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RESEARCH ARTICLE

# Development of a reusable low-cost facemask with a recycled hydrophobic layer for preventive health care

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**Abstract**

The current work focuses on designing a low-cost, reusable, and highly efficient facemask for protection from respiratory droplets that cause COVID-19, other infection-causing organisms, and dust allergies. Several masks available in the market are single-use that would choke the environment through plastic pollution or are expensive for the commoner to afford. In the present study, the facemask incorporates a waste-derived polyethylene terephthalate (PET) layer and a non-woven polypropylene (PP) layer sandwiched between two tightly woven cotton layers. Combining these layers provides comfort and breathability, besides high bacterial and particulate filtration efficiency. Moreover, the unique PET layer provides mechanical strength and a 3D shape that enables hindrance-free speaking and prevents spectacle fogging. Compared to commercial N95 masks, the developed mask can be reused up to 30 washes and recycled with zero waste discharge ensuing green technology. Moreover, the mask was produced at an affordable cost of Rs. 17 (0.22 USD), including labor charges, and sold at a 100% profit margin @ Rs.35 (0.45 USD) per unit. Further, the mask was certified by neutral testing agencies and provided to a population of more than 6 lakhs, thus significantly contributing to the mitigation of COVID-19.

**Keywords** COVID-19 · Multilayered facemask · Recycled membrane · Polyethylene terephthalate · Non-woven polypropylene

## Introduction

The unprecedented spread of the SARS-CoV-2 virus to more than 200 nations worldwide caused greater than 6.5 million fatalities; the need for a facemask had become highly essential. According to the WHO, the virus is transmitted by airborne mechanisms via liquid droplets, aerosols, or from contaminated surfaces (World Health Organization(WHO) 2020). In 2021, COVID-19 is still in circulation due to mutations of the new coronavirus, which continue to cause infections and fatalities in several nations (Coccia 2022a). Medical workers were normally the only ones allowed to wear facemasks in the workplace, and surgical facemasks were most frequently worn. This world has changed due to the COVID-19 outbreak, including using masks during social interactions. This procedure is now widely accepted and believed to prevent infections successfully (Haller et al. 2022). As the pandemic began, there was a marked difference in the number of infections between South Asian and western countries, with facemask culture in South Asia being identified as the reason for the difference. The COVID-19 pandemic had a negative influence on the well-being of human beings and emphasized the flaws in the need to innovate and provide affordable personal protective equipment (PPE) along with a structured global supply chain (Rowan and Laffey 2021). The main transmission route between people is the infection-loaded aerosols and droplets. The average size of the virus-containing aerosols is 5 μm in diameter. The primary source of these aerosols is exhalation matter like coughing, sneezing, and oral communication. Most of the cotton masks currently available in the market are not up to the filtration efficiency standard to

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stop smaller aerosols from entering the human respiratory system (Keisar et al. 2023). Evaluating a country's readiness to deal with pandemic dangers is one of the major issues with the COVID-19 pandemic catastrophe. According to the Global Health Security Index, the USA and the UK were placed first and second in 2019, indicating the good capacity of both nations to deal with a serious bio catastrophe, including a pandemic. In 2021, the COVID-19 epidemic evolved, and the Lowy Institute advises assessing nations' relative success based on several factors. The policy reactions to the COVID-19 epidemic in Eastern and Western nations are examined in Anttiroiko 2021 in terms of how socio-economic background, institutional structure, culture, and technological level might influence these responses. According to the report, Asian nations demonstrate proactive initiatives, while Western countries choose reactive policy measures. To order to deliver prompt policy responses in society, the COVID-19 pandemic crisis management is often built on effective multilevel governance, incorporating national, rural, and urban institutions (Coccia 2022b). To deal with the COVID-19 pandemic catastrophe initially, governments used non-pharmaceutical means of management such as lockdowns and quarantine. In recent years, the global danger to people's well-being and a complex range of social and economic effects has increased due to the frequency of viral illnesses. The planet Earth and human existence are seriously threatened by microbial viruses and how they interact with the ecosystem in the atmosphere (Gollakota et al. 2021). Regarding coronavirus, multiple research experiments have shown that SARS-CoV-2 genetic material may dwell in the air for at least 3 h and perhaps up to 16 h. To prevent the transmission of COVID-19 from one individual to another in the absence of wind, many governments have issued rigorous guidelines for people to maintain a social distance of at least 2 m between each other and stay away from populated areas (Cao et al. 2021). Facemasks made of polypropylene (PPN) have also become popular as an option to prevent the transmission of possibly contagious respiratory particles. Additionally, several studies have demonstrated that coughing may discharge potentially contagious saliva. Previous studies have demonstrated that droplets are created in the aerosols during speech, breathing, and sneezing (Hairch et al. 2022). Moreover, the mathematical models indicate that the present vaccination penetration in many nations is inadequate to accomplish pandemic control, notwithstanding the amazing efficiency of certain COVID-19 vaccines and their high protection rates against symptomatic disease, especially severe sickness. The limitations of immunization alone have low efficiency; hence, non-pharmaceutical interventions (NPI) are required as additional interventions. Regardless of the coronavirus variety, the masks impede the virus' ability to spread at the level of a physical barrier. Masks and vaccinations are far less expensive to implement than other NPI measures, which have large economic and social consequences. Despite this, a sizeable portion of society is vocally opposed to both of these NPI policies. Although there was a sizable amount of variability between trials, the overall pooled analysis demonstrated a significant decrease in COVID-19 incidence with mask use (Brüssow and Zuber 2022).

As a result, to avert the virus spread, the WHO and several healthcare experts recommend wearing a facemask as the first line of defense for preventing infections (World Health Organization (WHO) 2020). The existing facemasks like surgical masks and cloth masks became scarcely available in the market, and it was soon recognized that single-layer non-medical masks are ineffective against the SARS-CoV-2 virus, and specialized facemasks are needed to curb the infections. Specialized masks like N95 and medicated masks had greater efficiency and could prevent infections, but their availability was limited, and they were not affordable to the common man. Thus, the existing supply chain for surgical and N95 masks could not cater to the steep and sudden increase in demand as it was mandatory to wear a facemask for every individual. With the surge in facemask demand and the shortage of commercial mask availability, there was a need to design and develop an alternative solution for producing efficient and affordable facemasks. Also, to mitigate the impact of COVID-19 on the common man the developed facemasks needed to be easily accessible, durable, and reusable, which can be directly inducted into the healthcare systems. The standard N95 grade masks available in the market are single-use, disposable, and have high costs per unit (World Health Organization (WHO) 2020; Stokes et al. 2021). Also, a few non-medical facemasks have been designed with a non-return valve to allow exhaled air to come out of the mask, which is considered unsuitable for COVID-19 prevention (Pecchia et al. 2020). In other commercial masks, layers of the facemask are made up of non-degradable polypropylene materials, which will result in a significant carbon footprint and burden the ecological environment as a new source of pollution (Chua et al. 2020; Ji et al. 2020). Considering this framework, many academics and researchers have been exploring new methodologies for developing reusable and repurposed facemasks and respirators focused on meeting the regular standards of PPEs without causing any environmental pollution (Gertsman et al. 2020; O'Hearn et al. 2020; Aljabo et al. 2020). Moreover, the reuse procedures and technique must be simple and guarantee the facemask's originality in terms of shape, size, breathability, performance, and filtration efficiency (Rodriguez-Martinez et al. 2020; Mawkhlieng and Majumdar 2021; Levine et al. 2021).

To prevent the transmission of the COVID-19 virus, the present study aims to design a low-cost multilayered facemask in which one layer is derived from waste membrane modules to meet the requirement and demand. The distinct hydrophobic polyethylene terephthalate (PET) layer from the waste spiral wound reverse osmosis (RO) or ultrafiltration (UF) membrane module can be recycled and repurposed as a layer of the facemask. Usually, these modules are discarded after a single use and do not have a specific remediation mechanism, and therefore, recycling the PET permeate spacer layer from these modules will reduce the carbon footprint and prevent plastic pollution (Pontié et al. 2017). The central PET layer derived from waste membranes advocates the "waste to wealth and health" approach that also prevents 1 ton of plastic waste generation for every 2 lakh masks produced. PET is one of the key layers in the facemask that provides structural integrity, mechanical strength, tortuosity, and durability to the facemask owing to its hydrophobic and warp-knit structure. Reusing and repurposing of the PET layer from waste membrane modules provides an economically viable alternative and concurrently enables sustainable waste remediation. The hydrophobic PET layer incorporation into designing the facemask has been made keeping in mind the prolonged usage time of ≥ 8 h, as it allows forming a 3D design that is comfortable, snug fit, and does not restrict any facial movements while speaking and breathing. This waste-derived robust PET layer repels respiratory droplets effectively, has sufficient tensile strength to maintain structure and size, and dries quickly, allowing the masks to be washed and reused. Upon comprehensive study into the materials to be used in the facemask, the sequence of the textile layer, PET layer, polypropylene layer, and finally, again, the textile layer was executed as an adequate combination of strong protection at an inexpensive price with good aesthetics. Therefore, the development of the current facemask was intended to keep the common man safe from infections through germs, pathogens, particulate matter, and chemical aerosols transmitted from person to person, as well as protection against dangerous dust, fumes, vapors, and gases. Overall, the performance of the formulated masks was assessed in terms of water and air permeability, washability, bacterial and particulate filtration efficiency, contact angle, mechanical strength, water holdup capacity, candle flame extinguishing capacity, breathability, splash resistance, and non-flammable nature. A comparative cost estimation detail of the masks is also presented.

## Materials and methods

### Research setting

The four-layer configuration has been adopted for preparing the facemask which is in the following sequence: tightly woven textile layer, waste membrane-derived polyethylene terephthalate layer, ultrathin hydrophobic polypropylene layer, and tightly woven textile layer. For the preparation of facemasks, a cotton textile layer of 72 GSM was procured from the Telangana State Handloom Weavers' Cooperative Society Limited. A cotton cloth used for the facemask was devoid of any starch components to ensure no shrinkage after washing. The ultrathin hydrophobic polypropylene (PP) of 25 GSM was purchased from Sangita Polyfabs, Balanagar, Hyderabad. The unique PET layer of 90 GSM was extracted from the waste spiral wound membranes by cutting and opening the edges and unwinding the membrane spirals used in drinking water treatment. The PET layer was later pre-treated by cleaning and disinfecting it with a mild detergent, followed by air drying under normal atmospheric conditions. Soft elastic strings with 8-mm thickness 3-mm diameter and adjustment beads were hand-picked from the local stores. In the construction of a 3D multilayered facemask, the first and fourth layers were opted to be cotton textile fabric intended to provide comfort to the user and good aesthetics. The two distinct hydrophobic layers, namely, PET and PP, were incorporated as the second and third layers sandwiched between the two cotton layers. The layout sequence of the mask and repurposing of the PET spacer from the used membranes of the water purification units is represented in Fig. 1(a) and (b).

Additionally, all the fabrics used in the mask preparation are thoroughly screened, devoid of any physical damages or splinters. Moreover, the cotton fabric is pre-washed to remove starch and to prevent shrinkage after stitching and usage. The mask was designed in two different sizes to fit both adults and children with dimensions of 9.5″ × 6.5″ and 6.65″ × 4.55″, respectively. In supplementary data, the templates for cutting the fabric in two sizes are well-represented in Figure S1(a). The 3D shape mask is represented in Figure S1(b), and the plastic beads were attached to the elastic ear loop, as shown in Figure S1(c).

### Data analysis procedure

The layers of the homegrown multilayered facemask were characterized by scanning electron microscopy (SEM) for examining the morphological features. The surface morphologies are scanned and captured using JEOL JSM 5410 SEM (Tokyo, Japan). Before the analysis, the surface of the individual layers of the mask was sputtered with gold for improving the material's conductivity as per standard norms. DSA100M model Goniometer (Kruss, USA) was used to analyze the surface hydrophilicity by employing the sessile drop technique at ambient temperature conditions. During contact angle analysis, a water droplet was positioned on the surface of the PP layer and measured within 5 s of instant dropping for an accurate value.

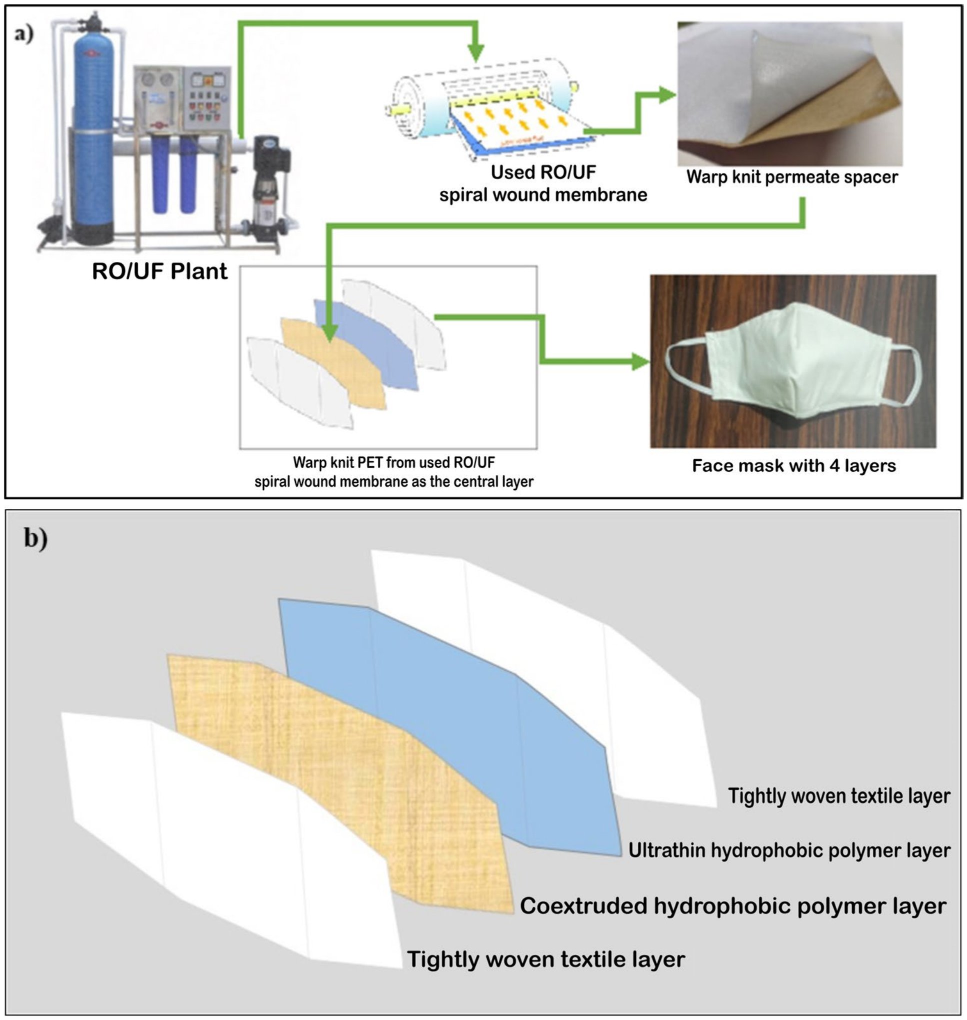



**Fig. 1** **a** Extraction of PET layer from used membranes of drinking water purification plants. **b** Sequential arrangement of the mask layers

## Measures of variables

### Air and water permeability test

For the estimation of air and water permeabilities of the developed facemask, a stainless steel testing unit was assembled and carefully secured with flanges on both sides, as shown in Fig. 2. Polyurethane pipes were connected to the inlet and outlet sides for the test cell. Also, control valves and pressure gauges are attached to the feed, permeate, and reject lines to adjust and read the pressure, respectively. A sample mask of a 0.0072-m$^2$ area was cut into a circular shape that could fit in the test cell. After arranging the sample mask into the test cell, the air was allowed to pass into the cell, maintained at 0.5-bar pressure. Under the applied pressure, the air flowing from the downstream side was

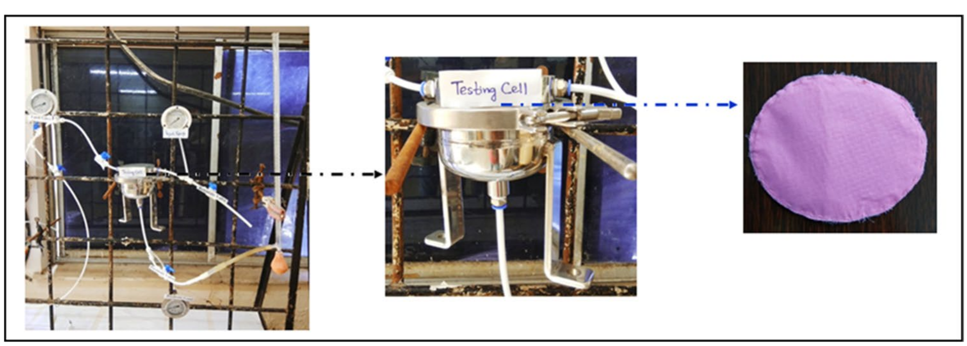



**Fig. 2** Air and water permeability test setup

measured using a soap bubble flow meter when it reached a steady state. The water permeability test was performed at a pressure of 0.5 bar in the test cell to allow the water to permeate through the mask and collected the permeate at regular time intervals to measure the water permeability of the mask.

To better understand the reusability of the masks, they were washed with mild detergent multiple times and kept for drying. Further, these masks were examined for the transformations for every 5 wash intervals and continued until 30 washes. To comprehend the washable nature, the developed mask was tested by observing the main parameters such as appearance, fitness, breathability, and durability. All the experiments were replicated with the commercially available cotton mask (reusable) to evaluate and compare the performance of the masks.

#### Bacterial and particulate filtration test

The preliminary bacterial filtration efficiency (BFE) and particulate filtration efficiency (PFE) test was conducted to determine the number of bacteria and particulate matter passing through the mask. The sample was primarily sterilized under UV-C radiation for 15 min on both sides to eliminate any prior microbial contamination. Simultaneously, culture medium plates were prepared by pouring 30 mL of nutrient agar media into each petri dish and allowed to solidify. After solidification of the nutrient media, the sterilized mask was placed aseptically on one plate, and another plate was left uncovered with nutrient media alone. These plates were exposed to 100 L of air for 4 h and incubated at 37 °C for 24 h in a bacterial incubator. In the end, the colonies were counted to determine the bacterial filtration efficiency using a colony counter. Moreover, the individual layers were also tested to determine BFE following the analogous procedure. In the PFE test, the fine uniform particulate matter was initially injected through the mask under the air and water media. Furthermore, the filtered media can be evaluated in terms of particulate matter. All experiments were performed in triplicate to attain accurate results. For further validation, the developed multilayered facemask was tested by an external agency, South India Textile Research Academy (SITRA) in terms of BFE (ASTM F 2101), PFE (ASTM F 2299), splash resistance, and breathability (ASTM F 1862) as per American Society for Testing and Materials (ASTM) standards.

## Results and discussion

### Characterization studies

The surface morphologies of cotton fabric, recycled PET, and PP layers are provided in Fig. 3(a)–(c). Additionally, the PP layer was tested for its hydrophobicity by examining the contact angle. DSA100M model Goniometer (Kruss, USA) was used to analyze the surface hydrophilicity by employing the sessile drop technique at ambient temperature conditions. During analysis, a water droplet was positioned on the surface of the PP layer and the contact angle was measured within 5 s of instant dropping to obtain an accurate value. The schematic representation of contact angle measurement is illustrated in Fig. 4(a).

The surface morphology of the cotton layer shows tightly inter-woven cotton threads, representing tight porosity. The SEM image of extracted warp-knit PET layer shows a uniform and highly porous structure that aids in the easy air passage. Moreover, it can be visualized from Fig. 3, the surface SEM image of the electro-spun PP layer, that the strings of PP are interlocked in a way that allows the passage of air leaving behind the dust, particulate matter, bacteria, and viruses.

The contact angle of the PP layer was found to be 121.6°, indicating high hydrophobicity that aids in the effective separation of the respiratory droplets by creating a greater threshold critical pressure to penetrate the mask, according

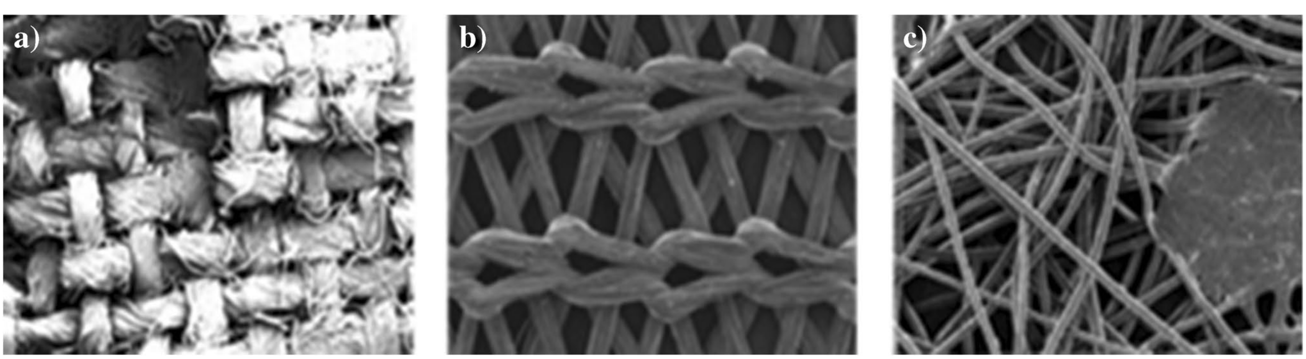



**Fig. 3** Surface morphological images of **a** cotton fabric, **b** warp-knit PET, and **c** electro-spun PP layers

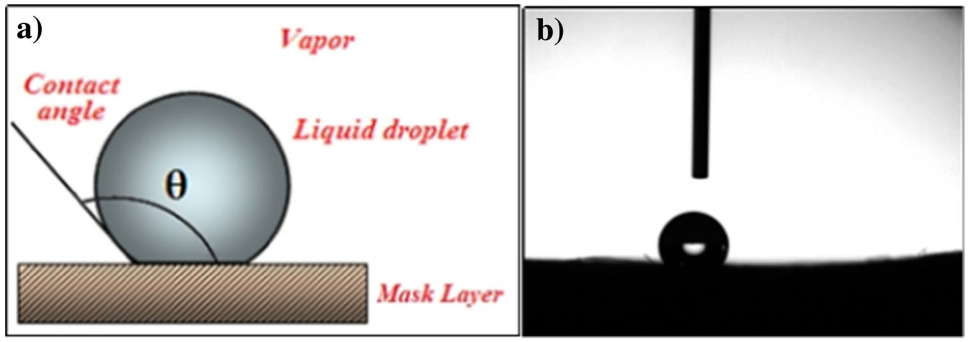



**Fig. 4** Contact angle measurement. **a** Schematic representation. **b** Actual photograph

to the Young–Laplace equation (Eq. (1)) (Liu and Cao 2016). The contact angle of the PP layer is seen in Fig. 4(b).

$$\Delta p = \frac{2\gamma \cos\theta}{r} \tag{1}$$

where $\Delta p$ is the pressure difference across the fluid interface, $\gamma$ is the surface tension, $r$ is the circular cross-sectional radius of the water droplet, and $\theta$ is the contact angle.

## Experimental results

The working mechanism of the developed facemask mainly depends on the construction material. The motive of combing cotton textile, PET, and PP layers is to create a nonlinear, strenuous path that restricts the entry of pathogens and respiratory droplets of 0.3 to 10 µm in size. Moreover, the mask layers are arranged in such a way that they barricade the foreign particles by a molecular sieving mechanism, as shown in Fig. 5. Also, the rejection of particulate matter is mainly based on three principles: inertial impact, diffusion, and electrostatic attraction. The dust and aerosol particles of ≥ 1 µm having sufficient inertia are filtered through its outer filtration layer. The particles of 0.1 – 1 µm exert low inertia, and flow through the mask under diffusion mechanism, but get stuck as they pass through the torturous path formed by the mask fiber matrix. On the other hand, the statically charged particles attract oppositely charged particles and filter them through a charge attraction mechanism. A pictorial representation of mask filtration principle is illustrated in Figure S2 of supplementary data whereas the working mechanism of the developed multilayer mask is shown in Fig. 5.

The experiments were conducted to study the performance of the developed facemask in terms of air and water permeability, washability, BFE, and PFE. After conducting the experiments, the results were calculated accordingly and discussed below.

### Air and water permeability analysis

The air and water permeability tests for the designed mask were conducted in a single-stage process. From this experiment, the air and water permeabilities of the designed mask were found to be 843,496 L/m$^2$·h and 1185 L/m$^2$·h, respectively, at an applied pressure of 0.5 bar. It can be concluded that the designed mask is highly permeable to air and resistant to water. This proves that the mask is highly breathable

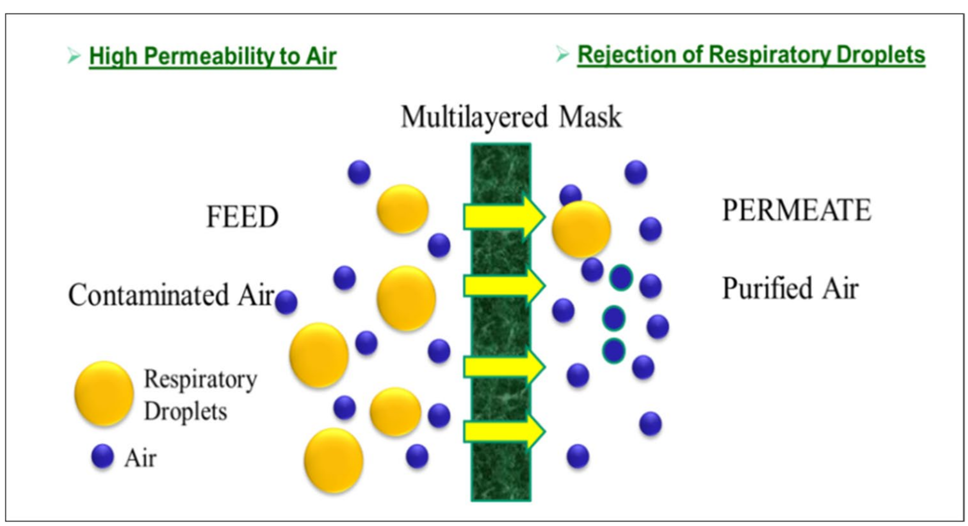



**Fig. 5** Filtration mechanism

and restricts the entry of respiratory droplets containing bacteria or viruses. Hence, further experiments on bacterial and particulate filtration can justify the overall performance of the mask.

### Washability (durability) analysis

The durability analyses of the masks (indigenous, and commercial) were noted at 0, 5, 10, 20, and 30 washes. The fundamental parameters like breathability, appearance, fitness, flame extinguishing capability, shape and size, and water repulsion capability were analyzed to estimate the durability of the masks. The mask's breathability, appearance, fitness, shape, and size were assessed visually by wearing the facemask. In the case of the flame extinguishing test, the candle flame was tried to be blown out after wearing the mask. In case the flame was not extinguished, the droplets emanating from the respiratory system were minimal and the mask was supposed to have passed the test. In the water repulsion test, 10 mL of water was poured into the mask, and holding time was recorded until the water started dripping. The flame extinguishing and water hold tests are illustrated in Figure S3(a) and (b) supplementary data. From Table 1, it can be observed that all the parameters tested for the indigenous facemask show that the mask was intact, and not much difference in properties was observed even after 30 washes, with only a negligible change in the water repulsion test. In the case of the commercial mask, the results in Table 2 reveal that it could not withstand all its properties after 5 washes. Additionally, the commercial facemask could not pass the flame extinguishing test even when it was not washed even once and got extinguished immediately by one or two blowings (exhalation) from the mouth/nose.

### Bacterial and particulate filtration efficiency

The preliminary BFE test conducted at the laboratory showed that the developed mask could reject 87% bacteria. As discussed in the "Materials and methods" section, after incubation of the nutrient agar plates for 24 h, both the uncovered plate and plate with mask were placed under an illuminated colony counter, and the number of colonies was noted. It was witnessed that the uncovered plate had 31 bacterial colonies, while the plate covered with the mask had only 4 bacterial colonies, which corresponds to 87% rejection. Figure 6(a) and (b) present the uncovered and mask-covered nutrient agar plates with bacterial colonies, respectively. Thus, the indigenous bacterial filtration test revealed that the designed multilayered facemask is highly efficient in rejecting aerobic bacteria from passing through.

Moreover, the preliminary particulate filtration test was conducted by injecting fine uniform particulates under air and water media. The illustrations of this test are provided in supplementary data (Figure S4(a) and (b)). The multilayered facemask could restrict particulate matter entry under air and water media.

### Validation and economic viability of the designed facemask

The developed multilayered facemask was validated as per the ASTM methods discussed in the "Materials and methods" section. Table 3 represents the results obtained from SITRA, which shows that the developed multilayered mask exhibits high breathability, splash resistance, and excellent BFE and PFE. Additionally, the designed multilayered facemask has been evaluated for the total expenses required for manufacturing an individual mask. In this context, a detailed cost estimation analysis has been carried out to

**Table 1** Durability analysis of indigenous facemask

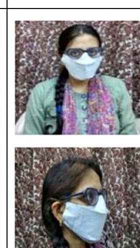
| Parameters | 0 washes | 5 washes | 10 washes | 20 washes | 30 washes |
|---|---|---|---|---|---|
| Breathability | ✓ | ✓ | ✓ | ✓ | ✓ |
| Appearance | ✓ | ✓ | ✓ | ✓ | ✓ |
| Fit | ✓ | ✓ | ✓ | ✓ | ✓ |
| Candle Flame Extinguishing Test | Passed | Passed | Passed | Passed | Passed |
| Shape & Size | ✓ | ✓ | ✓ | ✓ | ✓ |
| Water Repulsion (Hold up time in Seconds) | 252 | 247 | 235 | 227 | 157 |
| Images for Comparison |  |  |  |  |  |

**Table 2** Durability analysis of commercial facemask

| Parameters | 0 washes | 5 washes | 10 washes | 20 washes | 30 washes |
|---|---|---|---|---|---|
| Breathability | ✓ | × | × | × | × |
| Appearance | ✓ | × | × | × | × |
| Fit | ✓ | × | × | × | × |
| Candle Flame Extinguishing | Failed | Failed | Failed | Failed | Failed |
| Shape & Size | ✓ | × (Shrinking observed) | × | × | × |
| Water Repulsion (Hold-up time in sec) | 3 sec | 2 | 1 | 0 | 0 |
| Images for Comparison |  |  |  |  |  |

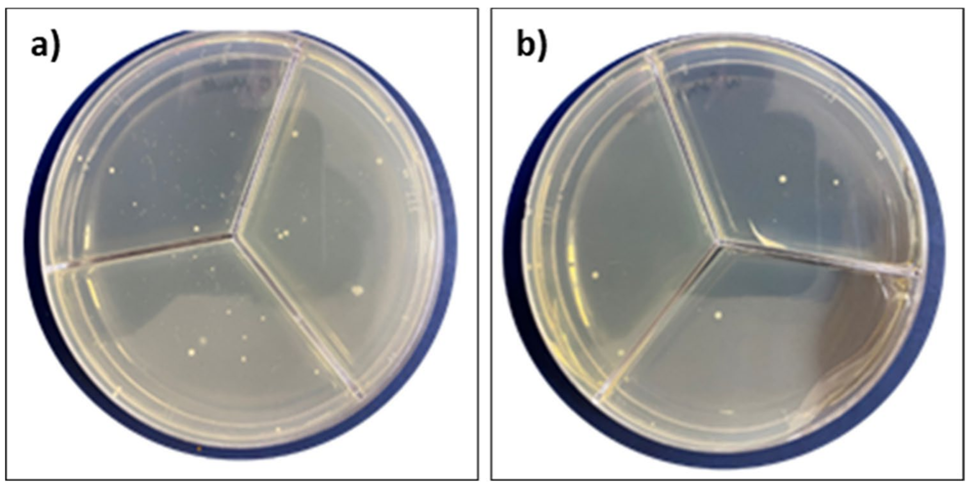



**Fig. 6** Nutrient agar plates with bacterial colonies: **a**) uncovered plate and **b**) plate covered with the mask

**Table 3** SITRA analysis data for the designed facemask

| Parameter | Value |
|---|---|
| Flammability (> 5 s) | Passed with 38.8 s |
| Breathability (Pa/cm$^2$) | 211.01 |
| Splash resistance | Pass |
| Bacterial filtration efficiency (%) | 95.7 |
| Particulate filtration efficiency (%) | 83.57 |

assess the commercial feasibility of the mask. The materials used for the design of multilayered masks are readily available in the market, and the costs for a unit piece are provided in Table 4.

The cost incurred for the PET layer includes the charges for extraction and cleaning of PET spacer from waste RO membranes. From the above economic analysis, it can be concluded that the developed multilayer facemask is affordable for the standard population.

**Table 4** Cost estimation for the designed multilayered SaanS facemask

| Name of component | Price (in Rs) |
|---|---|
| Recycled PET layer | 6.18 |
| PP layer | 3.78 |
| Textile fabric (2 layers) | 1.98 |
| Elastic bands | 0.8 |
| Deionized water | 0.004 |
| Amenities (including stitching charges) | 3.5 |
| Beads | 0.62 |
| Total cost per mask (Rs.) | 16.884 (0.21 USD) |

### Comparison between the indigenous SaanS facemask and commercial N95 facemask

The efficacy of the mask was well-compared with the commercially available N95 mask in terms of reusability, hydrophobicity, air permeability, water permeability, tortuosity, % BFE, and affordability. All the tests have been conducted in an indoor facility wherein the experimental parameters were maintained the same for both the indigenously developed masks and the commercial masks. Table 5 presents the technical assessment of the indigenous and commercial facemask. It can be depicted that the commercial N95 mask has very few reusable properties whereas the indigenously developed mask proved to be reusable. Since the developed mask can retain its property up to 30 washes, there would be comparatively less demand of new masks and waste generated by it. On the other hand, using PET and PP layers in the indigenous masks gives added hydrophobic characteristics with higher repulsion to respiratory droplets than other facemasks with only a PP layer. Unlike commercial facemasks, the incorporation of a waste-derived PET layer aids in reusing the waste membrane, diminishing the pollution caused to the environment. Moreover, the air permeability of the designed mask is almost 2.2 times greater than the commercial mask ensuring high breathability and comfort, making it, especially during long hours of usage, for frontline COVID warriors. Also, these masks are currently highly suitable for students and employees who are working for a prolonged duration of time. Moreover, the combination of PET and PP lamina and cotton textile provided high tortuosity and low water permeability to ensure high rejection of particulate matter. The superior feature of the developed mask is that the required manufacturing expenses are around Rs 17.

Even at a 100% profit margin, the mask cost would be much lower than the commercially available N95 masks. Overall, the indigenously developed facemask is technically superior, washable, economical, and follows green technology.

Moreover, the indigenous facemask's general properties and filtration efficiency data are compared with the various commercially available branded masks, as presented in Table S1 in the supplementary data.

### Free distribution of the developed masks in schools, hospitals, villages, and orphanages

Furthermore, with the help of Cipla Foundation, Mumbai, several NGOs could access IICT's facemask technology to attain financial support for procurement of capital machinery and materials required for manufacturing 1-lakh masks for free distribution as part of societal welfare. In that time, the authors conducted online training sessions for NGOs and start-up companies. The online training pictures are shown in supplementary data in Figure S5(a). These programs helped manufacture developed multilayered masks, which were distributed in and around 30 schools, 2 hospitals, and a few orphanages across 57 villages that covered 26 districts in the Indian States of Telangana, Andhra Pradesh, Karnataka, and Maharashtra. The photographs of mask distribution to the ordinary people and children in villages and orphanages are shown in supplementary data in Figure S5(b) and Fig. 7, respectively. Also, the online sessions aided in attaining sustainability goals by providing elderly support, social inclusion, and partnership in action.

### Commercialization and business analysis

Despite the amazing effectiveness of vaccination, the pandemic affected populations of all races, religions, and communities across the globe. Due in part to the difficulty of conducting controlled clinical trials, there is little information available about the effectiveness of using a facemask. Wearing a facemask does not provide the same level of personal protection as immunization, but one may anticipate synergistic benefits from combining both measures as the masks primarily provide source control of viral spread where vaccinations are less effective (Brüssow and Zuber 2022). Thus, there was a need for bulk manufacturing of affordable and reusable masks. A few available reusable masks in the

**Table 5** Technical comparison of the indigenous and N95 masks

| Properties | Indigenous mask | Commercial N95 mask |
|---|---|---|
| Reusability | High (washable texture) | Low |
| Hydrophobicity | High (PET and PP layers) | High (PP layer) |
| Air permeability* | High (843,496 $L/m^2 \cdot h$) | Low (384,250 $L/m^2 \cdot h$) |
| Water permeability* | Low (1185 $L/m^2 \cdot h$) | Moderate (3156 $L/m^2 \cdot h$) |
| Tortuosity | High (more no. of layers) | Low |
| % bacterial filtration efficiency | 95.7 | 95–98% |
| Non-return valve | No valve, for better safety | Valve is provided |
| Affordability | Rs. 17/- (0.21 USD) | Rs. 100/- to 300/- (1.26 to 3.77 USD) |

*Tested at 0.5 gauge pressure and $28 \pm 2$ °C temperature

**Fig. 7** Usage of the facemasks by children, adults, and frontline workers in schools, hospitals, and orphanages

market are too pricey for the common people to purchase, especially in developing countries. Therefore, as a key to public protection, the affordable indigenous mask was commercialized and made available in the market with the brand name "SaanS." Unlike other masks, the developed facemask follows a green technology as it can be recycled with zero waste discharge, as mentioned in the leaflet shown in Fig. 8. The mask is sterilized before disposal and then segregated into four layers. The cotton layers are incinerated while the PET and PP layers are recycled back as reusable plastic for mixing with coal tar in road construction In the view of the common people and frontline sanitization workers, the cost-effective multilayered mask was introduced in the market. To meet the demand, CSIR-IICT moved its novel mask technology concept to market place and thereby transferred this technology to a few NGOs, namely, Ambuja Cement Foundation at Himachal Pradesh; Mann Deshi Foundation based at Pune; HelpAge India in Bihar and Pondicherry


**Fig. 8** Mask leaflet with instructions for use and safe disposal

**Table 6** Summary of mask production, revenue earned, and employment generated (business data)

| Name of the partner | Location | Total no. of masks produced | Total no. of masks sold | Total revenue generated (million rupees) | Total nos. of women/elderly impacted through livelihood |
|---|---|---|---|---|---|
| Maandeshi Foundation | Pune and Satara | 86,450 | 58,665 | 1.85 | 100 |
| Halo Medical Foundation | Andur | 86,504 | 79,061 | 2.27 | 15 |
| | Lohara | 73,644 | 100,750 | 2.01 | 15 |
| Ambuja Cement Foundation | Nalagarh (H.P.) | 73,000 | 70,608 | 2.11 | 10 |
| | Surat | 18,807 | 17,707 | 0.53 | 8 |
| HelpAge India | Supaul | 224,753 | 166,422 | 6.65 | 250 |
| | Cuddalore | 103,885 | 97,380 | 3.87 | 102 |
| Total | 8 locations | 649,259 | 560,593 | 19.32 | 500 |

states; Halo Medical Foundation in Pune, Divya Disha, Hyderabad; and one start-up named Khar Energy Optimizers, Hyderabad. The technology was transferred to the NGOs exclusively to manufacture and supply multilayered protective facemasks to frontline warriors at an affordable price. Thus, through this scheme, financial literacy and preventive healthcare measures attained the motive towards sustainability. The commercialization of these masks through the foresaid NGOs created rural employment and empowerment that provided elderly support and livelihood generation. On the whole, in August 2020–2022, the total number of masks produced are 649,259 and the total number of masks sold stood at 560,593. This generated revenue of 19.32 million rupees (242,906.97 USD) and created employment for 500 women and senior citizens, whose livelihoods had earlier been impacted by the pandemic. The NGOs' mask production and sales details are mentioned in Table 6.

## Conclusion

The sudden onset of COVID-19 pandemic has led to the execution of various safety measures, in which wearing the facemask became the prime line of defense. Taking this aspect into consideration, a low-cost multilayered reusable facemask was designed. The development of the indigenous mask also involves the "waste to wealth" concept by incorporating the warp-knit permeate spacer (PET) derived from waste spiral wound membrane modules as one of the crucial layers, which gives shape and strength to the mask. Along with the PET layer, the PP layer provides hydrophobicity besides exhibiting electrostatic repulsion towards pathogens. The cotton textile layers are placed in the first and fourth positions to ensure comfort, reject the larger particles entering the mask, and improve appearance. Moreover, the mechanical strength and shape retaining capability enabled the facemask in a unique 3D shape that extended from the nose bridge to the chin, leaving an air gap between the mouth and the inner layer of the facemask. The 3D folding feature of the mask is seamless and gives an intelligent fit to the user's face that enables easy facial movements, and hindrance-free speaking, besides preventing spectacle fogging. Apart from these features, the designed mask has exhibited excellent filtration properties, which include 95.7% bacterial filtration efficiency and 83.5% particulate filtration efficiency for the smallest particle size of 0.3 μm. From the overall observations and other comparison studies, it can be concluded that the developed mask is highly breathable, reusable with excellent physical and mechanical properties, affordable, and comfortable to the users. Usually, the prolonged usage of the facemask in the extremely humid climatic conditions may lead to sweating and chances for itching sensation. While the developed mask provides a gap between mouth and mask, which aids in easy breathability and avoids the above-stated problems besides being comfortable. Moreover, the cotton layer provided towards the mouth helps control the sweat. Thus, the mask's utility can be extended to prevent respiratory infections such as tuberculosis, dust allergy, and environmental pollution. Additionally, the development of the facemask diminished the waste PET generated by RO membranes and followed green technology. The reusability of the mask is the key feature, which decreases the prerequisite of the mask and the pollution caused by it. Given these merits, the facemasks have been commercialized, and their sales figure has proved their viability. Furthermore, the production and distribution of masks through NGOs have provided many socio-economic benefits like financial literacy, elderly support, livelihood generation, and partnership. Thus, the designed mask was highly capable of restricting the foreign particles entering the respiratory tract and has effectively controlled COVID-19. Thus, such development helps the nation to have better control over the spread of viruses leading to the pandemic.

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**Data availability** The data used in the current study will be available from the corresponding author upon request via email.

## Declarations

**Consent for publication** The authors declare that they have consent to publish.

**Competing interests** The authors declare no competing interests.

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