design technology has brought together many researchers from the field of engineering, nanotechnology, material science, aerosol science, surface science, and the public health domain to improve SFM's role in effectively curtailing disease spread and in extending its functionalities beyond being a protective covering alone. SFM, otherwise known as biosensing FM, which has played significant roles in curtailing the spread of COVID-19 disease, is commonly an easy-to-use, multilayered (microfiber, nanofiber, and microfiber) personal protective equipment most often made from nonwoven fabric [2], [29], [30]. In Fig. 2, the visual look of the different types of FMs is presented. Type 2 (a) is woven (meaning that fabric threads are interlaced), while others are nonwoven.

1) Characteristics of SFMs: SFMs are protective coverings, and like every other nanobiosensor-based device, are characterized by the ability to acquire and monitor vital body signs via multiple sensors. Such vital recordings, which may include but not limited to cardiorespiratory signals, body temperature, blood pressure, steps taken per day, body motion, sleep duration, hydration level, and respiratory rate (Ivanoska-Dacikj

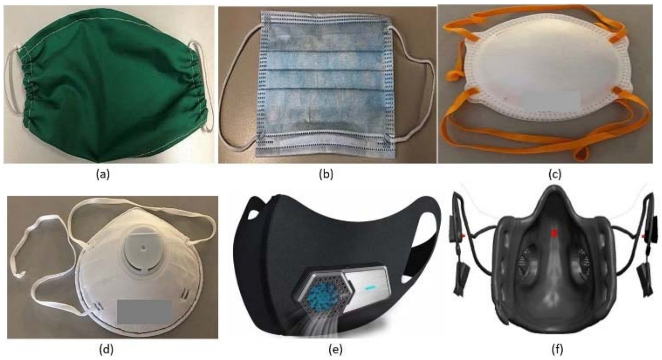

Fig. 2. (a) Homemade FM [2]. (b) Typical surgical FM [2]. (c) Filtering facepiece mask [2]. (d) Filtering facepiece mask with a valve gadget [2]. (e) Reusable smart air FM[2]. (f) Three-dimensional AG-47 SmartMask [29].

and Stachewicz, 2020), can be used for noninvasive detection of COVID-19 viral antigens [10] and other diseases in the body. In addition, some SFMs use saliva samples collected on FMs to detect diseases [7]. Texturally, SFMs are usually air permeable, flexible, hydrophobic, strong, and extensible and can exist in different cross-sectional shapes, fineness, fiber length, and levels of absorbency [30], [31]. A typical nonwoven fabric is often made from polyester, polypropylene, polycarbonate, or polystyrene [21].

B. SFMs Design, Technologies, and Architectures

In this section, design methods, technologies, and architectures of some emerging SFMs are discussed. In order to monitor the breathing conditions of people in real time in a pandemic situation, Zhong et al. [32] designed a self-powered SFM from two ultrathin Au/parylene/Teflon AF films pressure sensors with a thickness of ≈5.5 m and a weight of ≈4.5 mg. Its corona charging is fit with a Dongwen DW-N503-4ACD2 or DW-P503-4ACD2 power source, a ground electrode, and a corona needle. The SFM possesses high electrostatic induction efficiency and is readily sensitive to breathing airflow; however, it is nonair permeable. In the work of Zhu et al. [18], the application of harmonic sensors in the remote sensing of liquid levels, mechanical cracks, vital signs, humidity, and so on was extended to cough detection and monitoring in COVID-19 situations. The authors propose a wireless SFM based on a lightweight harmonic sensor with the capability for continuous and rapid monitoring of cough associated with COVID-19. The smart mask design is built on a passive harmonic tag with a lumped element-based frequency multiplier, a meander-line antenna operating at 1.5 GHz for generating interrogation signals to the wearer, and an inverted-F antenna operating at 3.0 GHz and generates time-series information from which the frequency and pattern values of the cough are obtained.

In another study, Escobedo et al. [33] developed an SFM that uses an opto-chemical sensor and Hydroxypropyl methylcellulose polymer to effectively monitor the possible hyper reinhaling of gaseous CO_2. This is to allow for a smart approach to managing the adverse effect and discomfort of prolonged use of an FM by wearers. The architecture of the SFM is made up of three components, which include a

[2]https://tinyurl.com/9sbu8jpy

Fig. 3. Sample architecture of a SFM with CO_2 monitoring capability and its (a) NFC sensing tag, (b) CO_2 sensing layer, and (c) smartphone application for support [33].

near-field sensing tag, a CO_2 concentration sensing layer, and a smartphone-based front-end application, as presented in Fig. 3. The low-power near-field sensing tag is microcontroller-enabled and allows for processing and control of the SFM's data. In addition, the CO_2 sensing layer allows for an automatic detection and measurement of the gaseous CO_2 concentration on the FM, while the smartphone application layer offers end-users' visualization support and control of parameters of interest, including the real-time display of the level of concentration of gaseous CO_2 on the FM.

Hyysalo et al. [15] (introduced a smart 3-D printed FM made with a FlexFill 98A filament that is made from thermoplastic polyurethane. Although it is comfortable to wear, it is difficult to establish that the smart mask is energy efficient and weight friendly owing to its need for an alternative power plan, which may pose a weight burden on the wearers. In another related study, an open-source SFM tagged "Facebit" was developed by Curtiss et al. [34]. Facebit uses contactless ballistocardiography to monitor heart rates from the head's micromovements, also with inbuilt capabilities to detect mask degradation and improper fit. Its hardware is built from an NRF2832 SoC board with a chip antenna on the BMD-350 BLE Module. The three sensors on the board include the Si7051 temperature sensor, the LSM6DSL 6-DOF inertial measurement unit and the LPS22HB barometer. Facebit is capable of harvesting energy from sunlight via a flexible PowerFilm MP3-37 4.49 × 1.44 in 150 mW solar panel and from head movements using a "shaker," a fabricated lightweight harvester. Kinetic force in breath is also converted into electrical energy using a triboelectric nanogenerator. The energy requirement of the Facebit wearable is also complemented by a tiny 105 mWh primary cell battery.

Gravina et al. [35] developed a smart mask based on an improved Copper3D technology and Ultimaker Cura. The mask, embedded with temperature, accelerometer, humidity, and light sensors, is powered up with a lithium battery and has smartphone application support. The authors also adopted support vector machine and Naïve Bayes algorithms to detect when a mask is worn and if it is properly worn. In the work of Fois et al. [29], an anti-COVID-19, active-passive filtering device tagged "AG47-SmartMask" is proposed. The AG47-SmartMask is embedded with sensors that continuously monitor the cardiopulmonary activities of the wearer, including the heart rate and the body temperature for early detection of COVID-19 especially in asymptotic sufferers. AG47-SmartMask uses an ARM 32-bit Cortex-M4 CPU and an STM32L4R5AI ARM-M4 Ultralow Power microcontroller unit in its design. The filter is nondisposable as it can be used for a minimum of 60 days at a stretch. Lazaro et al. [36] developed an integrated dual heat flux sensor characterized with an FFP2 mask with capabilities to detect cough events and remote healthcare monitoring, including breathing and temperature; however, its power generation is based on an AtTiny402 microcontroller powered by a 500 mAh lithium polymer (LiPo) battery.

In another work, Fischer et al. [17] developed "Masquare," a smart face covering that incorporates sensing electronics with layered textile and 3-D printed structures. It uses dual differential barometers (BME680 and LPS22HB), which equally act as a spirometer to measure transient airflow and respiratory pressure. To enhance users' experience and minimize cost, a low-cost, and customizable SFM was developed by Kim et al. [37] to monitor a wearer's face strain and temperature. The design approach of the SFM is based on wireless aerosol jet printing technology and a cloud-based data backup technique. The approach follows a 3-D face scanning of the user for geometry information, strain gauge sensor design and aerosol jet printing, customized sensor placement on a mask, and real-time transmission of sensor data to the cloud. In a similar manner, a low-cost closed-loop SFM was developed by Kalavakonda et al. [21]. The SFM design is based on an active mist generator with a piezoelectric transducer operating at 110 kHz and two laser scattering-based Sensirion SPS30 particulate matter sensors. Further, it presents the wearers with a mobile application support interface to monitor battery levels and conduct surrounding air quality checks.

A "body to device-to-cloud" model-based SFM tagged "Lab-On-Mask (LOM)" was proposed by Pan et al. [38]. The noncontact LOM design is composed of data processing modules, signal processing sensors, and Bluetooth data output. It uses a polydimethylsiloxane board to embed the monitoring sensors for blood pressure, heart rate, and blood oxygen saturation. Regarding self-powered SFMs, Ghatak et al. [30] proposed a low-cost multilayer self-powered smart mask (MSSM) made from tribo-series material. It is self-customizable to provide maximum comfortable texture and safety when in use. The MSSM has an inner, middle, and smart layer. The inner and the middle layers are triboelectric filters solely for filtering the COVID-19 virus. The smart layer becomes self-activated automatically through the vocal activities of the wearer. The MSSM thermal power generation strategy originates from static and triboelectricity and up to 0.4 W/s, which is capable of electrocuting incoming virus-invaded aerosols due to its high aerosol infiltration efficiency. In the work of Kalavakonda et al. [21], a closed-loop control system was used to sense and determine ambient air quality. This also involves the activation of a piezoelectric actuator, which has the capacity to generate a mist spray to load and spray surrounding airbornes.

Liu et al. [39] used nylon fabrics, polytetrafluoroethylene, and a linear motor-based triboelectric filtering approach to develop a self-powered washable FM with electrostatic adsorption capability. In another attempt, Chua et al. [25] developed a sandwich-structured electret nanogenerator with electrospun PEI nonwoven-based SFM. The SFM serves the dual purpose of dynamically removing particulate aerosols and generating electricity, as well as monitoring respiratory rates. The high energy efficiency of the SFM makes it possible for it to be used continuously for an average period of 40 h. The experimental process in the production is based on orderly steps, including the PEI nonwoven, corona charging basically to inject charges into the PEI nonwoven, a sandwich-structured nanogenerator assemblage of 5×5 cm^2 and characterization. The PEI-based SFM has, however, not been widely adopted for commercial use as it is still subject to further validation and testing. In Table II, some emerging SFMs, their associated features, and functional contributions are presented.

V. Opportunities, Challenges and Future Research Directions in SFM Technology

In this section, we discuss the opportunities, challenges, and future research direction for the development and use of SFM technology, especially in the management of the COVID-19 pandemic.

A. Opportunities

Besides offering possible low-cost and off-the-shelf rapid protective response in the emergency pandemic outbreak, SFMs also have the potential to act as a pervasive means of making calls and sending text messages[3]. The emergence and use of SFMs, owing to their ubiquitous and sensing abilities, may indicate the first step in the automatic collection, storage, and analysis of health data emanating from vital body signs, body fluid composition, temperature readings, heart readings, breath and remote spatiotemporal health information, and so on [41]. This development may birth the building of dedicated servers and data centers for SFMs. In academia and industry, data engineers and scientists can use data obtained from SFM to generate key insights that can contribute to more social good. For example, predictive monitoring of vital signs and disease progression. In addition, beyond curtailing the spread of the COVID-19 pandemic with the use of SFM, it can also be adapted to managing other airborne communicable diseases. Other potential areas of application of SFM may involve noninvasive and real-time monitoring of the human body's physiological vital signs toward early disease detection and management [17]. It may be used as an air purifier and odor data acquisition tool for potential early automated detection of oral squamous cell carcinoma and other oral cavity cancers. Furthermore, since SFM has the potential to acquire personal health metrics, data acquired may help in building user-aware and personalized health information recommendation systems for wearers. Furthermore, SFMs can help to reduce the environmental toll, health hazard, and cost challenges associated with the disposable FMs. From the socioeconomic point of view, postlegislative approval of

[3]Spring Wise (2020). SMF connects to phones for remote calling and texting. Health and Wellbeing. Available://https.www.donutrobotics.com

TABLE II
SOME EMERGING SFMS, THEIR ASSOCIATED FEATURES AND FUNCTIONAL CONTRIBUTIONS

#	Authors	Design Method / Concept	Re-Usability	Energy-awareness	Self-Power Generation	Aerosol Filtration Efficiency	Functional Contribution
1	[32] Zhong et al. (2022)	self-powered SFM from two ultrathin Au/parylene/Teflon AF films pressure sensors with a thickness of ≈5.5 (m) and a weight of ≈4.5 mg	Yes	Yes	Yes. Its corona charging is fitted with a Dongwen DW-N503-4ACD2 or DW-P503-4ACD2 solar power source, a ground electrode and a corona needle.	High	- This manuscript describes a smart mask that can monitor people's breathing conditions in real time. - A limitation is that it is not air permeable.
2	[18] Zhu et al. (2022)	a lightweight SFM based on a passive harmonic sensor with a lumped element-based frequency multiplier, a meander-line antenna operating at 1.5 GHz and an inverted-F antenna operating at 3.0 GHz	Yes	Yes	No	High	A wireless SFM for cough detection and rapid monitoring in Covid-19 situations. A limitation is that it is not energy efficient as it cannot generate its own power. Alternative power plan must always be provided to keep it in use.
3	[15] Hyysalo et al. (2022)	IoT-based SFM based on a flexible hermoplastic polyurethane-based filament FlexFill 98A	Yes	Yes	No. It uses rechargeable battery	High	End user interface for data aggregation. A limitation is that it is not energy efficient as it cannot generate its own power.
4	[34] Curtiss et al. (2021)	FaceBit: built from NRF2832 SoC board with a chip antenna on the BMD-350 BLE Module. Embedded sensors on the board include the Si7051 temperature sensor, the	Yes	Yes	Yes. Though Facebit uses a thin 105 mWh primary cell battery, it has the ability to harvest energy from motion,	High	- Facebit is an open source SFM with a companion mobile app that provides an interface to aid research. - Its energy efficiency allows battery power conservation for up to 11 days. on-device health metric capture and
		LSM6DSL 6-DOF Inertial Measurement Unit and the LPS22HB barometer.			sunlight and breath to complement its energy requirements via a flexible PowerFilm MP3-37 4.49X1.44in 150mW solar panel		monitoring of mask fit, mask wear time, mask degradation, respiratory and heart rates.
5	[35] Gravina et al. (2021)	SFM with improved Copper3D technology and Ultimaker Cura embedded with temperature, accelerometer, humidity and light sensors	Yes	Yes	No. It is powered up with a lithium battery	High	SFM is able to monitor temperature, motion and can detect when a mask is worn and if it is properly worn. A limitation is that it is not energy efficient as it cannot generate its own power.
6	[29] Fois (2021)	AG47-SmartMask: uses an ARM 32-bit Cortex-M4 CPU and a STM32L4R5AI ARM-M4 Ultra Low Power microcontroller unit in its design.	Yes. The filter can be used for a minimum of 60 days at a stretch.	Yes	No	High	SFM is able to monitor the cardio-pulmonary activities including the heart rate and the body temperature of wearers for early detection of Covid-19. A limitation is that it is not energy efficient as it cannot generate its own power.
7	[36] Lazaro et al. (2021)	AtTiny402 microcontroller with an integrated dual heat flux sensor	Yes	Yes	No. It uses a 500 mAh lithium polymer battery.	High	A smart mask based on long range technology that is capable of supervising breathing and temperature rates as well as detecting cough events. A limitation is that it is not energy efficient as it cannot generate its own power.
8	[17] Fischer et al. (2021)	Masquare: It incorporates sensing electronics with thin multilayers of textile and 3D printed structures. It uses differential barometers (BME680 and LPS22HB) that equally act as spirometer	Yes	Yes	No. It uses removable battery that has USB port in the main control module for recharging purposes	High	presents a smart mask that is capable of close supervision of health status, for air filtering, respiratory pressure monitoring purposes. A limitation is that it is not energy efficient as it cannot generate its own power.

TABLE II
(Continued.) Some Emerging SFMs, Their Associated Features and Functional Contributions

9	[40] Ashford (2021)	Modular neck corset wearable garment tagged "Doki Doki" with bespoke	Yes	No	No	N/A	Data-driven neck corset wearable capable of collecting and visualizing emotive and environmental data from heart rate and locations to aid social interactions. A limitation is that it is not energy efficient as it cannot generate its own power.
10	[37] Kim et al. (2020)	SFM with wireless aerosol jet printing technology and a cloud-based data backup technique	Yes	Yes	No. Battery power	High	Low-cost and customizable SFM capable of monitoring a wearer's face strain and temperature. A limitation is that it is not energy efficient as it cannot generate its own power.
11	[21] Kalavakonda et al. (2020)	SFM is based on an active mist generator with a piezoelectric transducer operating at 110 kHz and two laser scattering based Sensirion SPS30 particulate matter sensors	Yes	Yes	No. battery power.	High	Low-cost SFM with a mobile application support to monitor battery levels and conduct surrounding air quality checks. A limitation is that it is not energy efficient as it cannot generate its own power.
12	[38] Pan et al. (2020)	SFM tagged "Lab-On-Mask“. It uses polydimethylsiloxane board to embed data processing modules and signal processing sensors	Yes	Yes	No. Battery power.	High	SFM is equipped with the ability to monitor blood pressure, heart rate and the blood oxygen saturation rate. A limitation is that it is not energy efficient as it cannot generate its own power.
13	[30] Ghatak et al. (2020)	multilayer SFM made from tribo-series material and operates based on electrification and electrostatic induction	Yes	Yes	Yes. thermal power originates from static and triboelectricity and up to 0.4W per second	High	a low-cost, safe and customizable SFM optimized to provide efficient air filtration in a cost-effective manner. It provides maximum comfortable texture.
14	[41] Masna et al. (2020)	SFM based on piezoelectric actuator, particle matter sensor and active closed-loop protection	Yes	Yes	Not mentioned	High	presents a smart phone application for alert counts. Can measure air quality and spray surrounding aerosols. However, it has not been widely adopted for commercial use and may still be subjected to further validation and testing before full deployment and commercialization.
15	[39] Liu (2018)	SFM based on polytetrafluoroethylene and a linear motor-based triboelectric filtering approach	Yes	Yes	Yes	High	SFM with electrostatic adsorption capability. It has not been widely adopted for commercial use and may still be subjected to further validation and testing.
16	[42] Cheng et al., (2017)	Sandwich-structured electret nanogenerator with Electrospun Polyetherimide (PEI) nonwoven	Yes	Yes. It can conserve energy and used continuously for an avg. period of 40 hours	Yes.	High	SFM is able to dynamically remove particulate aerosols. It has the ability to remotely monitor respiratory rates of humans.

the wide deployment, and use of SFMs across many nations globally shall be a great opportunity for the global economy to grow. Technically, it may also facilitate capacity building, empowerment opportunities, and tech job creation for young entrepreneurs, technocrats, local and international tech markets and businesses, and may also lead to rise of local manufacturers of SFMs. Internationally, SFM technology may be greatly beneficial to boosting bilateral trade agreements and economy growth among different nations of the world with respect to commercialization and import/export relations around SFM raw materials, which, in turn, may translate into increased gross domestic product and reduced recession globally.

B. Key Concerns and Challenges

The key concerns and challenges regarding the development and use of SFM discussed in this section include government policy and public surveillance, safety, security, and privacy issues, and specification and standards issues.

1) Government Policy, Regulations, and Public Surveillance: Are there existing government policies that govern the development and use of SFM and its data? Are there approved minimum regulatory standards and specifications for the design of SFMs and other techno-driven healthcare devices, as well as the use of health data collected? For example, before the emergence of COVID-19, the production, distribution, and use of cloth face coverings like surgical masks were are cleared and regulated by the Food and Drug Administration (FDA) in the United States. FDA is a governmental agency that is saddled with the responsibility to ensure that public health is protected. An agency in the U.K. saddled with a similar responsibility is the medicines and healthcare products regulatory Agency (MHRA). Since the emergence of COVID-19, a major concern, however, is that it is largely unknown how well democratic government policies around the world have embraced technology-driven approaches to respond to the fight against communicable diseases, and most especially COVID-19. The sensing nature of SFM makes it a potential tool for human monitoring [43] and identification[4]. This raises concern of possible active surveillance and censoring of the public and their opinions by the government [5]. Since surveillance potentials of the SFM poses high risk to human rights, in turn, it may frustrate and jeopardize public acceptance of its use [13]. If no regulation is in place, abuse of use is inevitable.

2) Safety, Ethical, Security and Privacy Issues: It is important to establish security measures and privacy control, perhaps by enacting certain governmental policies, which can address the potential abusive use of SFM technology and data. This is to ensure that the safety and privacy of the wearers of SFMs are not breached or intentionally locked-in. For example, a breach in health data privacy may lead to discrimination against the owner [15]. The procedures governing the acquisition, storage, and use of data sourced from SFMs must be well-regulated to avoid unethical violations by consumers.

3) Specification and Standards Issues: Governmental policies and certifications are to be enacted to establish and uphold the minimum acceptable quality standards, operational standards, and minimum requirement specifications to be met by SFM manufacturers before final approval is obtained toward mass production to the public. Matuschek et al. [2] affirmed the need for a well-defined recommendation for the use of SFMs. An example is ensuring that the techno-driven protective clothing does not pose safety, privacy, and other health burdens to the wearers regardless of their age or existing comorbidities.

C. Future Research Directions

This study has some limitations. First, the review of SFMs conducted is limited to those published and indexed in the SCOPUS database. Second, most of the SFMs discussed in this article are still in their prototype stage and emerging, so there is a possibility that some changes and improvements may be made to the SFMs over time that may extend the current scope reported in this article. A lot of future research opportunities are evident with the emergence of SFMs. In the meantime, there may be a need to conduct a global spatiotemporal readiness assessment of the adoption and use of SFM by the public. This attempt is necessary to understand public opinion regarding certain controversial issues surrounding its use. In preparation for the next-generation protective SFM, future research can investigate how smart sensing can accurately discriminate particles and aerosols of the different airborne diseases for easy and accurate detection and disease-specific customization of SFMs from the design stage. The emergence of connected masks network is also becoming imminent. This may necessitate the need for the development of dedicated cybersecurity algorithms, security protocols, and frameworks to build resilience toward secure SFM networks and clusters. In addition, developing forensic readiness frameworks [16] with SFM use-cases may also be necessary for gathering digital forensic evidences for future forensic investigation in case of a security or privacy breach in connected masks. Furthermore, how mobile computing and SFM technologies can collectively provision a more sustainable, scalable and efficient means of health services and data management is also worthy of investigation.

[4]https://news.northwestern.edu/stories/2022/01/fitbit-for-the-face-can-turn-any-face-mask-into-smart-monitoring-device/

VI. Conclusion

In light of the deadly COVID-19 disease pandemic, FMs were introduced to curtail its widespread. Some emerging evidence have established that the proper use of quality FMs could help in mitigating the spread of the viral disease [12]. The use of traditional FMs in pandemic situations comes, however, with a number of challenges, including but not limited to the high susceptibility of infection or reinfection of the wearer, airflow obstructions, cultural misunderstanding and stigmatization, limited social interactions and communications, quality control and cost issues. Recently, innovation in FM design has taken on a new dimension with the emergence of SFMs. SFM is a multisensor device with the capability to intelligently provide multiple dedicated healthcare services beyond being a protective face cover. In this article, the main purpose is to provide a concise systematic review of the features, architecture, design, opportunities, challenges, and future research directions of the emerging SFMs.

From our findings, common features of the emerging SFMs include reusability, self-power generation ability, energy awareness, and aerosol filtration efficiency. In addition, extended capabilities of SFMs include but are not limited to the automatic detection of microbes and aerosols, remote health-metrics sensing and monitoring, disease screening and diagnosis, air quality sensing, mask usage time sensing, wireless CO_2 monitoring, mask fitness sensing, head and body motion sensing. These extended capabilities have eliminated the challenges of the traditional FMs. Furthermore, SFM can also serve as a tool for messaging and calling to aid effective communication among people in pandemic situations. Similarly, we discover that most of the SFMs have mobile application interface support for the end-users of the SFMs. A number of challenges identified with the use of SFM in literature include limited public acceptance owing to possibility of public surveillance, privacy and security concerns, lack of government policy, regulations and standards that define and establish quality control and ethical manner for the collection, storage, and the use of SFM data. Therefore, it may be interesting for the stakeholders to understand how the use of SFMs affects the people socially beyond its function as a wearable device to curb COVID-19 transmission. Understanding the end-users' experience and opinions about how the use of SFM can be made more effective is also important for it to gain wider public acceptability. In addition, being wearable, issues relating to appearance, weight, and level of comfort of SFMs should be taken into consideration to aid user acceptance. Finally, it would be useful to extend and integrate SFM with multiple classes of antimicrobial agents for early detection and prompt effective management of the COVID-19 disease pandemic and other communicable disease outbreaks in the future with wide public acceptance. The high tendency that SFMs could participate in an Internet-of-Things network also necessitates the need for cybersecurity measures to be developed or put in place to secure its communication and data.

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