Community Masks – from an Emergency Solution to an Innovation Booster for the Textile Industry

Batt, Till; Herwig, Gordon; Annaheim, Simon; Clement, Pietro; Furer, Lea; Hirsch, Cordula; Varanges, Vincent; Caglar, Baris; Michaud, Véronique; More Authors

DOI
10.2533/chimia.2022.249

Publication date
2022

Document Version
Final published version

Published in
Chimia

Citation (APA)
Batt, T., Herwig, G., Annaheim, S., Clement, P., Furer, L., Hirsch, C., Varanges, V., Caglar, B., Michaud, V., & More Authors (2022). Community Masks – from an Emergency Solution to an Innovation Booster for the Textile Industry. *Chimia*, *76*(3), 249-254. https://doi.org/10.2533/chimia.2022.249

doi:10.2533/chimia.2022.249 Chimia 76 (2022) 249–254

Community Masks – from an Emergency Solution to an Innovation Booster for the Textile Industry

Till Batt[a], Gordon Herwig[a], Simon Annaheim[a], Pietro Clement[b], Lea Furer[b], Cordula Hirsch[b], Vincent Varanges[c], Baris Caglar[cd], Véronique Michaud[c], Jing Wang[e], Gilles Richner[f], Peter Wick[b]*, and René M. Rossi[a]*

Abstract: The COVID-19 pandemic resulted in shortages of personal protective equipment and medical devices in the initial phase. Agile small and medium-sized enterprises from regional textile industries reacted quickly. They delivered alternative products such as textile-based community masks in collaboration with industrial partners and research institutes from various sectors. The current mask materials and designs were further improved by integrating textiles with antiviral and antimicrobial properties and enhanced protection and comfort by novel textile/membrane combinations, key factors to increase the acceptance and compliance of mask wearing. The safety and sustainability of masks, as well as taking into account particular needs of vulnerable persons in our society, are new fields for textile-based innovations. These innovations developed for the next generation of facemasks have a high adaptability to other product segments, which make textiles an attractive material for hygienic applications and beyond.

Keywords: Air permeability · Antiviral facemask · COVID-19 pandemic · Filtration efficiency · Wearing comfort

Till Batt studied textile technology at Reutlingen University. During his research at Deutsche Institute für Textil- und Faserforschung (DITF) and his PhD at Stuttgart University, he investigated a new generation of the meltblow process for the production of ultrafine fibers. From 2013 he worked for MANN+HUMMEL GmbH as a Senior R&D Expert mainly in the development of air filters. Till joined the Empa Laboratories as a researcher in 2020, focussing on the implementation and coordination of the Innosuisse project ReMask.

Gordon Herwig obtained his MSc from the University of Technology Chemnitz (2014), focusing on chemical and physical phenomena in polymers. He continued working there until 2015. Inspired by an internship at The Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Melbourne, Australia, he then conducted his PhD research at the University of Warwick, UK. After receiving his PhD (2019) with support by The Leverhulme Trust, he joined the Empa Laboratories in St. Gallen, where he managed the research within ETH foundation and Innosuisse projects on encapsulation strategies and nanofiber membrane-textile composits.

Peter Wick heads since 2010 the research laboratory for Particles-Biology Interactions at the Federal Laboratories for Materials Science and Technologies Empa in St. Gallen. He received his PhD degree in 2002 at the University of Fribourg, Switzerland. He has published more than 130 papers, is member of the advisory board of the Swiss Action Plan on Nanomaterials, member of the EDQM working group for NBCs, Member of the national COVID-19 Science Task Force, Editorial Board Member of Nanotoxicology, associated editor of the Journal NanoImpact, and coordinator of the Swiss National Contactpointnano.ch.

René Rossi studied applied physics at the University of Neuchâtel and obtained his PhD at ETH Zurich. Since 2003, he has led the Laboratory for Biomimetic Membranes and Textiles at Empa, which develops novel smart fibers, textiles and membranes for body monitoring, drug delivery and tissue engineering applications. A special focus is to develop physical and numerical skin/body models for the analysis of the interactions between materials and the skin. René Rossi is adjunct professor at the Department of HealthSciences and Technology at ETH Zurich and invited professor at the University of Haute-Alsace in Mulhouse/France.

**Correspondence:* Dr. P. Wick[a], E-mail: peter.wick@empa.ch ; Dr. R. M. Rossi[a], E-mail: rene.rossi@empa.ch
[a]Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Biomimetic Membranes and Textiles, Lerchenfeldstrasse 5, CH-9014, St. Gallen, Switzerland; [b]Empa, Swiss Federal Laboratories for Materials Science and Technology, Particles-Biology Interactions Laboratory, Lerchenfeldstrasse 5, CH-9014, St. Gallen, Switzerland; [c]Laboratory for Processing of Advanced Composites (LPAC), Institute of Materials (IMX), Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015, Lausanne, Switzerland; [d]Aerospace Manufacturing Technologies, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629HS, Delft, Netherlands; [e]Institute of Environmental Engineering, ETH Zurich, CH-8093, Zurich, Switzerland; Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Advanced Analytical Technologies, CH-8600, Dübendorf, Switzerland; [f]Federal Office for Civil Protection FOCP, Spiez Laboratory, CH-3700, Spiez, Switzerland

1. Introduction

1.1 *The Outbreak of the COVID-19 Pandemic and its Influence on Research and Development*

What started as an unexplained lung disease in Wuhan in December 2019 has developed into probably the most severe pandemic since the 'Spanish flu': COVID-19. The cause is the new beta-coronavirus SARS-CoV-2, which is mostly transmitted *via* droplets and aerosols.[1–4] The severity and spread of the pandemic far exceeded initial assessments of the situation. Western countries have not faced crises like the COVID-19 pandemic over the last two generations, and initial thinking on how to manage the crisis underestimated the complexity of this pandemic as well as its impact on the economy and society.

Early in the crisis, a few stakeholders, mainly researchers and clinicians, worked under high pressure to understand the disease, explored the mode of infection, established non-pharmaceutical measures for prevention and decontamination, developed diagnostic tests as well as treatment strategies and vaccines. The World Health Organization recognized on March 11th 2020 the COVID-19 outbreak as a pandemic.[5] Thereafter, governments as well as several NGOs launched massive programs and investments providing means for the fight against COVID-19. In a very short time, an unprecedented global commitment to fight against this disease has arisen. As a logical consequence in this challenging time, a boost of innovations in health-related technologies was registered. Several diagnosis test systems were established,[6] allowing a fast and cost-effective identification of COVID-19 infected persons. Multi-institutional exchange of patient data was facilitated to define the most efficient treatment, *e.g.* Remdesivir.[7] Novel software applications were developed to monitor contacts and facilitating contact tracing[8] and resource planning.[9] Large pharmaceutical industries teamed up with innovative SMEs and regulators to develop and approve novel vaccines using state-of-the-art RNA-based technologies like vaccines from BioNTech-Pfizer[10] or Moderna[11] in record time while still keeping efficacy and safety.

In this perspective, we discuss and explore how the global COVID-19 crisis has and will boost innovation in the textile industry in Western countries. Europe and North America were the most important medical textiles markets already before the pandemic[12] and the crisis led to the very fast development of new products, promoted by existing technologies in medical filtration or technical textiles.

Several scientific studies showed that non-pharmaceutical measures such as facemasks are effective means in the fight against a pandemic.[13–15] As a result, these gained increased acceptance among general population and politicians in Western countries. The effect of wearing facemasks to prevent person-to-person virus transmission depends on the filtration efficiency of the material as well as the type and design of the mask, and the compliance to correct mask handling and use.[16] Particle filtering facemasks (FFP) are personal protective equipment (PPE) routinely used by both medical and non-medical workers, already before the COVID-19 pandemic. FFP masks offer a high level of protection of the wearer (*e.g.* FFP2: ≥94% filtration efficiency for sub-micron particles) but have limited wear comfort and may cause discomfort during prolonged use due to their relatively low air permeability and tight fit.[17,18] Medical or surgical masks aim at preventing spread of germs and pathogens exhaled by medical personnel and thus protecting patients from infection. In the context of the present pandemic, medical masks have been in great demand as they limit the further spread of the virus by infected persons and thus, protect community by the source control effect.[19]

The first wave of the pandemic has drastically pointed out that the outplacing of the production of health-related consumer goods created a general dependency on a few producers. This led to the shortage of several basic health care products including protective facemasks in several industrialized countries. Thus, the global demand for facemasks could not be satisfied, leading to export bans in most of the producing countries.[20] Unfortunately, lockdowns provoked a production stop and the very large increase of the mask demand led to a temporary collapse of supply. This shortage of masks triggered different emergency-based product development efforts in the prioritization of the use of alternative materials such as textiles, their potential reuse, as well as decentralized, local productions. The European textile industry, which is already highly specialized in complex technical or medical products with high added value due to the pressure of global competition, was an important driver in today's innovative textile solutions. Textile engineers, in close collaboration with material scientists and physicians, very rapidly proposed novel solutions for facemasks to overcome the global shortage.

Textiles by their nature have a fibrous structure, creating a two- or three-dimensional porous structure, which can, if smartly designed, sufficiently retain droplets down to micro-size range. Their main benefits compared to paper and disposable nonwoven structures are the enhanced lifetime due to their mechanical stability and washability. Isotropic fibrous nonwoven materials are state-of-the-art for facemask filtering layers. Mainly due to their low cost and customizable porosity, these materials are the first choice for single-use products. However, they offer restricted mechanical and dimensional stability, leading to a short lifetime. Advanced textile technologies allow the adjustment of the porous structures to obtain defined pore sizes for customized filtration properties and air permeability and at the same time offer multiple reusing cycles due to their durable fiber structures. Together with clinicians, researchers and regulators, recommendations[21,22] and normative documents[23–26] were published, defining the minimal requirements and specifications of a textile-based facemask – the so-called 'Community Mask'. During the pandemic, the increasing evidence of the role of aerosols as a transmission route for SARS-CoV-2 forced the textile industry to improve the filtration efficiency of community masks to higher values, reaching similar levels as for FFP masks. However, when worn by the general population, high wear comfort and easy-use were critical to achieve proper fitting on users' faces. One benefit of textile products is that they can be much more sophisticated due to the cut and sew process. Therefore, it is possible to produce masks with customized size and shape or even adjustable products, without investments in rigid ultrasonic welding machines.

High air permeability of a mask material can help to improve the acceptance of the wearer. Masks with insufficient air permeability can cause wearers to fiddle with the masks, unintentionally reducing their protective effectiveness. Thus, an optimization of the balance between the protective filtration efficiency and the air permeability of the mask had to be found.

1.2 *High Filtration Efficiency and Good Air Permeability of Facemasks: A Mission Impossible?*

The key challenge in the development of mask filter materials is to achieve a high filtration efficiency against small droplet and aerosol carriers of viruses while adding no extra resistance to breathing. Generally, specific types of facemasks, such as those certified under FFP (EN 149), medical masks (EN 14683), textile community masks and non-certified face coverings, differ in respect to air permeability and filtration efficiency (Fig. 1). The protection of tight-fitted and higher efficient FFP masks is highly recognized, yet they often do not meet the need to breathe easily, especially during physical work.[27] The newly developed community masks partly show an improved performance compared to medical facemasks and offer many possibilities for future developments explored in the next section, using new material combinations.

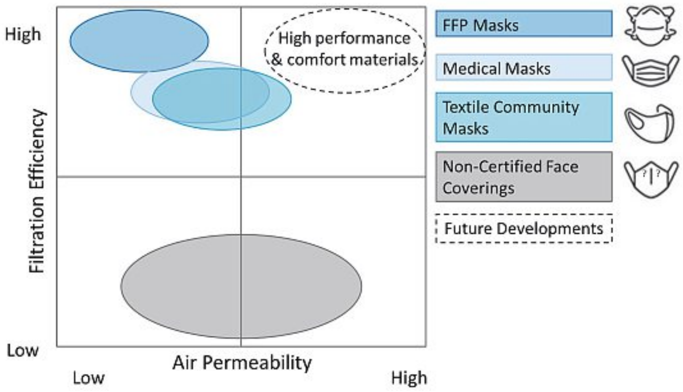

Fig. 1. Correlation between air permeability and filtration efficiency of different mask classes. Quality factors and performance of possible mask material categories (solid line area) compared to the ideal need (dashed line area).

First studies showed a certain correlation between high filtration efficiency and low air permeability.[28] However, the relationship between these two parameters for different kinds of mask depends on the complex interplay between many parameters, known from air filtration principles.[29,30] A selection of textile and membrane technologies could overcome a dependency for these two parameters, leading to innovative high performance and comfort materials.

The filtration efficiency of masks for small aerosols correlates with the fineness of fibers and pores, as well as the surface of the filter structure. A material design, considering a highly accessible fiber surface area is needed to capture most particles inside the porous structure and simultaneously allow easy breathing. Micron and submicron fiber structures utilize beneficial slip flow conditions[31] and electrostatic charges,[32,33] which can further increase the filtration efficiency, especially for sub-micron aerosols.

The filtration efficiency depends on particles and droplet sizes. The size for which a filter has its lowest efficiency is defined as the most penetrating particle size (MPPS). While larger particles and droplets, typically in the range of several micrometers up to hundreds of micrometers, are likely to carry a higher viral load than smaller ones, they are fairly straightforward to separate from an airflow with most porous structures. However, aerosol emitted during normal breathing and speaking are much smaller, with a modal value around 1 micrometer.[34–36] Consequently, filtration efficiency of micron and sub-micron aerosols must be considered, since those are large enough to carry respiratory pathogens such as SARS-CoV-2 (single virus diameter Ø 0.06–0.14 µm).[37]

The increasing evidence of airborne transmission mode and the urgent request of larger parts of the population for highly breathable materials for prolonged wearing times in indoor environments set the innovation vector towards novel mask concepts. State-of-the-art technologies from functional and intelligent textiles, as well as the development of new textile finishes such as antiviral treatments, have allowed to further tackle the conflicting protection and comfort requirements.

There is an ongoing debate with respect to sustainability and reusability of PPE.[38–40] Moreover, NGOs have pointed out[41,42] the emerging problem of mask waste and the need to consider concepts of circular economy in the newly established mask productions. This has spurred an increasing interest in masks with very long durability and easy maintenance. The requests from these different interest groups rapidly shifted the requirements for community masks from a low-cost, disposable product towards multifunctional systems, leading to large research programs in several industrialized countries and an innovation boost for the corresponding textile and textile machinery industry. What was first thought to be a short-term emergency production shift to address the mask shortage at the beginning of the pandemic gradually turned into an innovation game-changer for the textile industry.

2. Innovation in Progress

2.1 *The Innovation Pillars of the Next Generation of Facemasks*

Based on an improved understanding of SARS-CoV-2 infection routes over the past year, research and industry are now working diligently to develop improved products that go beyond the function of conventional medical and respiratory masks. Throughout the pandemic, facemasks 'evolved' continuously, with innovations triggered by additional requirements (Fig. 2). Mask fit and performance, as well as increased consumer awareness of health and sustainability issues are driving innovation in this area.

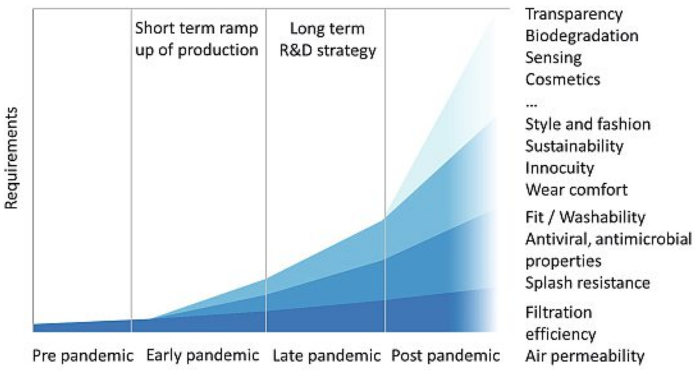

Fig. 2. Schematic depiction of the cumulative requirements for facemasks over the timeline of the pandemic. Shift from a simple mask item to a sophisticated product with an exponential boost potential for new developments.

It was recognized early in the pandemic that textile-based facemasks are valid alternatives to the existing mask standards providing fundamental source control. On the material level, innovation is mainly found on novel highly porous membranes, and electrostatic and/or antiviral functionalization.[43]

The development of electrospun membrane prototypes has shown that a new category of filtration media can be obtained with these nanofiber materials, leading to mask properties with superior combination of filtration efficiency and air permeability compared to common materials. The weight of the nanofiber layer in these materials is orders of magnitude lower compared to standard microfiber meltblown layers, which are commonly used in medical and FFP masks. This potentially lowers the ecological footprint of these materials. Due to their small fiber size and therefore extremely high surface area, nanofibers are known to offer a very high mechanical filtration efficiency even for sub-micron aerosols. To increase further the separation of virus-laden aerosols from the air, some masks are constructed with electrostatically charged ('electret') fibers.[33] These fibers have a persistent charge (triboelectric potential) leading to higher attraction of fine particles to the mask. However, charged filters are described to change their efficiency over lifetime, depending on ambient conditions.[44] Therefore, advanced filter standards are required to test and report discharged minimum fractional efficiency.[28,45] Innovative nanofiber membranes show a potential to combine both an outstanding mechanical filtration performance combined with a tailored electret charge during the spinning process. If nanofiber membranes are combined with textile substrates, they are well protected between the yarn structures of the outer fabrics. This enables the sandwich structure to withstand several cleaning cycles without significant loss in functionality.

With further functionalization of the fibers, antiviral and antimicrobial properties can be achieved (trap and kill).[46] For example, the integration of ZnO or Ag nanoparticles during fiber synthesis is used to make antimicrobial textiles[47] and investigations are ongoing to determine if these composites have antiviral capabilities.[48–51] Furthermore, cationic positive surface charges on fibers are described to attract negatively charged virus particles.[52] When deposited to the fiber surface the virus gets trapped and the positive surface charge will break the lipid structure of the virus which leads to an immediate inactivation. Consequently, such antiviral and -microbial properties lead to a reduction of the number of required changing or washing cycles and thus extend the lifetime of the masks without inducing a secondary smear infection risk.

Whereas medical masks are designed for single-use, textile masks provide the potential to be washed in household washing machines. Washing and reuse of medical masks is no requirement in the current standards nor recommended by their manufacturers. First results on medical masks further indicate a loss of electrostatic charge, which is locked inside their fiber structure and dissipates during household machine-washing, especially if a detergent is used. Washing can therefore lead to a drop in efficiency, mainly for sub-micron aerosol particle fractions and a loss of cationic positive surface charges with antiviral properties after washing. Therefore, developments of reusable masks must focus on improved mechanical filtration efficiency or more (washing) resistant electret charges. For reusable masks a washing procedure offering the maximum cleaning potential, without lowering the main functional parameters has to be defined. Furthermore, it is necessary to investigate the aging process of masks including the impact on physical properties that come with their prolonged use and washing. Other cleaning methods have been recently investigated to improve the availability of masks during times of shortage,[39] however, they are usually not available in common households.

Besides the filtration efficiency and prolonged use, the fit of the mask plays a crucial role. Leakage between face and mask is of major relevance in respect to the protection efficacy.[53–55] As the airflow follows the path of least resistance, aerosols that are following the air can be exhaled and inhaled through the gaps between the mask and the face. This is particularly relevant in mask materials characterized by low air permeability. A mask that optimally protects against aerosols must completely cover the mouth and nose and must fit tightly to the face, utilizing a sealing material or adaptive shape and size. Conversely, a close fit of a filtering facemask to the face can significantly reduce the level of comfort, due to lower air and moisture permeability.

Consequently, if the aerosols are following the air flow through the fine pores instead of by-passing the mask at the interface, masks with high air permeability not only improve the breathing resistance, but also the protection against aerosols.

With the obligation to wear masks in public transport or in public crowded areas, littering of disposable masks has caused increasing concerns on a local and global level when considering plastic pollution of the oceans. This has motivated the development of textile fabric masks meeting the requirements of existing mask standards but with novel concepts and material combinations to extend the lifetime of the products and thus their sustainability.[56] The development of a washable mask with antiviral properties meeting the European standard for medical facemasks (EN 14683) is a first example for such an innovation considering sustainability aspects.[52] and it can be expected that future products will include degradable, recyclable and circular materials.

Scientific studies showing the usefulness and providing information about the safe handling of facemasks have rapidly increased the acceptance by the wearers. However, at the same time, regular wearing over longer time periods has raised concerns about general health aspects. Headlines about skin irritation, headache or potential inhalation of released fiber (microfibrils) and other debris created new sources of anxieties in wide sections of the population. The release of fragments or fibers during the wearing and maintenance (washing) of facemasks is intensively debated and highly depends on the material used as well as the type of tests applied to simulate the mechanical load and ageing parameters during real use.[57,58] In a review assessing the effects of various facemasks on the physiological and perceptual responses to physical activity, the data suggest that for healthy individuals, there may be an increase in dyspnea, yet with only small and often difficult to detect effects even during intense physical exercise.[59] There is evidence that wearing a medical or FFP mask has no serious effect on oxygen supply or CO_2 intoxication.[60] However, patients with chronic obstructive pulmonary disease, breathing frequency, blood oxygen saturation and exhaled CO_2 levels may be affected by wearing FFP masks.[61] Such health and safety concerns can be confronted by the development of additional quality standards, which provide a certain assurance to the consumers that non-complying products are banned from the market. This is the reason why standardization efforts have been rapidly intensified for textile-based community masks in different industrialized countries and quality standards have been published swiftly.

2.2 *How a Simple Face Covering Stimulates the Whole Textile Industry*

The mandatory use of facemasks in most countries has obviously led to a massive increase of their market size and price, which promoted local production plants. The Swiss industry was able to react to the tight supply situation within a few weeks and to offer alternative products to the market, while the global supply chains mostly failed. However, after a few months, the production capacity has risen in low-wage countries which has forced the industry in Western countries to offer products with a higher added value, based on newest material research achievements. The growing diversity of requirements for facemasks has created new market opportunities for small and medium-sized enterprises. Economic, social and environmental value can be added by additional functions of next generation textile masks compared to single use products. It is realistic to meet and exceed the break-even points on all three of these aspects.

The development of quick solutions to tackle urgent market needs in the early stage of the pandemic could be stepwise transferred into long-term R&D strategies, opening the perspective for adjacent market segments and post pandemic product innovations (Fig. 3). We forecast that for many application areas, low-tech disposable products will be replaced by reusable, efficient and fashionable products with high comfort, with a closer focus on type and origin of raw materials, as well as on the overall weight and lifespan of the product.

The whole textile production chain from the single fiber to the final product, including additive coating and finishing processes is rather complex, but offers a plethora of new solutions for facemasks, with improved safety and comfort for the users leading to a broader acceptance.

Such innovations have already been recently presented in the form of transparent medical facemasks offering new quality of life for instance for deaf people relying on lip-reading.[62] The next step of innovation for transparent masks was made using the electrospinning technology by reducing the diameter of the fibers to 20–30 nanometers.[63] This technology has the potential to lead to further innovations for increased comfort (*e.g.* release of fragrances or skin-care substances). Developments are currently being made to integrate sensors or color indicators into the mask

Fig. 3. Schematic depiction of the innovation pillars for the next generation of facemasks with high technological adaptability to other product segments.

to detect either the presence of pathogens or the end-of-life of the products. Rapid prototyping and advanced manufacturing technologies like 3D printing have been used to customize the facemasks and thus increase the fit, with benefits for both the filtration efficiency and the wear comfort.

As for other consumer markets, the developments will be further driven by the needs of the society and new dynamics on the market are already visible. If the perceived benefit for the users and the ease-of-use of the products can be further improved, it can be expected that facemasks will become an article of daily use after the pandemic in Western countries, especially in wintertime for the protection from respiratory diseases like influenza.[64] These innovations will cross-stimulate other market segments and we can expect exponential growth in developments in the field of hygiene and medical technology, driven by advanced and smart textile technologies and novel surface treatments. This innovation boost, combined with possible political decisions about the systemic relevance of the textile industry for health care supply in future crises, can become a major game-changer for the whole textile industry in Western countries.

3. Conclusions

While the COVID-19 pandemic proved to be a tremendous challenge for industry to keep up with new demands, this provided a significant boost to innovation in various sectors including the textile industry. With shortages in personal protective equipment, such as medical facemasks in particular, novel fabric masks were established as an initial easy-to-produce countermeasure. To define and harmonize the quality of fabric masks, such as filtration efficiency, fit and air permeability, new guidelines for a 'Community Mask' were established, which had to be met with innovative concepts for the realisation of these requirements. Moreover, industry and research successfully joined forces to establish and optimise more effective, accessible and sustainable filter membranes, functional compositions and coatings for improved sterility and reusability, as well as strategies to improve wear comfort and fit. Not only has this enabled industry to remain in business and provide new products during the most restrictive time of the pandemic, it also resulted in innovative and competitive new products beyond personal protection equipment anticipating potential future needs.

Acknowledgements

The input from various Swiss companies from textile production and processing sectors is gratefully acknowledged. We further thank Innosuisse for funding the ReMask research project (contract number 46668.1 IP-EN). This work is dedicated to our esteemed colleague and researcher Giuseppino Fortunato.

Received: November 22, 2021

[1] J. A. Lednicky, M. Lauzard, Z. H. Fan, A. Jutla, T. B. Tilly, M. Gangwar, M. Usmani, S. N. Shankar, K. Mohamed, A. Eiguren-Fernandez, C. J. Stephenson, M. M. Alam, M. A. Elbadry, J. C. Loeb, K. Subramaniam, T. B. Waltzek, K. Cherabuddi, J. G. Morris, C. Y. Wu, *Int. J. Infect. Dis*. **2020**, *100*, 476, https://doi.org/10.1016/j.ijid.2020.09.025.

[2] Y. Li, H. Qian, J. Hang, X. Chen, P. Cheng, H. Ling, S. Wang, P. Liang, J. Li, S. Xiao, J. Wei, L. Liu, B. J. Cowling, M. Kang, *Build. Environ*. **2021**, *196*, 107788, https://doi.org/10.1016/j.buildenv.2021.107788.

[3] A. Hartmann, J. Lange, H. Rotheudt, M. Kriegel, TU Berlin **2020**, https://doi.org/10.142797/depositonce-10331.

[4] Y. Shen, C. Li, H. Dong, Z. Wang, L. Martinez, Z. Sun, A. Handel, Z. Chen, E. Chen, M. H. Ebell, F. Wang, B. Yi, H. Wang, X. Wang, A. Wang, B. Chen, Y. Qi, L. Liang, Y. Li, F. Ling, J. Chen, G. Xu, *JAMA Intern. Med.* **2020**, *180*, 1665, https://doi.org/10.1001/jamainternmed.2020.5225.

[5] D. Cucinotta, M. Vanelli, *Acta Biomed*. **2020**, *91*, 157, https://doi.org/10.23750/abm.v91i1.9397.

[6] M. R. Benzigar, R. Bhattacharjee, M. Baharfar, G. Liu, *Anal. Bioanal. Chem*. **2021**, *413*, 2311, https://doi.org/10.1007/s00216-020-03046-0.

[7] J. H. Beigel, K. M. Tomashek, L. E. Dodd, A. K. Mehta, B. S. Zingman, A. C. Kalil, E. Hohmann, H. Y. Chu, A. Luetkemeyer, S. Kline, D. Lopez de Castilla, R. W. Finberg, K. Dierberg, V. Tapson, L. Hsieh, T. F. Patterson, R. Paredes, D. A. Sweeney, W. R. Short, G. Touloumi, D. C. Lye, N. Ohmagari, M. Oh, G. M. Ruiz-Palacios, T. Benfield, G. Fätkenheuer, M. G. Kortepeter, R. L. Atmar, C. B. Creech, J. Lundgren, A. G. Babiker, S. Pett, J. D. Neaton, T. H. Burgess, T. Bonnett, M. Green, M. Makowski, A. Osinusi, S. Nayak, H. C. Lane, *N. Engl. J. Med*. **2020**, *383*, 1813, https://doi.org/10.1056/nejmoa2007764.

[8] G. Cencetti, G. Santin, A. Longa, E. Pigani, A. Barrat, C. Cattuto, S. Lehmann, M. Salathé, B. Lepri, *Nat. Commun.* **2021**, *12*, 1, https://doi.org/10.1038/s41467-021-21809-w.

[9] J. D. Courcol, C. F. Invernizzi, Z. C. Landry, M. Minisini, D. A. Baumgartner, S. Bonhoeffer, B. Chabriw, E. E. Clerc, M. Daniels, P. Getta, M. Girod, K. Kazala, H. Markram, A. Pasqualini, C. Martínez-Pérez, F. J. Peaudecerf, M. S. Peaudecerf, U. Pfreundt, B. R. K. Roller, J. Słomka, M. Vasse, J. D. Wheeler, C. M. J. A. Metzger, R. Stocker, F. Schürmann, *Front. Public Heal*. **2021**, *9*, 71, https://doi.org/10.3389/fpubh.2021.607677.

[10] F. P. Polack, S. J. Thomas, N. Kitchin, J. Absalon, A. Gurtman, S. Lockhart, J. L. Perez, G. Pérez Marc, E. D. Moreira, C. Zerbini, R. Bailey, K. A. Swanson, S. Roychoudhury, K. Koury, P. Li, W. V. Kalina, D. Cooper, R. W. Frenck, L. L. Hammitt, Ö. Türeci, H. Nell, A. Schaefer, S. Ünal, D. B. Tresnan, S. Mather, P. R. Dormitzer, U. Üahin, K. U. Jansen, W. C. Gruber, *N. Engl. J. Med.* **2020**, *383*, 2603, https://doi.org/10.1056/nejmoa2034577.

[11] World Health Organization (WHO), 'Interim recommendations for use of the Moderna mRNA-1273 vaccine against COVID-19', **2021**, https://apps.who.int/iris/handle/10665/338862.

[12] Market Data Forecast, 'Medical Textiles Market Size, Share, Growth and Forecast 2021-2026', **2021**.

[13] M. Liang, L. Gao, C. Cheng, Q. Zhou, J. P. Uy, K. Heiner, C. Sun, *Travel Med. Infect. Dis*. **2020**, *36*, 101751, https://doi.org/10.1016/j.tmaid.2020.101751.

[14] D. K. Chu, E. A. Akl, S. Duda, K. Solo, S. Yaacoub, H. J. Schünemann, A. El-harakeh, A. Bognanni, T. Lotfi, M. Loeb, A. Hajizadeh, A. Bak, A. Izcovich, C. A. Cuello-Garcia, C. Chen, D. J. Harris, E. Borowiack, F. Chamseddine, F. Schünemann, G. P. Morgano, G. E. U. Muti Schünemann, G. Chen, H. Zhao, I. Neumann, J. Chan, J. Khabsa, L. Hneiny, L. Harrison, M. Smith, N. Rizk, P. Giorgi Rossi, P. AbiHanna, R. El-khoury, R. Stalteri, T. Baldeh, T. Piggott, Y. Zhang, Z. Saad, A. Khamis, M. Reinap, *Lancet* **2020**, *395*, 1973, https://doi.org/10.1016/S0140-6736(20)31142-9.

[15] Y. Cheng, N. Ma, C. Witt, S. Rapp, P. S. Wild, M. O. Andreae, U. Pöschl, H. Su, *Science* **2021**, *372*, 1339, https://doi.org/10.1126/science.abg6296.

[16] E. O'Kelly, A. Arora, S. Pirog, J. Ward, P. J. Clarkson, *PLoS One* **2021**, *16*, e0245688, https://doi.org/10.1371/journal.pone.0245688.

[17] A. Regli, A. Sommerfield, B. S. von Ungern-Sternberg, *Anaesthesia* **2021**, *76*, 91, https://doi.org/10.1111/anae.15261.

[18] A. Davies, K. A. Thompson, K. Giri, G. Kafatos, J. Walker, A. Bennett, *Disaster Med. Public Health Prep.* **2013**, *7*, 413, https://doi.org/10.1017/dmp.2013.43.

[19] H. Ueki, Y. Furusawa, K. Iwatsuki-Horimoto, M. Imai, H. Kabata, H. Nishimura, Y. Kawaoka, *mSphere* **2020**, 5, https://doi.org/10.1128/msphere.00637-20.

[20] Organisation for Economic Co-operation and Development, 'The face mask global value chain in the COVID-19 outbreak: Evidence and policy lessons',

2020, https://www.oecd.org/coronavirus/policy-responses/the-face-mask-global-value-chain-in-the-covid-19-outbreak-evidence-and-policy-lessons-a4df866d.

[21] National COVID-19 Science Task Force (NCS-TF), 'Recommendations on minimal specifications for community masks and their use – Swiss National COVID-19 Science Task Force', **2020**, https://sciencetaskforce.ch/en/policy-brief/recommendations-on-minimal-specifications-for-community-masks-and-their-use.

[22] Comfort, quality and safety with NF Barrier Masks - AFNOR Group, https://www.afnor.org/en/news/comfort-quality-safety-with-nf-barrier-masks/, accessed May 31, 2021.

[23] European Committee for Standardization (CEN), 'CWA 17553 - Community face coverings - Guide to minimum requirements, methods of testing and use', **2020**, https://www.cencenelec.eu/media/CEN-CENELEC/CWAs/RI/cwa17553_2020.pdf..

[24] Schweizerische Normen-Vereinigung (SNV), 'SNR 30000:2021 - Community masks - Basic requirements and test procedures', **2021**, https://connect.snv.ch/en/snr-30000-2021.

[25] British Standards Institution (BSI), 'BSI Flex 5555 v1.0:2021-01 - Community face coverings — Specification', **2021**, https://shop.bsigroup.com/products/community-face-coverings-specification?pid=000000000030430772.

[26] American Society for Testing and Materials (ASTM International), 'ASTM F3502-21 - Standard Specification for Barrier Face Coverings', **2021**, https://compass.astm.org/document/?contentCode=ASTM%7CF3502-21%7Cen-US.

[27] S. Fikenzer, T. Uhe, D. Lavall, U. Rudolph, R. Falz, M. Busse, P. Hepp, U. Laufs, *Clin. Res. Cardiol*. **2020**, *109*, 1522, https://doi.org/10.1007/s00392-020-01704-y.

[28] L. Maurer, D. Peris, J. Kerl, F. Guenther, D. Koehler, D. Dellweg, *J. Aerosol Med. Pulm. Drug Deliv*. **2021**, *34*, 11, https://doi.org/10.1089/jamp.2020.1635.

[29] D. Shou, J. Fan, L. Ye, H. Zhang, X. Qian, Z. Zhang, *J. Nanomater.* **2015**, *2015*, 1, https://doi.org/10.1155/2015/168392.

[30] Z. Pan, X. Zhang, Z. Sun, F. Jiang, L. Lin, Y. Liang, M. Tang, J. Wang, *J. Memb. Sci.* **2021**, *620*, 118925, https://doi.org/10.1016/j.memsci.2020.118925.

[31] S. A. Hosseini, H. V. Tafreshi, *Chem. Eng. Sci*. **2010**, *65*, 2249, https://doi.org/10.1016/j.ces.2009.12.002.

[32] B. Pourdeyhimi, S. Schick, R. Groten, H. Vahedi Tafreshi, *J. Sci. Med.* **2021**, *2*, https://doi.org/10.37714/josam.v2i4.60.

[33] A. Kilic, S. Russell, E. Shim, B. Pourdeyhimi, in 'Fibrous Filter Media', Elsevier, **2017**, pp. 95, https://doi.org/10.1016/B978-0-08-100573-6.00025-3.

[34] L. Morawska, G. R. Johnson, Z. D. Ristovski, M. Hargreaves, K. Mengersen, S. Corbett, C. Y. H. Chao, Y. Li, D. Katoshevski, *J. Aerosol Sci*. **2009**, *40*, 256, https://doi.org/10.1016/j.jaerosci.2008.11.002.

[35] G. R. Johnson, L. Morawska, Z. D. Ristovski, M. Hargreaves, K. Mengersen, C. Y. H. Chao, M. P. Wan, Y. Li, X. Xie, D. Katoshevski, S. Corbett, *J. Aerosol Sci.* **2011**, *42*, 839, https://doi.org/10.1016/j.jaerosci.2011.07.009.

[36] K. Haslbeck, K. Schwarz, J. M. Hohlfeld, J. R. Seume, W. Koch, *J. Aerosol Sci.* **2010**, *41*, 429, https://doi.org/10.1016/j.jaerosci.2010.02.010.

[37] N. Zhu, D. Zhang, W. Wang, X. Li, B. Yang, J. Song, X. Zhao, B. Huang, W. Shi, R. Lu, P. Niu, F. Zhan, X. Ma, D. Wang, W. Xu, G. Wu, G. F. Gao, W. Tan, *N. Engl. J. Med*. **2020**, *382*, 727, https://doi.org/10.1056/nejmoa2001017.

[38] Decontamination and Reuse of Filtering Facepiece Respirators, https://www.cdc.gov/coronavirus/2019-ncov/hcp/ppe-strategy/decontamination-reuse-respirators.html, accessed May 31, **2021**.

[39] W. He, Y. Guo, H. Gao, J. Liu, Y. Yue, J. Wang, *ACS Nano* **2020**, *14*, 13161, https://doi.org/10.1021/acsnano.0c04782

[40] CEN-CENELEC PPE Sector Forum, 'Workshop - Sustainability in PPE: addressing the challenges through standardization', **2021**.

[41] Health experts call for reusable PPE to protect people and planet, https://www.greenpeace.org/international/press-release/44356/health-experts-reusable-ppe-protect-people-planet/, accessed May 31, **2021**.

[42] M. Yudell, D. Roberts, R. DeSalle, S. Tishkoff, *Science* **2020**, *369*, 1314, https://doi.org/10.1126/SCIENCE.ABD9925.

[43] HeiQ Viroblock, https://heiq.com/products/functional-textile-technologies/heiq-viroblock/?no_popup=1, accessed May 31, 2021.

[44] W. He, Y. B. Zhao, F. Jiang, Y. Guo, H. Gao, J. Liu, J. Wang, *Sep. Purif. Technol*. **2020**, *233*, 116003, https://doi.org/10.1016/j.seppur.2019.116003.

[45] International Organization for Standardization (ISO), 'ISO 16890-4 - Air filters for general ventilation - Part 4: Conditioning method to determine the minimum fractional test efficiency', **2016**, https://www.iso.org/standard/57867.html.

[46] B. B. Hsu, S. Y. Wong, P. T. Hammond, J. Chen, A. M. Klibanov, *Proc. Natl. Acad. Sci. U. S. A*. **2011**, *108*, 61, https://doi.org/10.1073/pnas.1017012108.

[47] Y. Li, P. Leung, L. Yao, Q. W. Song, E. Newton, *J. Hosp. Infect*. **2006**, *62*, 58, https://doi.org/10.1016/j.jhin.2005.04.015.

[48] S. Galdiero, A. Falanga, M. Vitiello, M. Cantisani, V. Marra, M. Galdiero, *Molecules* **2011**, *16*, 8894, https://doi.org/10.3390/molecules16108894.

[49] H. Ghaffari, A. Tavakoli, A. Moradi, A. Tabarraei, F. Bokharaei-Salim, M. Zahmatkeshan, M. Farahmand, D. Javanmard, S. J. Kiani, M. Esghaei, V. Pirhajati-Mahabadi, A. Ataei-Pirkooh, S. H. Monavari, *J. Biomed. Sci.* **2019**, *26*, 70, https://doi.org/10.1186/s12929-019-0563-4.

[50] S. M. Imani, L. Ladouceur, T. Marshall, R. Maclachlan, L. Soleymani, T. F. Didar, *ACS Nano* **2020**, *14*, 12341, https://doi.org/10.1021/acsnano.0c05937.

[51] V. Palmieri, F. De Maio, M. De Spirito, M. Papi, *Nano Today* **2021**, *37*, 101077, https://doi.org/10.1016/j.nantod.2021.101077.

[52] Livinguard Technology scientifically proven to destroy >99.9% of SARS-CoV-2, https://livinguard.com/products/, accessed May 31, 2021.

[53] R. Perić, M. Perić, *J. Appl. Fluid Mech.* **2020**, *13*, 1911, https://doi.org/10.47176/jafm.13.06.31812.

[54] Deutsches Institut für Normung (DIN), 'DIN EN 149 - Atemschutzgeräte - Filtrierende Halbmasken zum Schutz gegen Partikeln - Anforderungen, Prüfung, Kennzeichnung', **2009**, https://doi.org/10.31030/1527555.

[55] A. V. Mueller, M. J. Eden, J. M. Oakes, C. Bellini, L. A. Fernandez, *Matter* **2020**, *3*, 950, https://doi.org/10.1016/j.matt.2020.07.006.

[56] M. Schmutz, R. Hischier, T. Batt, P. Wick, B. Nowack, P. Wäger, C. Som, *Sustain.* **2020**, *12*, 1, https://doi.org/10.3390/su122410245.

[57] E. Hernandez, B. Nowack, D. M. Mitrano, *Environ. Sci. Technol.* **2017**, *51*, 7036, https://doi.org/10.1021/acs.est.7b01750.

[58] Y. Cai, T. Yang, D. M. Mitrano, M. Heuberger, R. Hufenus, B. Nowack, *Environ. Sci. Technol*. **2020**, *54*, 4847, https://doi.org/10.1021/acs.est.9b07395.

[59] S. R. Hopkins, P. B. Dominelli, C. K. Davis, J. A. Guenette, A. M. Luks, Y. Molgat-Seon, R. C. Sá, A. W. Sheel, E. R. Swenson, M. K. Stickland, *Ann. Am. Thorac. Soc*. **2021**, *18*, 399, https://doi.org/10.1513/AnnalsATS.202008-990CME.

[60] T. Rebmann, R. Carrico, J. Wang, *Am. J. Infect. Control* **2013**, *41*, 1218, https://doi.org/10.1016/j.ajic.2013.02.017.

[61] S. Y. Kyung, Y. Kim, H. Hwang, J. W. Park, S. H. Jeong, *Respir. Care* **2020**, *65*, 658, https://doi.org/10.4187/respcare.06713.

[62] Surgical Face Mask Transparent Type II MaXsmile, https://www.flawaconsumer.com/en/masks-products/transparente-gesichtsmaske-typ-ii-maxsmile/, accessed May 31, 2021.

[63] GRS-021/17 - HelloMask – transparent Mask for Medical Care, https://www.grstiftung.ch/de/search~grs-021-17~.html?search=hello mask, accessed May 31, 2021.

[64] European Centre for Disease Prevention and Control (ECDC), 'Influenza virus characterisation - Summary Europe, April 2021', Stockholm, **2021**, https://www.ecdc.europa.eu/en/publications-data/influenza-virus-characterisation-summary-europe-april-2021.

License and Terms