

Design and Development of 3D Structured Personalised Nose Mask for Better Protection of Human Respiratory Health from Air Pollutants in Asthma Patients

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1 Abstract

Conditions of asthma aggravates in patient due to severity of air pollution. Masks serve as a critical barrier, protecting individuals from exposure to polluted air. Research reports suggest majority of the inhaled air that people breathe-in passes through nose.

This design project proposes a 3D-structured, aesthetically appealing nose mask with replaceable filter media that not only offers efficient cleaning of inhaled polluted air but also ergonomic fit to the wearer. This mask is designed using advanced facial 3D scanning techniques, aligning it with United Nations Sustainable Development Goals (SDGs).

The present work addresses the challenges associated with conventional masks, such as fit, comfort, filtration efficiency, and environmental sustainability. The proposed solution aims to enhance utility for users while minimizing ecological impact.

This research explores the complexities of mask design, including material selection, ergonomic considerations, and the integration of advanced filtration technologies to ensure comprehensive respiratory protection.

The scope of this study encompasses the design, development, and an evaluation of a personalized 3D-printed nose mask, highlighting its effectiveness, sustainability, and practical applications in real-world scenarios.

Keywords: Air pollutants, 3D Scanning, Sustainable Design, SDGs and Respiratory protection.

2 Introduction

Air pollution, a major issue the world is facing currently, has its enormous impact not only on the environment but also has significant toll on public health at an alarming rate. Unmindful usage of natural resources, improper combustion of fossil fuel and minimal efforts to mitigate the pollution has led to this grave situation of anthropogenic air pollution, today¹. Air pollution emissions occur at many stages in product's life cycles resulting in emissions that undergo several types of physical and chemical transformations to contribute to a wide range of health and environmental impacts, such as deterioration of air quality, toxicological stress on human health and ecosystems, photo-oxidant formation (smog), stratospheric ozone (O₃) depletion, climate change, degradation of air resources and its quality, among others².

Environmental and air pollution has, by now, been regarded as a greater threat for mankind than communicable diseases. Several research reports published worldwide have disclosed about the serious impacts of air pollution and its significant contribution towards the damage of public health. It acts as an important stimulus for the development and exacerbation of respiratory disease such as asthma, chronic obstructive pulmonary disease and lung cancer (please see the Figure 1). Over the past few years, the effects of prolonged exposure to air pollution has been intensified to alarming levels, likely to cause serious impacts on the cardiovascular activity in human body, brain and mental development in children and adolescents, kidney failure, etc.

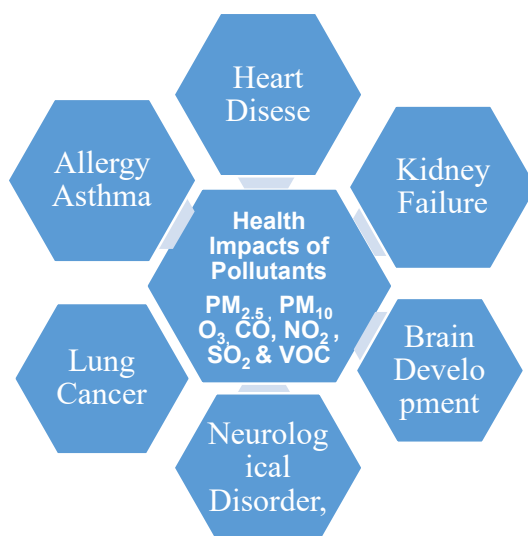


Figure 1: Established outcomes of short-term and long-term exposure to air pollutants (gaseous and particulate³)

The Global Burden of Disease (GBD) study has reported 3.1 million all-cause and all-age deaths worldwide due to the terrible impact of air pollution in the year 2010. Moreover, ambient air pollution ranked 9th among the modifiable disease risk factors and accounts for 3.1% of global disability-adjusted life years, an index that measures the time spent in the states of reduced health⁴.

According to a recent World Health Organization (WHO) research, 1 in 9 global deaths are attributable to air pollution, and more than 90% of people on Earth breathe bad air. 1.6 million of the 6.5 million fatalities worldwide that were attributed to poor air quality⁵ happened in India alone. According to a study conducted by the Indian Council for Medical Research (ICMR), air pollution killed 16.7 lakh Indians in 2019⁶ and destroyed ₹2.6 lakh crore of the country's economy. The Sustainable Development Goals (SDGs) of the United Nations Development Fund (UNDP)⁷ have called on nations worldwide to lessen the number of illnesses and fatalities caused by air pollution.

PM_{2.5}, a particulate matter with a diameter of less than 2.5 and less than 0.1 μm , is particularly harmful as it can enter the body's circulation system⁸ through the lungs of humans and can cause physiological changes in human body (please refer to Figures 2 and 3 below for examples). In addition to these gaseous and solid particulate pollutants,

such as ozone (O₃), nitrogen dioxide (NO₂), volatile organic compounds (VOCs) (benzene, toluene, and xylene), dichloromethane, trichloroethylene⁹, and other VOCs), even smaller biological pollutants, such as bacteria and viruses, are also causing air pollution. These pollutants enter the human body through breathing, leaving a serious negative impact on people's quality of life and pose a serious threat to the public life.

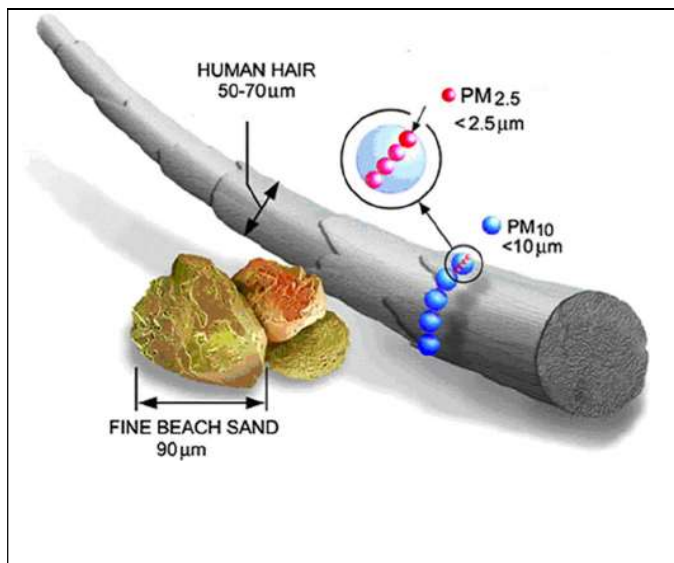


Figure 2: Size comparison of PM 2.5 and PM 10 against the average diameter of a human hair (~70 μm) and fine beach sand (~90 μm) (Source: Guaita et al., 2011).

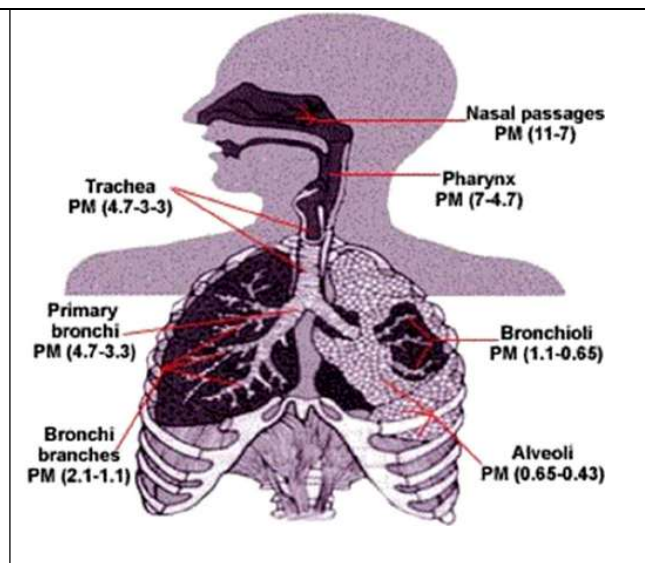


Figure 3: Deposition potential for particles of varying sizes in micron (μm) (Source: Londahl et al., 2006)

To safeguard both the environment and human health from the harmful consequences of air pollution, a number of control measures have been investigated, created, and put into use. Nonwoven solutions based on nanofibers have been shown to be superior to others in terms of both functionality and aesthetics when it comes to protecting oneself against air pollution. The creation of 3D electro-spun nonwoven fibrous mat and its uses as a filter media for protecting human health from air pollution has been discussed in this article.

3 Nano-Fibrous Nonwoven and Respiratory Protection against Air Pollution:

Filter mediums are generally made of conventional micron-sized nonwoven fibrous materials and sub-micron sized electro-spun, nano-structured fibrous materials in

designing and developing various filtering apparatuses or devices. Due to its micro-sized fiber diameter (several to tens of microns), the conventional filter media result in pore size of large dimensions and brings lot of drawbacks that are difficult to overcome. These drawbacks translate into relatively low filtration efficiency, bulkiness, and low quality factor, particularly when it comes to filtrating ultra-fine (PM_{2.5} or smaller) airborne particles.

To mitigate these issues and to optimize the efficacy of those conventional nonwoven fibrous materials, researchers, around the world has fabricated a novel and wonderful nonwoven material called as nanofibers. Figure no 4 as shown below would give an idea how nano fibres differ with conventional fibre in sizes.

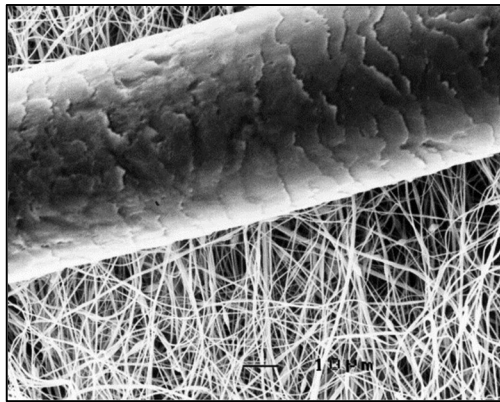


Figure 4: Comparison of Nano fibre with conventional fibre¹⁰

These nanofibers are created using a very special process called electrospinning, which is now well-known for its ability to produce fibrous materials with nano-sized structure that are highly functional and of high strength that are unable to accomplish via traditional textile processing methods. Conversely, nanofibers have enormous applications in high-performing and functional areas like filter medium, adsorbing layers in protective devices, tissue engineering, drug delivery, and optical electronics, to mention a few, because of their inherent properties like diameter in sub-micron size, higher surface area with better porosity, and so on.

Air filter for personal protection should ideally have a high air flow, low resistance, and high PM filtration efficiency¹¹ Because of their substantially smaller pore sizes and fiber diameters (100–800 nanometers) with a much lighter basis weight. Reduced fiber diameter of the nanofibers improves their interaction with the contaminants, increasing their capacity

to collect submicron particles and, in turn, improving the filtration efficiency of the filter devices by eliminating the tiniest, ultra-fine biological aerosols, such as viruses and bacteria. Electrospun nanofiber materials are commonly used in human respiratory protection devices because of these special qualities. The nano-fibrous web is an excellent option for chemical and biological protective materials because of its larger surface area, which can offer reactive sites for chemicals and biological elements. The nano-web's (3D electro-spun fibrous web) sub-micron nanopores have strong moisture and vapour transport capabilities, making them suitable for use in human and personal protective respiration gear to combat the negative impacts of air pollution¹⁰.

4 Control Mechanism and Devices:

The amount of particulate matter in the air has grown to be a severe environmental problem that requires immediate attention from researchers worldwide in order to develop new and more effective technologies that can lessen the harmful effects on the environment and public health. The majority of people work, live, and play in highly populated areas, increasing their exposure to a wide range of contaminants and diseases. Because of the decreased quality of life, increased absenteeism from work owing to illness, and decreased productivity at work, it lowers population well-being and has a significant negative economic impact¹². Therefore, it has become a must now for the clean and quality air, not only for quality life for the public but also for large number of industrial processes that provide and fulfil many basic and essential needs for human life¹³.

Therefore, filtration of air has become imperative and acknowledged as a crucial control mechanism in order to eliminate airborne PMs from the air stream and to offer protection against them. In the medical and biological industries, where extremely pure, sterile air is essential, filtration is also a must.

This filtration mechanism serves as the foundation for the development and construction of filter devices, which are often used to provide clean air for human breathing. Numerous mechanical and electret fibrous filter types as well as filtration membranes based on nanofibers are employed in a variety of applications to purify the air, particularly to protect against respiratory activities in humans. The main purpose of respiratory protection

devices (RPDs) is to shield users from airborne particles that include chemical, biological, and radioactive substances, among other respiratory risks. Examples of these respiratory protection devices that shield the human respiratory system from exposure to airborne particulates are Filtering Facepiece Respirators (FFR). The following figure (figure 5) shows different types of FFR for respiratory protection of human health.



Figure 5: Different Types of Filtering Facepiece Respirators (FFR) used for human protection¹⁴

5 Issues with Optimal Use of Filter Media in Current Masks and Its Sustainability

With manufacturing of masks nearly about 15 million¹⁵ pieces daily and the requirement of approximately 65 million (as per very conservative calculation during pandemic period) masks daily, India is poised to be responsible for huge land-fills as most of those masks are disposable after single use (as was advisable, too). The currently available layered masks, such as triple layer medical mask or N-95 respirator masks are all disposable. After single-use, these masks are being thrown away to dust bins and then to landfills. Huge number of raw materials could be saved if some parts of these masks are being recycled and reused. These triple layer masks, comparatively cheaper, are not free from flaws; one of them being their lower filtration efficiency in containment of certain types of air pollutants. Whereas the N-95 respirator masks provide better protection through its highly efficient filter media sandwiched in between its layers but come at a much higher cost than that of these triple layer masks in the market.

The number of COPD cases in India was a staggering 55.3 million in 2016 and is the second common cause of deaths due to non-communicable disease (NCD)¹⁶ and air pollution increases the risk of it in healthy people. Evidence from India suggested the COPD prevalence increases with age and exponentially after 30 years of age. The

estimated prevalence of COPD ranged from 0.1% to 0.9% between the age group of 5 years to 29 years while the incidence ranged from 1.6% to 28.3% in population above 30 years of age. Both India and China contributed to 33% of the world population and accounted for 66% of COPD mortality¹⁷.

The clean air provides better living conditions and increases the chances of reduction in mortality due to air pollution. Inhaling clean air can reduce the risk of developing lung cancer, heart disease, stroke, and both acute and chronic respiratory conditions like asthma. Both in the short and long term, lower air pollution levels are better for respiratory and cardiac health. In observational studies, it is found that wearing masks is associated with a lower risk of contracting viral respiratory infections¹⁸. Therefore, it is inevitable that the consumption of masks is highly recommended for protecting oneself from the ill effects of air pollution. From the number of COPD patients mentioned above, it is evident that a huge number of masks are required to give protection to such patients if they want to wear masks and lessen the severity of their disease. Such large quantity of masks which are mostly made of synthetic polymers like polypropylene or some other mostly non-biodegradable polymers create long term hazard for ecology. Polypropylene may take 20-30 years to degrade¹⁹. Even if some biodegradable polymers are being used, the magnitude of waste generated by frequent disposal of such large quantity of masks is posing serious threats to global environment and ever-increasing burdens of landfills. It poses an environmental threat to the humanity that led to unsustainable practices as per the UN's SDGs policy. Moreover, most of the time such kind of masks are entirely made up of the filter media, except for industrial gas masks and that kind of design issues lead to the suboptimal use of the filter fabric / media that also creates a sustainability concern for the environment.

Another issue that is of importance is the discomfort of wearing masks on the faces of the wearers during various activities. A study has shown that 70 to 90 % of inhaled air is taken through nasal cavity during normal activities²⁰. It is therefore justifiable to say if only noses are covered the similar protection can be achieved against air pollution.

Till date the mass manufacturing of masks happens based on scientifically analysed design templates. Therefore, there are ample scope of design innovation and customisation in the field of masks.

6 Seamless Protection through Sustainable Design Innovation

Face is an important part of human physiology for different functional activities like eating, expression of emotion, interpersonal communication and above all, it represents one's own identity. People covered with masks hinder these normal activities by muffling sounds and covering facial expressions during live communication²¹. Therefore, the present state of the art of face mask design, manufacturing and usage opens up further scopes to research, innovation and improvisation in design sustainably as has been attempted in this work. Through this work a sustainable design innovation approach is being researched upon where the following concerns have been attempted to address: -

- a) Multi-zonal Design; creation of a multi zonal design where the effective filtration zone and the holding zone on the nose are detachable. This would enable disposal of the filters on the filtration zone after their recommended lifecycle and replacement with fresh filter media and at the same time, recycling and reusing the holding zone can be practiced for prolonged period of time within its effective lifespan.
- b) Customisation in Design; designing a system of customisation of the shape of the holding zone as per nasal contour of individual wearer using existing 3D scanning and image processing technologies.
- c) Modular Fabrication System; manufacturing of the nose masks in seamless modular form employing latest 3D printing technology eliminating multiple manufacturing steps.

7 Methodology

7.1 Development of Customised Face & Nose Mask

As mentioned in the section 6, customisation and ergonomic designing of the mask is the way forward to mitigate the negative impact of air pollution and to make the currently available masks more sustainable. The following sections describe the 3D scanning and modelling techniques of mask.

7.1.1 3D Scanning, Image Processing and Modelling of Customised Face and Nose Mask

A slew of equipment was used to 3D print the face and nose mask. A hand-held 3D scanner was used to scan the face of the subject. The scanner was named as Structure Sensor (ST 01) made by Occipital Inc., USA. The scanner was attached to a tablet with 4 GB RAM and 64 GB storage space to real-time visualisation of the scanned image in 3D format through an app called as Structure SDK that would help save the image in the internal storage space of the tablet.

The 3D scanned image was then imported and processed through specialised software named as Skanect Pro provided by the Occipital Inc. After the processing of the 3D scanned image, the file was exported to another 3D editing software named as Rhinoceros 3D (version 7) design software. The detailed method of the process from scanning to printing of the face mask is described in several steps in the below section.

To get the customised face and nose mask, the face scanning was done first. The subject for 3D scanning was volunteered by one student and her face was scanned using the hand-held scanner (Structure Sensor) and Structure SDK app installed in the tablet to get accurate face contour of the subject.

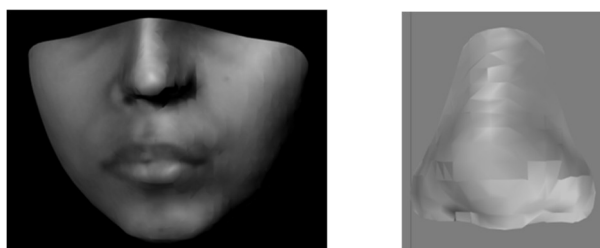


Figure 6: Cropped face scan for getting the face and nose contour of the subject

The scanned file was then exported to software called Skanect Pro for editing and bettering its image quality. The pictures of the editing process (Prepare-Record-Reconstruct-Process-Share) have been shown in the following section.

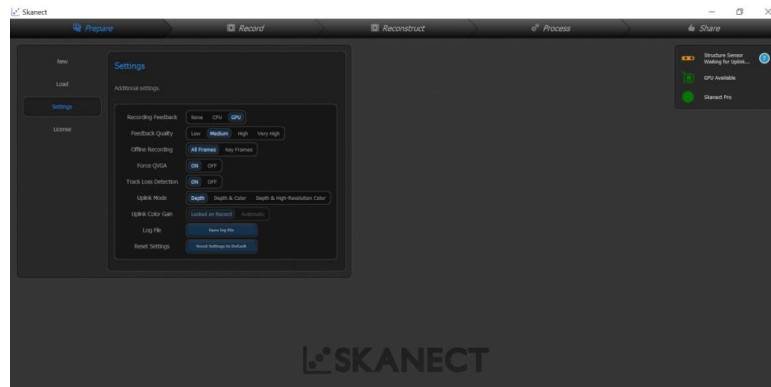


Figure 7: The home page of the Skanect Pro software by Occipital Inc.

The edited version of the Skanect Pro file was then exported to a visual editing software Rhinoceros 3D (version 7) and both the mask (face & nose) was designed using the peripheral face contour of the subject, required for the effective coverage of the face of the subject which is desirable for leak-proof mask.

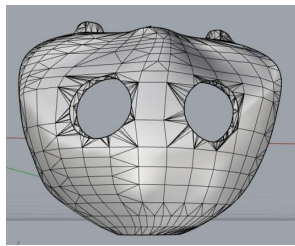


Figure 8: Digital 3D mesh image of face mask created in Rhinoceros

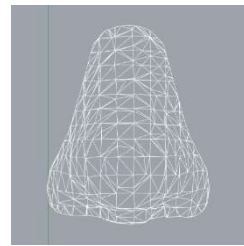


Figure 9: Digital 3D mesh image of nose mask created in Rhinoceros

Once the editing was done, the file was saved in (dot)(.)STL format for its being ready for the 3D printing. The file was then exported to 3D printer's editing software (Ultimaker Care) to finally edit the 3D printable file to get its dimensions (thickness, length, width and height) right.

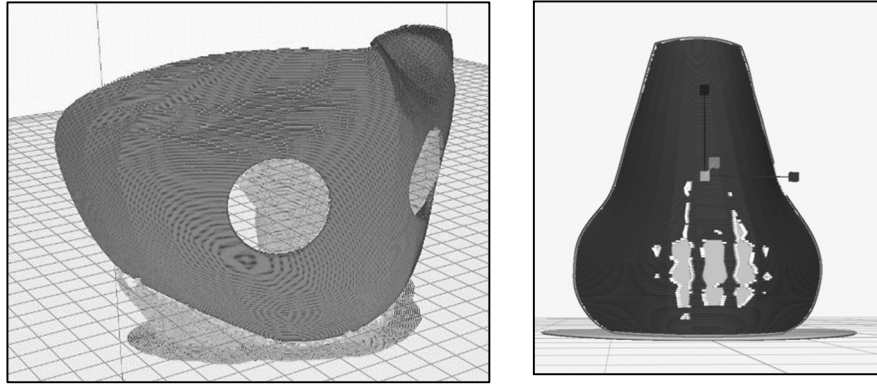


Figure 10: 3D Printable file for printing of face & nose mask

The customized face & nose mask was 3D printed using a variety of tools. The subject's face was scanned with a handheld 3D scanner. Named Structure Sensor (ST 01), the scanner was produced in the United States by Occipital Inc. A tablet with 64 GB of storage and 4 GB of RAM was used with the scanner to enable real-time 3D visualization of the scanned image using the Structure SDK application programme (app), which also helped save the image to the tablet's internal storage.

After that, the 3D scanned image was imported and analysed using Skanect Pro, a specialised software programme made available by Occipital Inc. Following the 3D scanned image processing, the file was sent to Rhinoceros 3D (version 7) design software for printing. which is another 3D editing program.

After the editing, the file was saved in Dot(.)STL format for its preparedness for the 3D printing. The file was then exported to 3D printer's editing software (Ultimaker Care) to finally edit the 3D printable file (pls see the below figure 11 and 12) to get its dimensions (thickness, length, width and height) right and 3D print them.



Figure 11. Actual 3D printed face mask in different views



Figure 12. Actual 3D printed nose mask in different views

7.1.2 Development of 3D Electro-spun Fibrous Web

7.1.2.1 Material Used:

Nylon 6, and formic acid was used to electro-spin the fibrous filter media.

7.1.2.2 Equipment Used:

The 3D nano-fibre web was fabricated in the electro-spinning machine of make E-spin Nanotech, model –E-spin Nano at the Chemical & Biochemical Processing Division of ICAR-NINFET, Kolkata (pls refer to figure 13). Further developmental work with different polymers is under progress.



Figure 13: Electrospinning machine with facility of three-dimensional fibrous mat

8 Conclusion

This prototype development demonstrates the concern related to design, manufacturing and usage of face and nose masks.

The face and nose mask design were planned in two distinct parts. The holding part, which was 3D printed during this work, was made of TPU (Thermoplastic polyurethane) which is flexible, nontoxic and can be used for prolonged period. The second part; disposable filters can easily be fitted into the customised void spaces of the holding part, as depicted in the above figures.

This would allow the holding zone/part to be reused for an extended amount of time until it reaches its effective life, while the filter sections may be disposed of after the specified lifecycle. It is anticipated that this design project will lessen the environmental impact associated with discarding a significant number of used masks and their filter media.

Through process of customisation, it is possible to establish a second skin-like fit for the nose mask on the user's face and nose, which determines the contour design of the nose mask based on the unique face pattern of each subject. As a result, there would be less contaminated air leaking during inhalation and exhalation.

The use of 3D printing in the production of the facial and the nasal mask for this project suggests that a modular, one-step, seamless manufacturing method may be possible. This aids in addressing the issues raised by the complexity of the current manufacturing process about the filter fabric preparation, cutting, stitching, etc. The one-step 3D printing conversion procedure from design to product also lessens the concerns about the quality variations in the face and nose masks emerging at those various stages of traditional manufacturing.

The fibrous 3D nano-web that has been developed is yet to be analysed for its properties and performances. The tests and its character analysis would be done soon.

Further Recommendation

Optimisation and standardisation of the scanning and image generation process could be the scope of further research. Development of an objective evaluation process to fine tune the fitting of the nose mask as per the user nose contour can be worked upon. Characterization and optimised performance evaluation of the 3D Nano-web filter should be done.

Roles of Author

Ideation and Concept Development (M.B.), 3D Scanning & Digital Design (M.B, S.B.), Product Experimentation & Fabrication (S.B, M.B, S.M.), Original Draft Writing – (M.B.), Review of Draft – (S.B., S.M.), Overall Supervision (S.B, M.B., S.M., A.Mitra and A. Mukhopadhyay).

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