INNOVATION IN MANUFACTURING PERSONAL PROTECTIVE EQUIPMENT

TOWARD SUSTAINABILITY AND CIRCULARITY

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from the British people

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Contents

Acronyms

AAMI	Association for the Advancement of Medical Instrumentation
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
FDA	Food and Drug Administration
IS	Indian Standards
ISO	International Organization for Standardization
NABL	National Accreditation Board for Testing and Calibration Laboratories
NIOSH	National Institute for Occupational Safety and Health
OECD	Organisation for Economic Co-operation and Development
OSR M1	Open Standard Respirator Model 1
PAPS	Powered air protection system
PET	Polyethylene terephthalate
PLA	Polylactic acid
PPE	Personal protective equipment
UK	United Kingdom
UNEP	United Nations Environment Programme
UNICEF	United Nations Children’s Fund
US	United States
WHO	World Health Organization

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Foreword

Personal protective equipment, or PPE, has been a critical health-care supply for managing the COVID-19 crisis, but it has also proven to exacerbate the global waste challenge. As the use of disposable PPE such as masks and gloves grows, so too does plastic waste, ending up in landfills, rivers, and oceans.

Most PPE is inexpensive and single use by design and can contain a range of different plastics, from polypropylene and polyethylene in face masks and gowns, to nitrile, vinyl, and latex in gloves. Rising awareness of the negative impact that disposable PPE has on the environment is leading companies to embrace innovative approaches to reduce this waste. A growing number of manufacturers are trying to make reusable PPE that is appropriate for consumers, such as face masks, but also for medical professionals, such as gowns and coveralls. The approaches include using more environmentally friendly and reusable materials to produce PPE, ensuring materials are properly recycled, and minimizing waste and pollution.

To support the production of PPE in developing countries, IFC recently developed a global advisory program[1] on PPE manufacturing, in partnership with the UK government. This report forms part of this program and builds on an IFC webinar from November 24, 2020,[2] which first highlighted how the global waste challenge has been exacerbated by the growing use of PPE in response to the COVID-19 pandemic.

This report showcases how select manufacturers are exploring circular economy opportunities. With a growing world population and the potential of future pandemics, the demand for PPE will likely continue to rise. While many of the innovations profiled in this report are in the early stages of adoption and have not yet been scaled, we hope that by shining a spotlight on what is possible, manufacturers will find inspiration to develop new products and services. However, manufacturers cannot sustainably meet global PPE demand alone. By using their purchasing power to choose goods and services with reduced environmental impact, governments and health sector players can make an important contribution to shifting away from single use, plastic-based PPE.

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[1] https://www.ifc.org/wps/wcm/connect/industry_ext_content/ifc_external_corporate_site/manufacturing/priorities/ppe+production.

[2] https://www.ifc.org/wps/wcm/connect/industry_ext_content/ifc_external_corporate_site/manufacturing/events/webinar_how+to+start+ppe+production.

Executive summary

Adopting circular economy approaches is becoming an increasingly important part of policy makers' agendas in the fight against climate change. These approaches include reducing material inputs, using more environmentally friendly and reusable materials when producing goods, ensuring materials are properly recycled, and minimizing waste and pollution. They have become even more important in the wake of the COVID-19 pandemic, with personal protective equipment (PPE) becoming an inseparable part of daily life. Manufacturers across the globe had to increase PPE production, which inevitably created a surge in plastic waste because polypropylene is still the main material used to manufacture PPE for health-care workers.

A recent research study estimates that, since the outbreak, the amount of plastic waste generated globally is 1.6 million tons per day. Furthermore, an estimated 3.4 billion single-use face masks and shields are being discarded every day.[3] This unpredicted increase in plastic waste is happening at a time when countries are reluctant to recycle products because of the lack of complementary decontamination steps and coordination in waste management.

Some manufacturers took this opportunity of increased PPE production to adopt circular economy approaches that can be replicated by others. Decentralized production and material sourcing became more important as supply chains were severely disrupted by the pandemic. This has accelerated the ongoing changes in conventional production methods, with businesses embracing a cradle-to-cradle manufacturing model—that is, rethinking the design of their products from the starting point at the sourcing stage through to the end of the product's life.

This is not without its challenges. For example, when replacing plastics with alternative materials, manufacturers need to ensure that these materials meet quality standards set by standards institutions and enforced by governments.

However, PPE manufacturers cannot shoulder the responsibility of the global plastic waste challenge alone. This publication calls on a broad range of stakeholders along the PPE value chain to work together to shift toward a more sustainable and circular PPE ecosystem (Table 1.0).

This report takes stock of approaches that PPE manufacturers are taking to make their production more sustainable and achieve a true circular economy, while responding to COVID-19 PPE shortages. It does not provide a life-cycle assessment of each PPE product, which is needed to evaluate the environmental effects associated with each product against the benefits created. The approaches highlighted in this report can be grouped into four main categories[4]:

- **Circular inputs**: The use of renewable, bio-based, or completely recyclable materials as input.
- **Resource recovery**: Ensuring that useful resources and energy are recovered from disposed products by collecting and reprocessing products at the end of their life.
- **Product use extension**: Prolonging the lifespan of PPE products by choosing a design that allows the product to be repaired or by choosing durable materials as inputs for the main PPE parts.
- **Product as service**: The product-as-service model allows the consumer to use a product that is retained by the producer to increase resource productivity (for example, leasing PPE). This model allows PPE manufacturers to move from selling products to selling services.

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3 Benson, N.U., et al. 2021. "COVID Pollution: Impact of COVID-19 Pandemic on Global Plastic Waste Footprint." *Heliyon 7* (2).

4 These four circularity approaches are based on Accenture's circular economy business model grouping. Accenture Strategy. 2014. *Circular Advantage: Innovative Business Models and Technologies to Create Value in a World without Limits to Growth.*

TABLE 1.0: COLLECTIVE ACTION NEEDED TO SHIFT TOWARD MORE SUSTAINABLE AND CIRCULAR PPE

STAKEHOLDER	ACTIONS
Governments	• Develop policies and incentives (for example, extended producer responsibility, polluter pays principle, and formalized waste collection value chain) to avoid and reduce waste from disposable PPE made from plastics and promote more circular PPE • Encourage innovation and research and development in manufacturing medical-grade PPE with new materials • Establish minimum requirements and standards • Expand testing capacity for PPE to test and verify adherence to standards • Adopt new government procurement practices that help increase the demand for "greener" PPE products • Raise awareness among citizens on implications of increased use of disposable PPE for non-medical use
Municipalities	• Invest in sustainable PPE waste management solutions, including transportation, sorting, recycling, repurposing, and disposal in line with national policies • Increase awareness among the general public on proper disposal of PPE
Health sector players	• Adopt procurement practices that support the demand for greener PPE products, where these products are available • Collect feedback from medical professionals (end users) and work with PPE manufacturers to identify PPE products that are affordable, effective, safe, and environmentally friendly and that meet quality standards
PPE manufacturers	• Invest in research and development to unlock business opportunities for reusing, recycling, and extending the lifetime of PPE • Innovate in material science and waste management technologies to avoid or reduce waste generation
Financial institutions	• Extend finance to support companies that are transitioning to a sustainable PPE ecosystem
Standards institutions	• Improve existing standards for PPE to meet technical requirements (for example, safety, effectiveness, and breathability) while being more environmentally friendly • Develop new national standards for recycling and reusing PPE • Develop new standards or guidelines for collecting, handling, and sorting used PPE to ensure safety
Technology providers	• Use existing applications in other sectors or innovate in tracking end-of-life solutions for PPE (for example, automatic sorting, decontamination, shredding, and track and trace software)
General public	• Properly use and dispose of PPE (for example, disposable surgical masks vs. reusable fabric masks) • Properly dispose of single-use masks

Chapter 1 provides an overview of the (plastic) waste problem that has worsened during the pandemic, the impact of excessive waste generation on existing waste management infrastructure, and the continued efforts by international organizations and national governments to address these problems.

Chapter 2 introduces four circular economy approaches that can be adopted in PPE manufacturing to reduce dependence on depletable resources, reduce plastic use, and maximize the useful life of PPE. It also provides guidance on managing PPE waste to reap more value at the end of products' service life.

Chapter 3 profiles 11 companies that have adopted one or more of the four circular economy approaches. This publication does not endorse one innovation over the other. Moreover, IFC has not undertaken any independent assessment of the firms and the products presented in the case studies.

The main COVID-19 PPE products covered in this report include: (i) masks and respirators, such as surgical masks, medical masks,[5] and non-medical (civil use) masks[6]; (ii) coveralls, gowns, and aprons; (iii) gloves; and (iv) face and eye protectors, such as face shields and goggles (see Annex B for more detailed information on products and the certification standards).

While it is common to assume that "greener" products are more expensive than disposable products, initial analysis suggests that cost depends on the availability and cost of raw materials, the specific product, production methods, scale of production, number of intermediaries, and other factors—in addition to the environmental cost, including waste management. The report does not analyze the affordability of the featured PPE due to lack of relevant data.

[5] A medical mask is a standardized mask for use in health-care settings or by health-care professionals. It covers the mouth, nose, and chin, ensuring a barrier that limits the transmission of an infective agent between the health-care worker and the patient.

[6] A non-medical mask is a commercially available mask used by the public. It is generally not standardized and is not intended for use in health-care settings or by health-care professionals.

1 The waste challenge caused by COVID-19 PPE

The COVID-19 pandemic significantly increased the demand for PPE, leading to the creation of massive amounts of waste from discarded PPE from health-care facilities and the general public. Global PPE production increased by at least 300 percent at the peak of the pandemic, largely driven by a soaring demand for masks.[7] By December 2020, medical mask manufacturing alone spiked by as much as 1,200 percent.[8] Even after the pandemic subsides the PPE market will continue to grow, with global demand projected to continue increasing by about 6–9 percent between 2022 and 2025.[9]

This growing use of and demand for medical-grade and non-medical (or civil use) PPE has exacerbated the already significant global waste management challenge as the majority of PPE products are designed for single use. Prior to the pandemic, biomedical waste, including PPE, was generally incinerated. The PPE used by an additional estimated 5 billion people is adding to the waste volume that is already being generated and disposed of through incineration. Without a better end-of-life strategy, the volume of plastic waste is estimated to double in the next 20 years, and the amount finding its way into the world's oceans will rise fourfold.

Once the pandemic began, health-care workers and regular citizens were estimated to be using billions of face masks every month, along with gloves, gowns, and other PPE, with no system in place for collecting and disposing of them properly.[10] According to a World Wildlife Fund report, even if only 1 percent of masks are disposed of incorrectly, around 10 million masks per month will still end up in our rivers and oceans.[11] An online consumer survey conducted with 1,033 people across six countries (Australia, India, Singapore, Sri Lanka, the United Kingdom, and the United States) highlighted that PPE products are being improperly disposed of, with 35 percent of respondents discarding PPE as mixed waste and about 19 percent of respondents throwing them away in the streets.[12]

With governments worldwide mandating extensive use of PPE in public places, the World Health Organization (WHO) issued guidelines in February 2020 on the "rational use of PPE" by health-care workers. It updated these guidelines in December 2020 based on lessons learned since the start of the pandemic (Box 1.1).

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7 Based on a report by the UK Foreign, Commonwealth & Development Office, "COVID-19—PPE Demand and Supply Perspectives," which provides an in-depth analysis of the current and future PPE market globally. It was completed in December 2020 and updated in March 2021.

8 Based on slide 27 of a report by the UK Foreign, Commonwealth & Development Office, "COVID-19—PPE Demand and Supply Perspectives," which provides an in-depth analysis of the current and future PPE market globally. It was completed in December 2020 and updated in March 2021.

9 Based on a report by the UK Foreign, Commonwealth & Development Office, "COVID-19—PPE Demand and Supply Perspectives," which provides an in-depth analysis of the current and future PPE market globally. It was completed in December 2020 and updated in March 2021.

10 Prata, Joana, et al. 2020. "COVID-19 Pandemic Repercussions on the Use and Management of Plastics." *Environmental Science and Technology* 54: 7,760–5. https://pubs.acs.org/doi/pdf/10.1021/acs.est.0c02178.

11 Ciarlariello, Giulia. 2020. "Nello smaltimento di mascherine e guanti serve responsabilità." *WWF* (blog), April 29, 2020. https://www.wwf.it/pandanews/ambiente/nello-smaltimento-di-mascherine-e-guanti-serve-responsabilita/.

12 Selvaranjan, Kajanan, Satheeskumar Navaratnam, Pathmanathan Rajeev, and Nishanthan Ravintherakumaran. 2021. "Environmental Challenges Induced by Extensive Use of Face Masks during COVID-19: A Review and Potential Solutions." *Environmental Challenges* 3. https://www.sciencedirect.com/science/article/pii/S2667010021000184?via%3Dihub.

BOX 1.1: WHO GUIDELINES ON RATIONAL USE OF PPE BY HEALTH-CARE WORKERS

WHO's interim guidance on rational use of PPE in the context of COVID-19 (Annex 1)[13] recommends that when screening individuals for COVID-19, health-care workers use no-touch thermometers and thermal imaging cameras, and limit observation and questioning. During the screening, health-care workers should wear a medical mask in areas of known or suspected community, cluster, or sporadic SARS-CoV-2 transmission. Furthermore, they should be separated from the patients by a glass or plexiglass barrier and maintain a physical distance of at least 1 meter. When physical distance is not feasible or a screen is unavailable, eye protection (goggles or face shield) should be worn.

The rational use of PPE is different when health-care workers provide direct care to patients with COVID-19. In the absence of aerosol-generating procedures, health-care workers should at least wear a medical mask, a gown, gloves, and eye protection (goggles or face shield). When aerosol-generating procedures are performed, health-care workers should wear a respirator instead of a medical mask, a fluid-resistant gown or a gown and apron, gloves, and eye protection.

For all three scenarios, WHO recommends that health-care workers perform hand hygiene according to its five moments for hand hygiene.[14]

WHO's interim guidance on mask use in the context of COVID-19[15] advises all staff working in clinical areas to continuously use medical masks, and all staff in areas where aerosol-generating procedures are performed to use respirators (with no exhalation ports).

WHO's quality assurance and testing standards for PPE items used in the context of COVID-19 are included in its technical specifications of PPE for COVID-19.[16]

[13] https://www.who.int/publications/i/item/rational-use-of-personal-protective-equipment-for-coronavirus-disease-(covid-19)-and-considerations-during-severe-shortages

[14] https://www.who.int/gpsc/5may/Your_5_Moments_For_Hand_Hygiene_Poster.pdf

[15] https://www.who.int/publications/i/item/advice-on-the-use-of-masks-in-the-community-during-home-care-and-in-healthcare-settings-in-the-context-of-the-novel-coronavirus-(2019-ncov)-outbreak

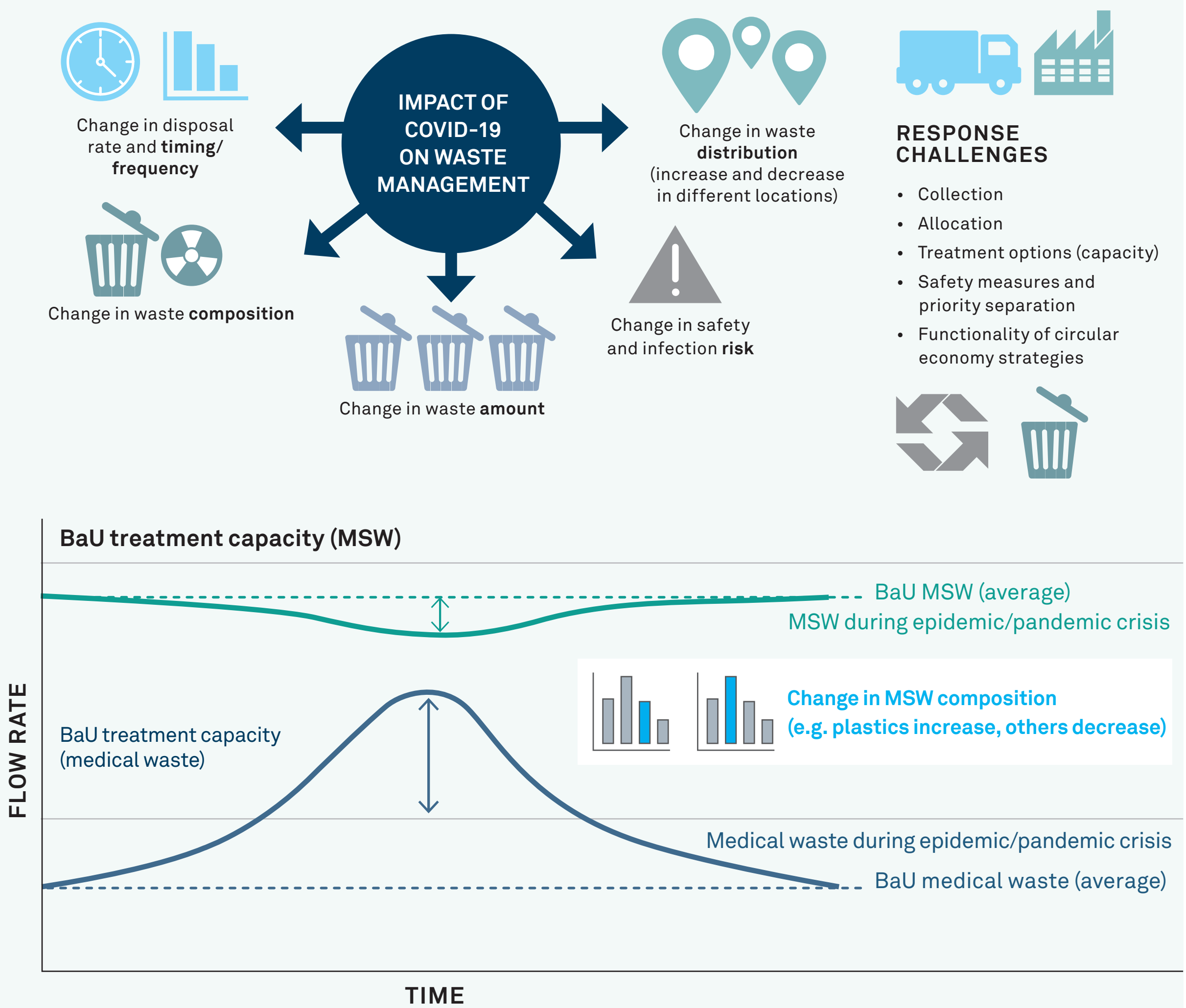
[16] https://www.who.int/publications/i/item/WHO-2019-nCoV-PPE_specifications-2020.1

1.1 The impact of COVID-19 on waste management

Globally, the infrastructure for waste management is generally designed for steady-state operations, based on population size and average waste output and composition, with only moderate variations.

The dramatic changes in waste generation and composition caused by COVID-19 (Figure 1.1) have largely overwhelmed the existing infrastructure.[17]

FIGURE 1.1: THE IMPACT OF COVID-19 ON WASTE MANAGEMENT



MSW: Municipal solid waste; BaU: Business as usual.
Source: Adapted from Fan, Yee Van, Peng Jiang, Milan Hemzal, and Jiří Jaromír Klemeša. 2021. "An Update on COVID-19 Influence on Waste Management." *Science of the Total Environment* 754.

[17] Parashar, Neha, and Subrata Hait. 2021. "Plastics in the Time of COVID-19 Pandemic: Protector or Polluter?" *Science of the Total Environment* 759. https://www.sciencedirect.com/science/article/pii/S0048969720378050?via%3Dihub.

For instance, in Shanghai in mid-June 2020, the amount of hazardous waste increased by 1,120 percent and recyclables by 71.1 percent compared to the same period in 2019. According to a July 2020 study on China's COVID-19 waste management, the city of Wuhan, where the coronavirus first emerged, generated close to 247 tons of medical waste per day at the peak of the pandemic, nearly six times more than the amount generated before the pandemic. The city had to build a new medical waste plant and establish dozens of mobile waste treatment facilities to handle the surge.[18]

Another waste problem that COVID-19 triggered was an increase in microplastic pollution. Microplastics are defined as particles smaller than 5 millimeters in diameter derived from plastic articles. Most COVID-19 PPE contains polymers (a main ingredient of plastic), which increase environmental pollution and negatively affect human and animal health. Mismanagement and littering of plastic-based PPE does not only potentially pose a risk of virus transmission, but also pollutes land and marine ecosystems.[19] PPE waste discarded from different sources can enter rivers and oceans, leading to plastic pollution in the aquatic ecosystem. Macroplastics in masks and similar PPE products break up into smaller bits (microplastics) as a result of weathering or corrosion, which can negatively affect the food web by accumulating in aquatic species.[20] In addition, face masks (the most common PPE) can be a source of microfibers (the most prevalent type of microplastic) because they are mostly manufactured by nanofiber electrospinning.[21] The marine environment absorbs plastics' building blocks, toxins, and organic contaminants, making aquatic animals vulnerable to deadly poisoning.[22] PPE discarded in the soil can affect animals in similar ways.

This challenge is compounded by the increased use of plastics (such as cutlery and food containers) for hygiene reasons during the pandemic. In fact, the most pressing concern facing the plastics industry is how to dispose of all the waste that has piled up and how to prevent future accumulation. Like PPE, much of that waste is single-use plastic products such as bags and bottles that over decades fragment into microscopic particles that can harm wildlife and seep into the food chain. Plastic packaging alone accounts for almost half of all plastic waste.

Moreover, increased plastic production also adds to greenhouse gas emissions: for every kilogram of fossil fuel-based plastic produced, between 1.9 kg and 3.5 kg of carbon dioxide is released depending on the type of plastic.[23]

Figure 1.2 outlines how plastic-based COVID-19 PPE waste is mismanaged and how it enters the environment.

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18 Singh, Narendra, Yuanyuan Tang, and Oladele A. Ogunseitan. 2020. "Environmentally Sustainable Management of Used Personal Protective Equipment." *Environmental Science & Technology* 54 (14): 8,500–2. https://pubs.acs.org/doi/10.1021/acs.est.0c03022.

19 Sangkham, Sarawut. 2020. "Face Mask and Medical Waste Disposal during the Novel COVID-19 Pandemic in Asia." *Case Studies in Chemical and Environmental Engineering* 2. https://www.sciencedirect.com/science/article/pii/S2666016420300505?via%3Dihub; Mol, Marcos Paulo Gomes, and Sérgio Caldas. 2020. "Can the Human Coronavirus Epidemic Also Spread through Solid Waste?" *Waste Management & Research* 38 (5): 485–6. https://journals.sagepub.com/doi/10.1177/0734242X20918312.

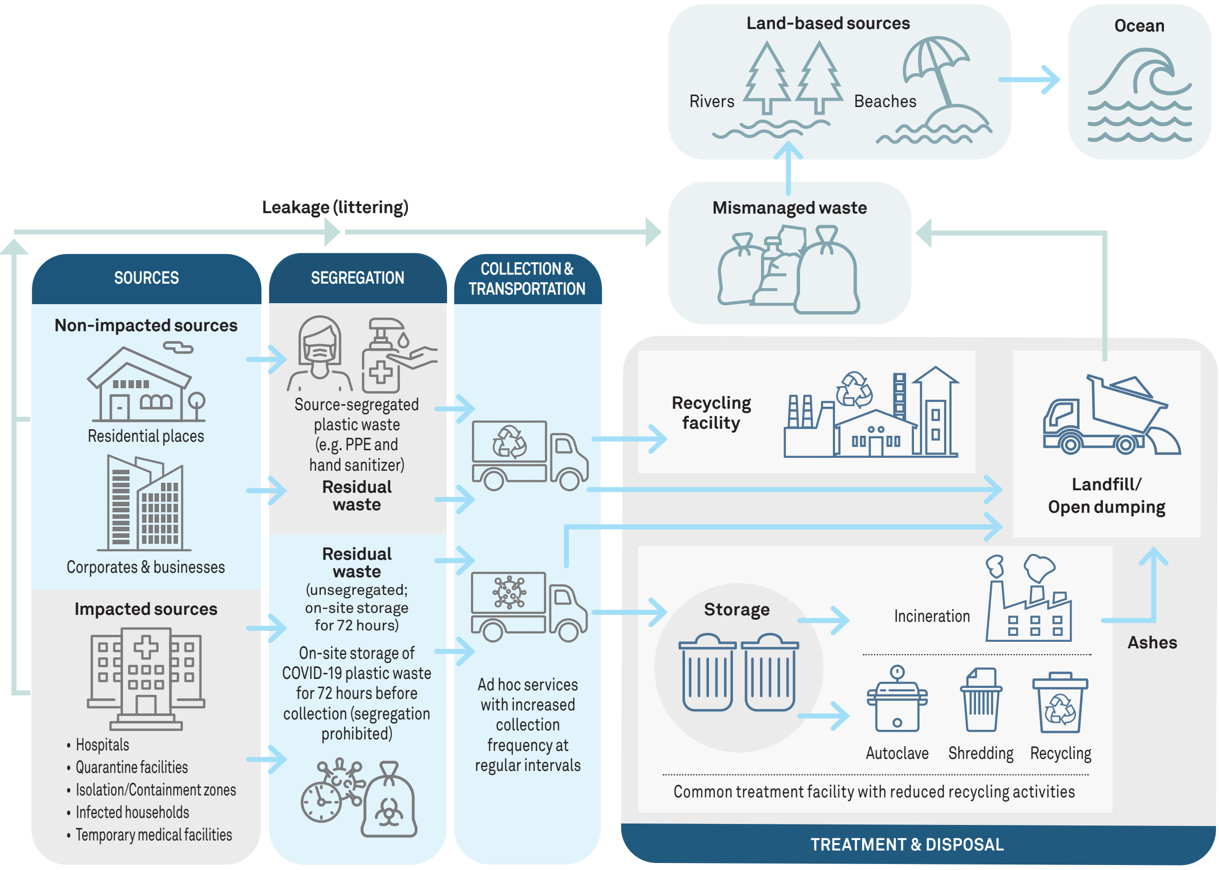
20 Yang, Yuyi, Wenzhi Liu, Zulin Zhang, Hans-Peter Grossart, and Geoffrey Michael Gadd. 2020. "Microplastics Provide New Microbial Niches in Aquatic Environments." *Applied Microbiology and Biotechnology* 104: 6,501–11. https://link.springer.com/article/10.1007/s00253-020-10704-x.

21 De-la-Torre, Gabriel E., and Tadele Assefa Aragaw. 2021. "What We Need to Know about PPE Associated with the COVID-19 Pandemic in the Marine Environment." *Marine Pollution Bulletin* 163. https://www.sciencedirect.com/science/article/pii/S0025326X20309978.

22 Williams-Wynn, Mark D., and Paramespri Naidoo. 2020. "A Review of the Treatment Options for Marine Plastic Waste in South Africa." *Marine Pollution Bulletin* 161 (B). https://www.sciencedirect.com/science/article/abs/pii/S0025326X20309036.

23 Wyns, Tomas, and Matilda Axelson. 2016. "The Final Frontier—Decarbonising Europe's Energy Intensive Industries." Institute for European Studies, Vrije Universiteit Brussel.

FIGURE 1.2: MISMANAGEMENT OF PLASTIC-BASED COVID-19 PPE WASTE



Source: Adapted from Parashar, Neha, and Subrata Hait. 2021. "Plastics in the Time of COVID-19 Pandemic: Protector or Polluter?" *Science of the Total Environment* 759. https://www.sciencedirect.com/science/article/pii/S0048969720378050?via%3Dihub.

1.2 The imperative to tackle COVID-19 PPE waste

A recent working paper entitled "Transforming the Medical PPE Ecosystem," which was published in August 2021 as a collaborative effort of over 50 individuals from global organizations active in the health sector, highlights the need for innovation to incentivize circularity and avoid waste generation to help transform the global PPE ecosystem.[24]

Over the past decade, the concept of a circular economy has evolved and gained importance as industry players and academia have recognized its role in transitioning to a low-carbon future. Working toward a circular economy is now a goal on many governments' policy agendas.[25] For example, the European Commission announced action plans for a circular economy[26] (March 2020) and zero pollution[27] (May 2021) as key deliverables under the "Green Deal"[28] agenda to reach carbon neutrality by 2050.

The transition to a sustainable ecosystem will require a structural change in production-consumption patterns, from how resources

[24] Rethinking PPE. 2021. "Transforming the Medical PPE Ecosystem: Joint Action Can Protect Healthcare Workers with Effective and High-Quality Personal Protective Equipment." https://www.theglobalfund.org/media/11243/publication_ppe-synthesis_paper_en.pdf.

[25] Brandão, Miguel, David Lazarevic, and Göran Finnveden, eds. 2020. *Handbook of the Circular Economy.*

[26] https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0017.02/DOC_1&format=PDF.

[27] https://eur-lex.europa.eu/resource.html?uri=cellar:a1c34a56-b314-11eb-8aca-01aa75ed71a1.0001.02/DOC_1&format=PDF.

[28] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en.

are extracted to how water, energy, and raw materials are consumed, and how goods are manufactured and transported.[29] A circular economy is a competitive alternative to the linear "take-make-dispose" model of consumption. It optimizes resource use at the design phase, creating more value from each unit of resource used by recovering and regenerating products and materials at the end of their service life.[30] Extending the lifespan of resources for as long as possible could cut some nations' emissions by up to 70 percent, increase their workforces by 4 percent, and greatly reduce their waste.[31]

Various international organizations (including WHO, UNICEF, UN-Habitat, UNEP, the European Commission, and the Asian Development Bank) and countries' pollution monitoring bodies and health organizations (such as the Occupational Safety and Health Administration, United States; the Ministry of Ecology and Environment, China; the National System for Environmental Protection, Italy; and the Central Pollution Control Board, India) have issued specific guidelines and advisories to manage COVID-19-related waste, particularly infectious waste contaminated with blood and other body fluids from COVID-19 patients.[32]

In addition to the prevailing biomedical waste management rules in various countries, these guidelines are mainly concerned with hygiene routines; the use of PPE; and the segregation, collection, storage, transportation, and proper treatment and disposal of potentially contaminated infectious waste as an emerging response to the steep increase in waste generated during the pandemic.[33]

Furthermore, to regulate the plastics economy, governments are adopting policies that require phasing out multi-layer plastics (as used in masks) and using high-quality polymers. This is because recycling becomes far more complex when dealing with products made of multi-layer plastics that cannot be separated, and low-quality, multi-colored polymers that are not easily recyclable. As a result, there has been a growing movement from PPE manufacturers to use single-layer plastics that can be recycled or alternative materials that are biodegradable or renewable. However, manufacturers must ensure that these alternative materials fulfill the requirements set by the main standards institutions. This provides an opportunity for new innovations and investments in research and development in the materials industry.

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[29] Lachman, Daniël. 2013. "A Survey and Review of Approaches to Study Transitions." *Energy Policy* 58: 269–76. https://www.sciencedirect.com/science/article/pii/S0301421513001675.

[30] Ellen MacArthur Foundation and McKinsey & Company. 2013. "Towards the Circular Economy: Opportunities for the Consumer Goods Sector." https://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/sustainability/pdfs/towards_the_circular_economy.ashx.

[31] Stahel, Walter. 2016. "Circular Economy." *Nature* 531: 435–8. https://www.nature.com/news/polopoly_fs/1.19594!/menu/main/topColumns/topLeftColumn/pdf/531435a.pdf.

[32] Parashar, Neha, and Subrata Hait. 2021. "Plastics in the Time of COVID-19 Pandemic: Protector or Polluter?" *Science of the Total Environment* 759. https://www.sciencedirect.com/science/article/pii/S0048969720378050?via%3Dihub.

[33] Penteado, Carmenlucia S.G., and Marco A.S. de Castro. 2021. "COVID-19 Effects on Municipal Solid Waste Management: What Can Effectively Be Done in the Brazilian Scenario?" *Resources, Conservation and Recycling* 164. https://www.sciencedirect.com/science/article/abs/pii/S0921344920304699?via%3Dihub; Yang, Yuyi, Wenzhi Liu, Zulin Zhang, Hans-Peter Grossart, and Geoffrey Michael Gadd. 2020. "Microplastics Provide New Microbial Niches in Aquatic Environments." *Applied Microbiology and Biotechnology* 104: 6,501–11. https://link.springer.com/article/10.1007/s00253-020-10704-x.

2 | Engaging in circular economy approaches

Meeting the surge in demand for PPE products during the COVID-19 pandemic became a priority for governments and PPE manufacturers worldwide. By adopting circular economy approaches, manufacturers contribute to the cycling of resources by slowing and narrowing the loops (Box 2.1). Despite a move toward a circular economy, the loop has not yet been closed. For most manufacturers, the "end step" is missing—that is, returning the used materials to the system through methods including collection, tracking, and reverse logistics of used PPE items.

PPE manufacturers can learn from the extended producer responsibility initiatives that are being applied to the plastic packaging industry. A circular economy approach should be inclusive, covering the whole value chain, from material sourcing to high-value material recovery processes or until the discarded waste is back in the system. Otherwise, the plastic waste resulting from increased PPE use will compound the global threat to our environment that mismanaged plastic waste poses.

This section outlines various circular economy approaches for PPE manufacturing and strategies to manage PPE waste that slow down or close the resource loops. Besides segregating and collecting PPE waste, decontamination techniques help recover resources, unlocking opportunities for reusing, recycling, or producing new items from PPE waste from health-care facilities.

BOX 2.1: CYCLING RESOURCES

Slowing down resource loops entails extending a product's useful life (via product use extension and product-as-service approaches) to slow down the overall flow of resources. It is achieved through the design of long-life goods and services such as repairing and remanufacturing.

Closing resource loops entails recycling resources following a holistic waste management and end-of-life strategy, which leads to the closure of the loop between post-use and production, to create a circular flow of resources (via circular inputs and resource recovery approaches).

Narrowing resource flows entails using fewer resources and/or material inputs per product. Linear business models already use resources efficiently (often referred to as reducing). By itself, resource efficiency does not affect the speed at which products are recycled or whether the resources are retrieved through recycling.[34]

[34] Bocken, Nancy M.P., Conny Bakker, and Ingrid de Pauw. 2015. "Product Design and Business Model Strategies for a Circular Economy." Paper presented at the Sustainable Design & Manufacturing Conference, Seville, April 12–14, 2015. https://www.rescoms.eu/assets/downloads/Business-models-and-design-for-a-closed-loop-FINAL.pdf.

2.1 Four circular economy approaches in PPE production

Circular economy approaches help regenerate used items in two ways: either by reusing the product or by extending the product's lifetime by repairing, remanufacturing, upgrading, or retrofitting it.

Once these goods come to the end of their service life, they are converted into other resources, thereby closing the loop in the industrial ecosystem and minimizing waste.[35]

To curb the ongoing "PPE pandemic," sustainable solutions and safer practices need to be adopted, including:

- Substituting plastic used in PPE through product redesign and material innovation.
- Decontaminating PPE for reprocessing through reuse, recycling, upcycling, or downcycling.
- Implementing automation in plastic waste management.
- Developing policy guidelines encouraging the adoption of sustainable waste management practices.
- Educating consumers on safe and accurate disposal methods.

Globally, PPE manufacturers have adopted various circular economy approaches to respond to PPE shortages and the growing accumulation of waste. These approaches can be grouped into four main categories: circular inputs; resource recovery; product use extension; and product as service. Some PPE manufacturers have adopted multiple approaches, while others have only adopted one based on their business model.

A circular economy approach built on the principles of resource conservation, efficiency, reuse, and material recovery offers an alternative to current unsustainable practices.[36] It is crucial for PPE manufacturers to rethink their product design before deciding on the best approach to adopt for their business.

Regardless of which approach is adopted, manufacturers should always consider other aspects of the product's life cycle, such as resource consumption during use (for example, using chemicals to disinfect an isolation gown for reuse), energy needed for production, and feedstocks; and the chosen end-of-life strategies such as recycling, reusability, or energy recovery.

BOX 2.2: RETHINKING PRODUCT DESIGN

Reimagining the design of a product may help maximize benefits and minimize negative environmental and societal impacts. Rethinking a product's design is not the only recycling strategy, but it allows manufacturers to think through alternative ways of sourcing raw materials (for example, circular inputs approach), redesigning products to recover resources at the end of their service life (resource recovery approach), offering their services as a product (product-as-service approach), and extending the service life of a product (product use extension approach) to slow down, narrow, or close resource loops.

[35] Stahel, Walter. 2016. "Circular Economy." *Nature* 531: 435–8. https://www.nature.com/news/polopoly_fs/1.19594!/menu/main/topColumns/topLeftColumn/pdf/531435a.pdf.

[36] MacNeill, Andrea J., Harriet Hopf, Aman Khanuja, Saed Alizamir, Melissa Bilec, Matthew J. Eckelman, Lyndon Hernandez, Forbes McGain, Kari Simonsen, Cassandra Thiel, Steven Young, Robert Lagasse, and Jodi D. Sherman. 2020. "Transforming the Medical Device Industry: Road Map to a Circular Economy." *Health Affairs* 39 (12): 2,088–97. https://www.healthaffairs.org/doi/10.1377/hlthaff.2020.01118.

Circular inputs

Circular inputs replenish naturally (renewable), can be used repeatedly, are produced from living organisms (bio-based), or can be recycled indefinitely without a substantial loss of quality.

However, harvesting raw materials in the food supply chain to make products is not counted as a circular economy approach as it competes with food supply and production. Innovative approaches are being adopted in PPE production to optimize material type and input at the design phase to prevent waste at production sites altogether.

The plastics pollution from discarded PPE compelled many manufacturers to explore alternative materials to replace petroleum-based plastics. For example, some manufacturers are using compostable bio-based raw materials (such as compressed hemp, bagasse, polylactic acid (PLA), and manmade cellulosic fibers) in place of plastics to make medical textiles or masks. (See Table A.1 in Annex A for other examples of materials that PPE manufacturers are using to make their products.) In doing so, manufacturers must ensure that these materials have the same functionality as the traditional input to meet the quality standards that a product demands in use.

BOX 2.3: REPLACING PLASTIC MATERIAL INPUTS WITH CIRCULAR MATERIALS

Plastic in COVID-19 PPE (particularly soft PPE such as masks, coveralls, and gowns) can be replaced with other organic and biodegradable materials (such as bioplastic) with similar properties (such as lightweight, high tensile strength, and ecological safety). Bioplastics made from biomass, which can be biodegradable or recyclable, are a key modern and sustainable alternative for reducing plastic waste and greenhouse gas emissions. One study suggests that using biodegradable plastic can reduce carbon dioxide emissions by 30–70 percent compared with conventional plastics.[37] However, the technology and scalability is limited.

Natural fibers such as cactus, banana, avocado, lotus, sisal, straw, maize, bamboo, hemp, coffee, and sugar cane can meet the standard requirements to produce non-medical masks and PPE,[38] while polysaccharides such as bamboo, hemp, coffee, and sugar fibers are used to produce recyclable PPE. Recent studies suggest that waste from tea leaves, sugar cane, coffee, and hemp fiber can be used to produce mask filters, as it contains polypropylene and enhances the properties of PLA in bioplastics.[39] Research is ongoing to develop biodegradable masks that meet the standards for medical PPE.[40] Recycling methods for bioplastics include mechanical recycling, pyrolysis, and solvolysis[41]—the same methods used for other plastics. Adding more polymer types will complicate the mechanical recycling process, as it does with recycling conventional plastics.

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37 Lackner, Maximilian. 2015. "Bioplastics." *In Kirk-Othmer Encyclopedia of Chemical Technology*, edited by Donald Othmer. https://onlinelibrary.wiley.com/doi/abs/10.1002/0471238961.koe00006.

38 Luhar, Salmabanu, Thadshajini Suntharalingam, Satheeskumar Navaratnam, Ismail Luhar, Julian Thamboo, Keerthan Poologanathan, and Perampalam Gatheeshgar. 2020. "Sustainable and Renewable Bio-Based Natural Fibres and Its Application for 3D Printed Concrete: A Review." *Sustainability* 12 (24). https://www.mdpi.com/2071-1050/12/24/10485.

39 Layt, Stuart. 2020. "Queensland Researchers Hit Sweet Spot with New Mask Material." *Brisbane Times*, April 14, 2020. https://www.brisbanetimes.com.au/national/queensland/queensland-researchers-hit-sweet-spot-with-new-mask-material-20200414-p54jr2.html; Ho, Sally. 2020. "Vietnamese Company Creates World's First Biodegradable Coffee Face Mask." *Green Queen*, June 9, 2020. https://www.greenqueen.com.hk/vietnamese-company-creates-world-first-biodegradable-coffee-face-mask/; Reuters. 2020. "From Field to Compost: French Firm Develops Hemp Face Masks." *Reuters*, September 11, 2020. https://www.reuters.com/article/us-health-coronavirus-france-hemp-mask-idUSKBN2621Z2.

40 Choi, Sejin, Hyeonyeol Jeon, Min Jang, Hyeri Kim, Giyoung Shin, Jun Mo Koo, Minkyung Lee, Hye Kyeong Sung, Youngho Eom, Ho-Sung Yang, Jonggeon Jegal, Jeyoung Park, Dongyeop X. Oh, and Sung Yeon Hwang. 2021. "Biodegradable, Efficient, and Breathable Multi-Use Face Mask Filter." *Advanced Science* 8. https://onlinelibrary.wiley.com/doi/10.1002/advs.202003155; Di Santarsiero, A., P. Ciambelli, G. Donsì, F. Quadrini, R. Briancesco, D. D'Alessandro, and G.M. Fara. 2020. "Face Masks. Technical, Technological and Functional Characteristics and Hygienic-Sanitary Aspects Related to the Use of Filtering Mask in the Community." *Annali di Igiene: Medicina Preventiva e di Comunità* 32 (5). http://www.seu-roma.it/riviste/annali_igiene/apps/autos.php?id=1339; Di Santarsiero, A., M. Guistini, F. Quadrini, D. D'Alessandro, and G.M. Fara. 2020. "Effectiveness of Face Masks for the Population." *Annali di Igiene: Medicina Preventiva e di Comunità*. https://www.annali-igiene.it/articoli/2020/online_ahead_of_print/Santarsiero-epub-12-2020.pdf.

41 Lamberti, Fabio M., Luis A. Román-Ramírez, and Joseph Wood. 2020. "Recycling of Bioplastics: Routes and Benefits." *Journal of Polymers and the Environment* 28: 2,551–71. https://link.springer.com/article/10.1007/s10924-020-01795-8.

Resource recovery

At the end of a product's life, the value of embedded materials and embodied energy can be extracted and reprocessed through recycling, upcycling, downcycling, or energy recovery.

The waste hierarchy is well thought out in this approach, starting from the design phase. During the design, manufacturers avoid overusing material to prevent waste generation and optimize the raw material input. The waste is returned to the production system to be recycled in closed loops to the extent possible. When this is not possible due to sterilization concerns, the first option to consider is upcycling; that is, creating a superior product from the waste that has more value compared with the original. Alternatively, the waste is downcycled to create a lower-value product. Where recycling options are not feasible, energy recovery options are considered, including tapping into the calorific value of the non-recyclable waste to generate heat or other forms of energy.

If the PPE is designed to be recycled, the waste could be converted into construction materials after it has been decontaminated. The extracted polypropylene and polyester derivatives from mixed or pure PPE waste could be used in road construction as a partial replacement for asphalt or bitumen, and for brick manufacturing.[42] Another example of recycling PPE is the RightCycle Program at Northern Michigan University, which is sponsored by Kimberly-Clark. Under the program, previously hard-to-recycle items such as protective clothing, safety glasses, and nitrile gloves are collected in separate bins and shipped to a Kimberly-Clark recycling partner in Millwood, West Virginia, where they are processed into plastic pellets that are then turned into new consumer products such as patio furniture, flowerpots, and plastic shelving.[43]

Other industrial applications, such as insulation for building wraps, industrial adhesive tape, plastic parts such as pipes, and masonry bricks, can also be explored. See Annex A for examples of PPE manufacturers that have adopted a resource recovery approach.

Product use extension

This circular economy approach prolongs the lifetime of PPE products by improving their durability and design.

If this approach is applied by itself, it helps to slow the resource loops rather than close them. Therefore, to combat the waste problem caused by COVID-19, it is important to combine this approach with recycling and up/downcycling strategies in the design phase.

Designing PPE made of distinct components allows parts to be replaced or upgraded. Durable materials should be chosen as input for the main parts, with the addition of a replaceable material that addresses hygiene concerns. When combined with sterilization techniques, the durable material inputs allow users to wear the PPE multiple times.

Product innovation in developing eco-friendly and reusable PPE is essential to reduce the generation of PPE waste. While re-processing and decontamination through methods such as moist heat, dry heat, ultraviolet treatment, and gamma radiation are important, there are few innovations specifically designed for PPE reuse; most of the industry relies on long-standing technologies.[44] Global examples include Thai Taffeta's isolation gowns, which are produced with durable materials and can be used between 50 and 100 times when disinfected using autoclave technology. Similarly, durable respirators made by Open Standard Industries can be used multiple times by replacing the filter material when needed.

There is an opportunity for PPE manufacturers to focus on using woven and knitted fabrics so that PPE products can be reused. Studies have shown that the performance of these fabrics against blood splash penetration is comparable to other types of PPE materials.[45]

Reusable materials other than cloth are also being developed and used to create face masks. The most advanced material is silicone, as is it easy to sterilize and reuse, adheres well to the skin to form a secure barrier, and can be manufactured in a relatively complex shape for medical and general use. See Annex A for examples of PPE manufacturers that have adopted this approach.

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[42] Adlakha, Nidhi. 2020. "India's 'Recycle Man' Makes Bricks from Discarded Face Masks." *The Hindu*, August 7, 2020.

[43] Northern Michigan University Foundation. 2021. "Transforming COVID PPE Waste." *Northern Magazine*, 110 (2).

[44] Ilyas, Sadia, Rajiv Ranjan Srivastava, and Hyunjung Kim. 2020. "Disinfection Technology and Strategies for COVID-19 Hospital and Bio-Medical Waste Management." *Science of the Total Environment* 749. https://www.sciencedirect.com/science/article/pii/S0048969720351810?via%3Dihub.

[45] Shimasaki, Noriko, Katsuaki Shinohara, and Hideki Morikawa. 2017. "Performance of Materials Used for Biological Personal Protective Equipment against Blood Splash Penetration." *Industrial Health* 55 (6): 521–8. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5718772/.

Product as service

The product-as-service approach allows consumers to use a product that the producer retains to increase resource productivity.

Workwear rental companies and PPE laundry services adopt this approach. This approach allows PPE manufacturers to move from selling products to selling services. It has several advantages: it increases customer loyalty by allowing companies to develop long-term relationships with their clients and it allows companies to modify the product design based on users' feedback.

As the final receiver of the product, companies following this approach implement a take-back mechanism. This gives them the opportunity to extract material value at the end of the service life of a PPE product. Some companies are using technological innovations to sync product and packaging data with recycling facilities via digital identity scanning to accurately track, trace, sort, and recycle their products.

The product-as-service approach seems to work best in advanced economies due to lack of digital infrastructure and industrial laundries in emerging economies. See Annex A for examples of PPE manufacturers that have adopted a product-as-service approach.

2.2 PPE waste management from a circular economy perspective

The ongoing proliferation of single-use disposable PPE in the health-care supply chain during the pandemic has given rise to higher environmental and economic costs.[46]

Efficiently managing COVID-19 PPE waste poses a considerable challenge for different components of the system, including source identification, segregation, collection and transportation, and treatment and disposal. Unlike single-stream plastics, it is challenging to recycle mixed plastic streams, including single-use and multi-layer plastics (such as masks), because they are not easily separable. Furthermore, while the plastic polymers used in producing PPE are not toxic, the chemical additives or residuals used in production can leach from plastic polymers once the PPE degrades, which can be hazardous to human health and the environment.[47]

Given the dramatic rise in the generation of plastic waste during the pandemic, many advanced waste management methods have been developed to specifically cater to COVID-19 biomedical waste, with minor variations in the general treatment of biomedical waste.[48] But there is no specific formalized waste management system for PPE streams for public waste management facilities to adopt.

BOX 2.4: RETHINKING DESIGN TO AVOID WASTE GENERATION

Some manufacturers design their PPE to avoid waste generation during manufacturing. Ahlstrom-Munksjö uses fewer raw materials without sacrificing barrier properties to produce breathable viral barrier fabrics. Similarly, Open Standard Industries, a start-up established during the pandemic, produces reusable respirators that use four times less filtering material than their disposable N95 equivalent. The key to avoiding waste during production and after use in both cases is material innovation and opting for materials that will help meet quality and safety standards (see Annex B for PPE standards).

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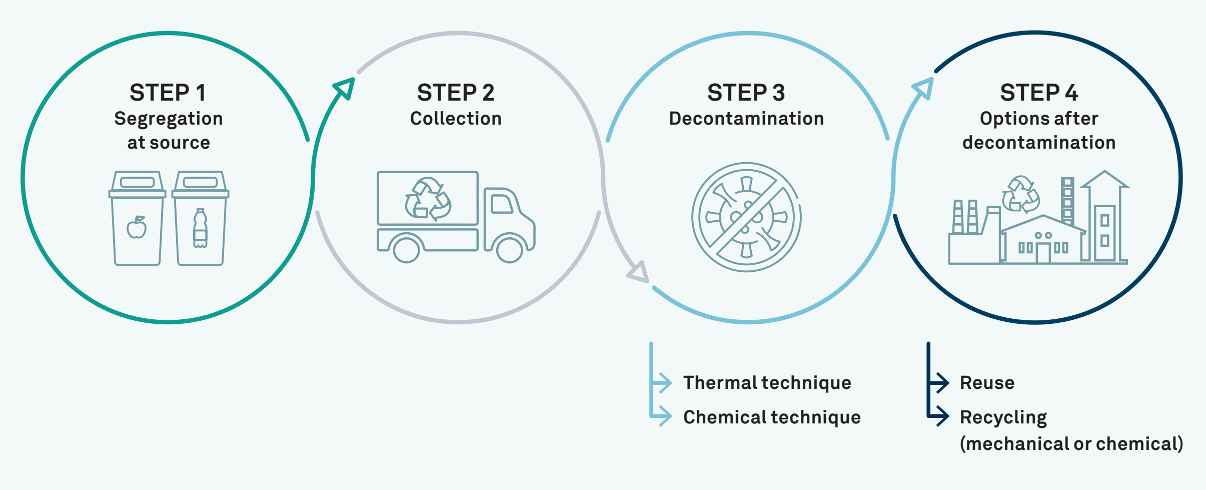
46 Silva, Ana L. Patrício, Joana C. Prata, Tony R. Walker, Armando C. Duarte, Wei Ouyang, Damià Barcelò, and Teresa Rocha-Santos. 2021. "Increased Plastic Pollution due to COVID-19 Pandemic: Challenges and Recommendations." *Chemical Engineering Journal* 405. https://www.sciencedirect.com/science/article/abs/pii/S1385894720328114?via%3Dihub.

47 Smith, Madeleine, David C. Love, Chelsea M. Rochman, and Roni A. Neff. 2018. "Microplastics in Seafood and the Implications for Human Health." *Current Environmental Health Reports* 5: 375–86. https://link.springer.com/article/10.1007%2Fs40572-018-0206-z.

48 Silva, Ana L. Patrício, Joana C. Prata, Tony R. Walker, Diana Campos, Armando C. Duarte, Amadeu M.V.M. Soares, Damià Barcelò, and Teresa Rocha-Santos. 2020. "Rethinking and Optimising Plastic Waste Management under COVID-19 Pandemic: Policy Solutions Based on Redesign and Reduction of Single-Use Plastics and Personal Protective Equipment." *Science of the Total Environment* 742. https://www.sciencedirect.com/science/article/pii/S0048969720340870?via%3Dihub.

FIGURE 2.1: FOUR KEY STEPS TO MANAGING PLASTIC-BASED PPE WASTE IN LINE WITH CIRCULAR ECONOMY PRINCIPLES



In a circular economy, the traditional waste management hierarchy, which focuses on safe disposal, is replaced with a new approach that prioritizes preserving the value of resources. The best way to prevent waste generation is by rethinking the product design and manufacturing process through optimizing the raw material inputs and material mix (for example, by reducing the number of materials used and replacing raw materials with alternatives that will not end up in landfills).

Without a coordinated waste management strategy to return the waste to the system, the resource loops cannot be entirely closed. New system designs with reverse logistics or take-back systems[49] and material innovations may pave the way for a more holistic circular economy approach within the PPE production sector.

The steps involved in managing plastic-based COVID-19 PPE waste in line with circular economy principles are as follows: segregate the waste at the source, properly collect the waste, and decontaminate the waste for resource recovery. If the PPE design allows for it, the PPE waste can either be reused or recycled after decontamination (Figure 2.1).

Step 1: Segregation at source

Segregating PPE waste at source is an essential step before it is collected. This is especially true for plastic-based PPE waste from non-contaminated sources (households and entities). However, in most countries, the current practice is to place PPE in the same recyclable bins as those for waste originating from contaminated sources, such as hospitals, quarantine facilities, containment zones, and infected households. This makes it more difficult to segregate the non-contaminated PPE waste from the contaminated PPE waste.

Step 2: Collection

If biomedical PPE waste originates from contaminated sources such as quarantine centers, it is generally collected in separate, clearly marked bins or bags. The waste-containing bags are then disinfected and sealed in double-layered plastic bags before being transported from the place of origin. Biomedical waste from contaminated resources accounts for 10–25 percent of COVID-19 PPE waste and should not be stored for more than 24 hours after it has been disposed of.[50] Biomedical waste from health-care facilities should be transported to waste treatment facilities for final disposal.

[49] Moving goods from their typical final destination to capture value, or dispose of properly, including remanufacturing and refurbishing.

[50] Rao, Venkateswara, and Sadhan Kumar Ghosh. 2020. "Sustainable Bio Medical Waste Management—Case Study in India." In *Urban Mining and Sustainable Waste Management*, edited by Sadhan Kumar Ghosh. Singapore: Springer Singapore. https://www.springerprofessional.de/en/sustainable-bio-medical-waste-management-case-study-in-india/17809084.

Step 3: Decontamination

Thermal and chemical techniques are used to decontaminate COVID-19 PPE waste.[51]

Thermal techniques

Autoclaving and micro/radio-wave irradiation are preferred methods for disinfecting waste that amounts to less than 10 tons per day. Autoclaving has a higher heat energy than microwave techniques and does not lead to a significant release of harmful gases. Compared to autoclaving, microwaving uses less energy, has limited heat loss, and has a smaller environmental impact.[52] In the case of disinfecting COVID-19-related waste, the microwave technique is often used in conjunction with autoclaving. Most thermal techniques use equipment and disinfectants that are readily available in clinics or hospitals and could be considered for sanitizing plastic-based COVID-19 PPE. Autoclaving and micro/radio-wave irradiation enable health-care workers to reuse COVID-19 PPE such as isolation gowns and respirators.

Chemical techniques

Ultraviolet germicidal irradiation, ethylene oxide, and vaporous hydrogen peroxide have been found to effectively disinfect used PPE biomedical waste, such as medical safety kits.[53] However, such chemical disinfection works more effectively if the used PPE is mechanically crushed into smaller fractions. Chemical disinfectants such as sodium peroxide or bleach could be viable options, with no reported hazardous by-product on treatment.[54]

While sterilizing COVID-19 biomedical waste is an essential step in managing plastic-based COVID-19 PPE, several potential options that form the basis of a circular economy—such as reusing, recycling, and using biodegradable materials—have become increasingly necessary to combat the plastic pandemic. The applicability will vary depending on the PPE product, market, type of waste stream, and how the product is used. However, it is clear that these options are considered more suitable for consumer PPE, whereas for hospitals (where there is a higher ratio of contaminated biomedical waste), disposal through incineration remains the primary option.[55]

Step 4: Options after decontamination

Once the PPE waste has been decontaminated, its use can be maximized through reuse or recycling if the material design allows.

To make products reusable, ongoing efforts to improve the materials used for PPE include:[56]

- Sourcing and designing alternative materials with sufficient filtering capacity.
- Designing PPE and respirators for better protection, breathability, and user comfort.
- Developing multifunctional masks and materials with hydrophobic, anti-viral and anti-microbial, self-disinfecting, and even sensing properties.
- Exploring new technologies to efficiently produce and customize masks (such as 3D printing).[57]

For recycling there are two main methods: mechanical and chemical. The most commonly used recycling method for the management of plastic-based COVID-19 PPE waste is mechanical recycling.

In **mechanical recycling**, identifying the condition of the plastic-based biomedical waste is essential to determine whether the waste needs to be cleaned to remove resin and contaminants. Chemical disinfection is commonly used in combination with mechanical shredding to pre-treat COVID-19 waste.

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[51] While there are other decontamination techniques, this report focuses on the most relevant techniques for contaminated COVID-19-specific PPE.

[52] Haque, Md. Sazzadul, Shariar Uddin, Sayed Md. Sayem, and Kazi Mushfique Mohib. 2021. "Coronavirus Disease 2019 (COVID-19) Induced Waste Scenario: A Short Overview." *Journal of Environmental Chemical Engineering* 9 (1). https://www.sciencedirect.com/science/article/pii/S2213343720310095?via%3Dihub; Belhadi, Amine, Sachin S. Kamble, Syed Abdul Rehman Khan, Fatima Ezahra Touriki, and Dileep M. Kumar. 2020. "Infectious Waste Management Strategy during COVID-19 Pandemic in Africa: An Integrated Decision-Making Framework for Selecting Sustainable Technologies." *Environmental Management* 66: 1,085–104. https://link.springer.com/article/10.1007%2Fs00267-020-01375-5.

[53] Polkinghorne, A., and J. Branley. 2020. "Evidence for Decontamination of Single-Use Filtering Facepiece Respirators." *The Journal of Hospital Infection* 105 (4): 663–9. https://www.journalofhospitalinfection.com/article/S0195-6701(20)30263-2/fulltext.

[54] Wang, Dan, Bao-Chang Sun, Jie-Xin Wang, Yun-Yun Zhou, Zhuo-Wei Chen, Yan Fang, Wei-Hua Yue, Si-Min Liu, Ke-Yang Liu, Xiao-Fei Zeng, Guang-Wen Chu, and Jian-Feng Chen. 2020. "Can Masks Be Reused After Hot Water Decontamination during the COVID-19 Pandemic?" *Engineering* 6 (10): 1,115–21. https://www.sciencedirect.com/science/article/pii/S2095809920301624?via%3Dihub.

[55] Masand, Drishti, and Michael Holman. 2020. "Mask Up: The Rising Need for Material Innovations in Face Masks." Lux Research. https://bit.ly/3uRRlhV.

[56] Masand, Drishti, and Michael Holman. 2020. "Mask Up: The Rising Need for Material Innovations in Face Masks." Lux Research. https://bit.ly/3uRRlhV.

[57] Chua, Ming Hui, Weiren Cheng, Shermin Simin Goh, Junhua Kong, Bing Li, Jason Y. C. Lim, Lu Mao, Suxi Wang, Kun Xue, Le Yang, Enyi Ye, Kangyi Zhang, Wun Chet Davy Cheong, Beng Hoon Tan, Zibiao Li, Ban Hock Tan, and Xian Jun Loh. 2020. "Face Masks in the New COVID-19 Normal: Materials, Testing, and Perspectives." *Research* 2020. https://spj.sciencemag.org/journals/research/2020/7286735/.

Chemical recycling can be used to process mixed or contaminated plastic waste that cannot be recycled mechanically for technical reasons. If it is not recycled, the waste would be incinerated or sent to landfills. Chemical recycling processes can be economical if implemented on a large scale. They are also more tolerant of contamination, and they yield polymers that are identical to the originals, avoiding downcycling. However, chemical recycling requires a high level of energy consumption and is costlier than mechanical recycling. A significant advantage of chemical recycling is its lower emission rates compared with end-of-life incineration solutions. A recent study found that chemical recycling (pyrolysis) of mixed plastic waste emits 50 percent less carbon dioxide than incineration of mixed plastic waste.[58]

[58] Cefic. 2020. "Chemical Recycling: Greenhouse Gas Emission Reduction Potential of an Emerging Waste Management Route." October 2020. https://cefic.org/app/uploads/2020/12/CEFIC_Quantis_report_final.pdf.

3 Companies with innovative circular economy approaches in PPE manufacturing

Globally, several multinational enterprises and start-ups are adopting innovative solutions using biodegradable, compostable, or recycled materials in PPE, while still ensuring that the materials meet the stringent performance standards and durability targets at affordable prices. Other business models are emerging where selling products is being replaced by a merchandizing service (performance-based model); and waste is being converted into new (and even superior) products such as construction materials or new PPE items.

This chapter profiles the innovations of 11 multinational and national PPE manufacturers. Annex A provides a more exhaustive overview of relevant companies, categorized by the four circularity approaches. The examples in this chapter provide multiple entry points to rethink circularity principles in PPE manufacturing.

BOX 3.1: DIGIMARC—DRIVING THE CIRCULAR ECONOMY THROUGH DIGITAL WATERMARKS

Product as service

US-based automatic identification and data capture software provider Digimarc is helping to drive the circular economy through digital watermarking. Digital watermarking embeds verifiable and traceable information on packaging and products, such as brand authentication and recycling information. Digimarc digital watermarks can be placed on various products and packages, including food and other fast-moving consumer goods, pharmaceuticals, and textiles.

During the pandemic, the company collaborated with a wide range of stakeholders to integrate its technology across the value chain of the textile and packaging sector. The technology is available globally through a vast partner network, with noted market traction in Germany, Japan, and the United States for digital watermarks for COVID-19 PPE products and services.

The company is also working to improve plastic recycling and sorting. Across Europe, the HolyGrail 2.0 Project, facilitated by AIM (the European Brands Association) on behalf of its 2,500 member organizations, and powered by the Alliance to End Plastic Waste, continues to demonstrate the viability of Digimarc's digital watermarking technologies for accurately sorting any waste, including plastics. The initiative is a collaboration between global brands, retailers, trade associations, printers, and converters across the packaging industry and recycling technology companies.

Digimarc technology makes any object or package "smart" by giving it a digital product passport, which links to virtually unlimited information stored in the cloud. As an Internet-of-Things object, the unique digital identity can be detected by a broad range of detection devices. In recycling facilities, the watermarks are used to identify and accurately sort waste objects, increasing the quality and quantity of recyclate to enter the circular economy for new products. The watermark is also detectable by smartphone cameras through the use of an app to engage and educate consumers.

DIGIMARC

PPE is an exciting new opportunity for digital watermarking solutions. The imperceptible digital watermark can easily be printed onto masks, woven into doctors' gowns, or integrated into the surface of plastic PPE in the form of a subtle decorative embossing effect. New technological solutions such as apps can then be developed to access the digital watermark and its connected data such as manufacturer and product identity, composition of materials, efficacy rating, and consumer instructions for proper disposal.

Digimarc's go-to-market strategy is built on a wide array of service providers so that brands and retailers can continue to use their current suppliers for enhancing products with the digital watermark. Similarly, the company's detection components are implemented by most leading manufacturers of scanning equipment.

Digimarc solutions can easily be adopted following training in digital watermarking software. Training could be customized for the PPE industry to increase the adoption of digital watermarks on PPE items and expand traceability and recyclability, to not only move toward a circular economy but also monitor the supply chain.

AHLSTROM MUNKSJÖ

Circular inputs | Resource recovery | Product use extension

COVID-19 PPE products offered

Ahlstrom-Munksjö is a multinational rolled goods manufacturer headquartered in Finland. The company offers innovative solutions to customers in the health sector worldwide. It produces high-performing non-woven medical fabrics that are used to make surgical gowns and drapes, pleated face masks, and protective apparel. The company's main customer groups are manufacturers and distributors of medical supplies, medical device companies, and medical converters.

Along the medical PPE value chain, Ahlstrom-Munksjö is involved in both raw material manufacturing (including face mask materials, medical barrier fabrics, medical and laboratory papers, and medical filter media), and end-product production and assembly (sterilization wraps).

During the COVID-19 pandemic, Ahlstrom-Munksjö introduced new mask fabrics made of alternative material to increase filtration performance. As an established manufacturer of non-woven fabrics, the company has been producing the inner and outer coverstock layer used for pleated surgical face masks. However, the middle filter media was something it did not start producing until COVID-19. Thanks to its in-depth knowledge of filtration materials and a common manufacturing platform, Ahlstrom-Munksjö was able to respond swiftly to the growing demand by expanding its manufacturing of face mask fabrics to product lines normally used for producing other fiber-based materials. Its offering includes a full range of protective face mask fabrics for non-medical masks, surgical masks, and respiratory masks.

Product technical features in terms of circularity

Ahlstrom-Munksjö's product offerings use renewable, bio-based, and non-petroleum-based materials that make the end product more sustainable. The company integrates innovative technologies in its design and production to extend the shelf life and performance of its products.

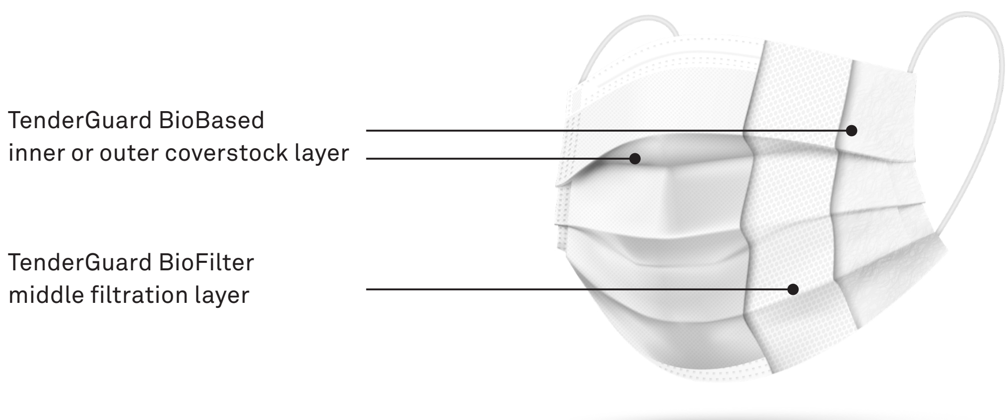
TenderGuard

The TenderGuard fabric is breathable, protective, soft, and non-irritating. In addition, the non-medical masks are biodegradable and compostable.

Medical face masks and surgical gown fabrics

TenderGuard Natural consists of wetlaid fabrics that are used as the inner or outer layer of a face mask. These fabrics are environmentally friendly and the inner layer is hypoallergenic. Through the inner and outer layers, TenderGuard Natural masks have a bacterial filtration efficiency of nearly 50 percent.

FIGURE 3.1: TENDERGUARD PRODUCTS



Source: Adapted from Ahlstrom-Munksjö brochure.

TenderGuard Smooth consists of bicomponent spunbond fabrics that are made with a proprietary technology that minimizes raised fibers. This creates a smooth surface to help eliminate skin irritation, which is essential for face masks. In addition, the fabric is strong and flexible, allowing for high-speed production.

TenderGuard SMS is a lightweight surgical fabric that is designed for superior comfort. It has a high repellency to protect against low surface-tension liquids such as blood, other body fluids, and alcohol. The fabric is made up of a multi-layer non-woven fabric commonly known as SMS (spunbond melt-blown spunbond). The top and bottom layers are made of spunbond polypropylene to provide strength, and the middle layer is made of melt-blown polypropylene to create a protective barrier. SMS has low lint and is highly breathable, which helps to keep the wearer cool and comfortable. The highest level of protection, which is used in high-risk environments such as operating rooms, is called breathable viral barrier fabric. This fabric has a barrier layer that consists of a monolithic film membrane that prevents viral penetration. Ahlstrom-Munksjö offers various breathable viral barrier fabrics for surgical and clinical environments.

Non-medical face mask fabrics

Ahlstrom-Munksjö's new face mask fabrics, TenderGuard BioBased and BioFilter, are joint efforts of the company's medical product development team and beverage and casing business team. By combining the knowledge of both businesses, the team created sustainable, renewable, and biocompatible materials that are ideal for non-medical face masks.

TenderGuard BioBased can be used as an inner or outer coverstock layer for a non-medical face mask. The fabric mainly consists of polylactic acid (PLA), which is a biopolymer made from sustainable and renewable sources, typically fermented plant starch. PLA is a bio-based alternative to synthetic spunbond materials that are produced from fossil fuels. This 100 percent bio-based plastic is preferred for its transparency, gloss, stiffness, printability, processability, and scent barrier. PLA is an ideal sustainable alternative to the standard polypropylene spunbond, which is most commonly used in face masks and face coverings. From a physical property standpoint, PLA is closer to polypropylene, with a similar touch and feel. In fact, apparel fabrics are made from the same PLA fibers and achieve a bacterial filtration efficiency of nearly 50 percent. Like TenderGuard Natural, achieving this level of efficiency with only the inner and outer layers is no easy feat. In addition, TenderGuard BioBased passes the ISO cytotoxicity and in vitro EpiDerm skin irritation tests, which confirm that it is non-toxic and non-irritating. The highly breathable fabric is comfortable to wear for long periods of time. It is also certified under European Norm EN 13432 as biodegradable and compostable under controlled conditions.

TenderGuard BioFilter is a sustainable filter media that can be used as a filter layer in face masks. The media is primarily designed for non-medical use and source-control filtering of infectious diseases. It can be used as a single layer or combined as a double filtration layer for higher filtration performance. The 100 percent bio-based fabric is made up of a special blend of cellulosic and cellulose-based manmade fibers.

TABLE 3.1: CIRCULAR DESIGN PRINCIPLES ADOPTED BY AHLSTROM-MUNKSJÖ

CIRCULAR PRINCIPLES	FEATURES	IMPLEMENTATION
Circular inputs	Biodegradable material inputs	The company produces medical fabrics made of bio-based plastic cellulosic and cellulose-based manmade fibers
Product use extension	Smart fiber as input to extend product lifetime	The company integrates innovative technologies in its design and production to extend the service life and performance of its products. The filter media is used for reusable face masks
Resource recovery	Recyclable	If collected, the products are recyclable

Resource recovery

COVID-19 PPE products offered

To address the plastic crisis created by COVID-19, Eco-Eclectic Technologies, a company based in India, created the P-Block 2.0—a brick made from recycled biomedical waste. This brick builds on the company's first innovation, the P-Block (bricks made from industrial paper and gum waste), which was developed in 2010. In recognition of the company's innovations, Eco-Eclectic Technologies' founder, Dr. Binish Desai—also called the "Recycle Man of India"—was featured in the Forbes "30 Under 30" Asia 2018 list of successful social entrepreneurs.

Experimental development of P-Block 2.0 started in April 2020 with used non-woven masks: the used masks were disinfected for two days and then mixed with special binders.

Product technical features in terms of circularity

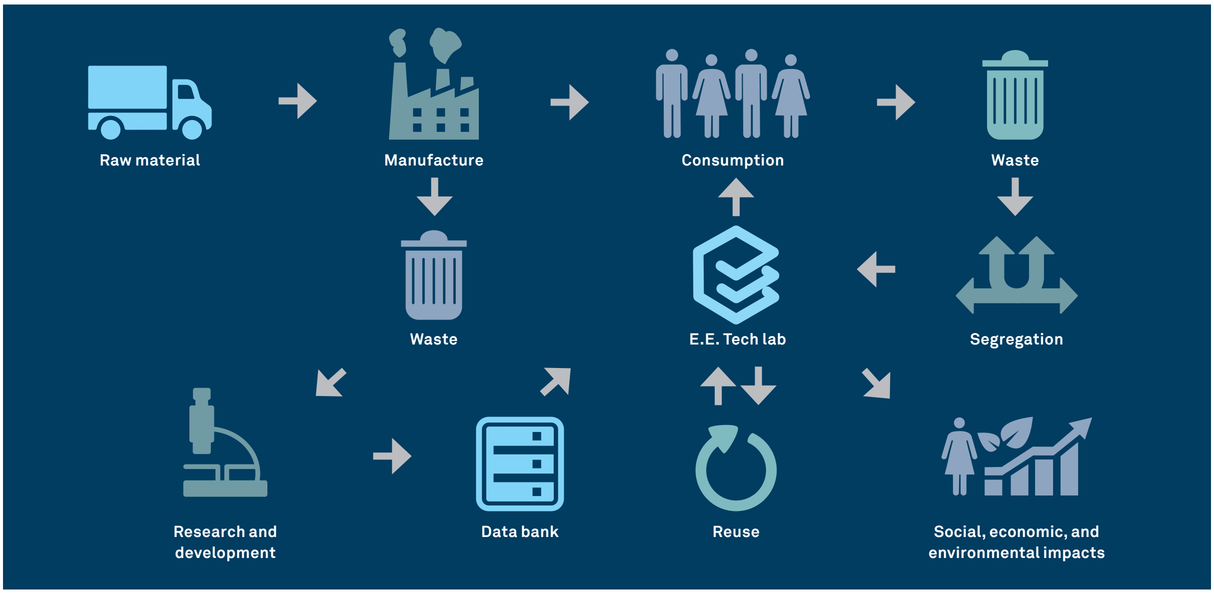
P-Block 2.0 is composed of 52 percent PPE (any non-woven material), 45 percent paper waste, and 3 percent binder. The process starts with the installation of "eco bins" specifically used to collect PPE waste across the cities of Surat and Valsad, including from different municipal corporations and local bodies, as well as from private hospitals, malls, film sets, and salons. In accordance with the Central Pollution Control Board guidelines, the PPE waste is quarantined for 72 hours in the eco bins. The bins are then opened, and the waste is washed in a pool of disinfectant. After following proper sanitation protocols, the material is shredded, disinfected again, added to industrial paper waste procured from paper mills, and mixed with binders. The mix is kept for 45 minutes before being set in molds. The bricks are naturally dried for three days, after which the product is ready to use.

The new variant, P-Block 2.0, is stronger and more durable than other brick blocks (AAC, red, or the original P-Block). It is three times stronger than conventional bricks, at twice the size and half the price. It is also fire-retardant, has insulating and insect-repelling qualities, is recyclable, and absorbs little water (less than 10 percent of its weight).

Circularity mapping

Eco-Eclectic Technologies' P-Block 2.0 bricks are made from recycled COVID-19 PPE waste (resource recovery approach). The disinfected PPE waste is shredded mechanically, molded, and then cast using a binder.

FIGURE 3.2: ECO-ECLECTIC TECHNOLOGIES' ECO ECONOMY



Source: Adapted from Eco-Eclectic Technologies' website material.

E-Tex Kawach

Circular inputs | Product use extension

COVID-19 products offered

E-TEX is a "smart textiles" start-up, incubated at the Indian Institute of Technology Delhi in 2019, that caters to the health-care sector through its technological innovations. The company's key achievement during the COVID-19 pandemic was its development and launch of a highly protective and affordable "Made in India" face mask, KAWACH. The founder, who is also a professor at the institute, states that KAWACH offers reusability, biodegradability, affordability, and scalability.

Product technical features in terms of circularity

KAWACH is a multi-layer mask made of 95–96 percent biodegradable materials. It offers 99.9 percent filtration protection against particles of 3 microns and 90 percent filtration protection against particles of 0.3 microns, making it comparable to N95 masks for engineered filtration (ASTM F 2101). The original mask is designed in three layers: both the outer and the inner layers are a fine gauge bio-washed fabric made of a knitted mesh of super fine combed cotton; the middle layer (<1 g) is a melt-blown non-woven polypropylene fabric sandwiched between two spunbond fabric layers. The material is thus soft, fibrous, and lightweight (<15 g), while using knitted layers provides extra comfort to the wearer.

Over the course of the pandemic, more innovations were added to the original features of the KAWACH mask based on feedback and requirements from hospitals and other customers. These included different finishing improvements, such as a splash-resistant outer layer, an odor-free inner layer, and water-repellent abilities. Different commercial versions are now available to the market, such as KAWACH Pro, which has a lightweight nano-finished fabric for splash and microbial resistance, along with water-repellent and anti-odor properties, while the KAWACH Fashion Pro is designed to offer an adjustable 3D fit and better breathability. These masks can be gently washed between 10 and 30 times in cold or lukewarm water (90–100°F), without steaming, line drying, or steam pressing, and without reducing the filtration efficiency below 90 percent. All masks are also tested and approved by a National Accreditation Board for Testing and Calibration Laboratories (NABL)-accredited lab using international standards (ASTM F2299, ASTM F2101, IS 16289:2014, ASTM F1862/F1862M-13, and 16 CFR Part 1610).

Circularity mapping

E-TEX products are biodegradable because the main component is cotton. In addition, KAWACH masks are washable due to their material choice and product design.

TABLE 3.2: CIRCULAR DESIGN PRINCIPLES ADOPTED BY E-TEX

CIRCULAR PRINCIPLES	FEATURES	IMPLEMENTATION
Circular inputs: E-TEX KAWACH masks are biodegradable	• Designed for recycling after use	• The outer and inner layers are made of a fine gauge bio-washed cotton fabric, which makes the product about 95% biodegradable
Product use extension: E-TEX KAWACH masks are durable and reusable	• Designed for durability • Material chosen to avoid single use	• Splash-resistant outer layer with nano-finishes, odor-free inner layer, and water-repellent abilities, as well as additional 3D fit design and breathability • Washable 10–30 times due to choice of cotton as base material, and sandwich construction of middle polypropylene layer, without reducing filtration efficiency below 90%

BOX 3.2: INNOVATIVE APPROACHES: "GREEN" RESPIRATOR

Resource recovery | Product use extension

Open Standard Industries

Motivation

The Open Standard Respirator Model 1 (OSR M1) is a reusable and comfortable N95 mask alternative, developed by Open Standard Industries in collaboration with MIT Media Lab alumni. There has been a large demand for a lightweight, reusable mask that provides both respiratory protection to the wearer and source control to help reduce the spread of large respiratory droplets to others by covering the wearer's nose and mouth. Masks are generally designed for one-way protection: that is, to capture droplets leaving the wearer to protect others around them but not the wearer themselves. In contrast, the problem with valved respirators is that they only filter the wearer's inhaled air, not their exhaled air, thus protecting the wearer but putting others around the wearer at risk in a situation such as the COVID-19 pandemic.

FIGURE 3.3: OSR M1

Source: © Andy Ryan

Innovation

These challenges have been addressed through Open Standard Industries' OSR M1 design. In addition to being reusable for non-medical use, OSR M1 masks are lightweight, check-valve-free, and function as industrial-grade respirators. The mask is designed to allow for two-way air filtration. It uses one quarter of the filtering material of a disposable mask by specifically designing the airflow through the mask. This material advantage will alleviate the amount of disposable products ending up as medical waste, increase the supply of high-quality masks, and reduce the cost of continued protection. The filter media inside the mask can be replaced as necessary, while the mask portion can be sterilized and reused over time. This means health-care workers do not need to rely on costly and scarce disposable respirators.

Facepiece: The mask has a silicone facepiece, which provides a comfortable seal around the face and blocks any unfiltered air from leaking past the filter. Disposable masks do not necessarily have a tight seal around the nose and chin, meaning air that is not filtered within the system can still enter or exit. Airborne viruses such as SARS-CoV-2 (about 0.1 microns in diameter) are carried on tiny particles that can pass through micro gaps. Having a tight seal on a mask ensures that all particles are being filtered in both directions. The challenge with existing N95 masks is that they lack a tight seal around the face so air can still enter. However, the OSR M1 design allows the mask to be manufactured in various sizes (small, medium, and large) to ensure that the seal fits tightly and covers the relevant parts of the face.

Scaffold: The mask has a rigid scaffold that can hold any type of filter material. Because of this, the user never has to touch the filter material. As all the air is directed through one space, the mask can be designed with less filter material because the filter does not have to provide structure around the face.

Filter: A larger filter area reduces the velocity of air passing through the filter media. Slower air increases the protection efficiency and reduces the breathing resistance of the non-woven filter materials. The filter media works by both blocking larger particles and pulling and latching tiny particles onto the filter fibers using an electric charge. Particles with lower kinetic energy cannot penetrate as far, meaning slower-moving particles can be blocked more effectively. At the beginning of the pandemic, there was a shortage of filter material. In response, the provided scaffold of the OSR M1 mask can accommodate any material if one cannot source the specific filter material (although only filter material can provide the full N95 protection). Offering the same protection level as N95 masks was one of the intended design elements of this mask.

Circular economy solutions: Longevity, reusability, and recyclability

OSR M1 masks adopt three circular economy principles: longevity, reusability, and recyclability. The masks are designed with materials that are both recyclable and durable; they can be sterilized many times, making them reusable. They are also designed using four times less filter material than disposable masks and are cost-effective (the mask pays for itself after 20 uses compared with purchasing disposable masks). The replaceable filter material is an electret non-woven polymer and the mask's main components are a medical-grade plastic filter compartment and a silicone facepiece. Thanks to its modular design, once the filter is disposed of, the skeleton of the mask is fully recyclable at the end of its service life, thereby reducing the sourced material ending up as medical waste. If the mask is worn occasionally, such as to visit a store or during a flight, it is possible to apply the "wait and reuse" method. That is, one can leave the mask hanging to dry until its next use, during which the virus on the filter media would substantially decay after seven days. Users applying this method are recommended to replace the filter at least once a month.

For the facepiece, the design team considered using a polyurethane-based piece but decided on silicone. Polyurethane is a recyclable material and has similar properties to silicone; however, there are certain rules for the manufacturing process when injection molding is applied for polyurethane. Silicone recycling is limited to downcycling due to a lack of utility-scale technologies and collection schemes, but it has better sterilization and skin-sensitivity properties than polyurethane because it can endure higher temperatures and autoclaving. Indeed, the filter decontamination was tested through autoclaving under ultraviolet C light and showed no change in its filtration capacity after 10 cycles.

Performance and scalability

The OSR M1 design leverages manufacturing processes that can be scaled but that also comply with regulatory requirements, particularly quality and safety regulations that will allow the mask to be produced globally. The team solely focused on the US market at first, wanting its mask to meet the core standards, which are a combination of standards established by the Centers for Disease Control and Prevention and the National Institute for Occupational Safety and Health (NIOSH). NIOSH's standard is recognized globally. Therefore, once the OSR M1 masks are approved, it will be possible to distribute them in other countries.

The mask has passed all pre-tests (NIOSH and ASTM), performed by the US Army Combat Capabilities Development Command Chemical Biological Center, corroborating its breathability performance and particle filtration efficiency. Regarding breathability, the dead space between the face and the mask can cause the remaining carbon dioxide to be re-inhaled, limiting the oxygen intake, but a test can be performed to ensure this problem is avoided. This test confirmed the OSR M1 mask's breathability compliance. Tests also affirmed that the two-directional source-control mask filters more than 99 percent of particles 0.075 microns and above. The US Army Medical Research and Development Command is supporting the NIOSH application process for the OSR M1 to become an industrial-grade N95 mask. The mask would also need to be validated by the US Food and Drug Administration and the Centers for Disease Control and Prevention to be fully certified as a medical-grade respirator.

FIGURE 3.4: FACEPIECE, FILTER, AND SCAFFOLD OF OSR M1

Source: © Andy Ryan

FORSTA MEDTECH

Resource recovery | Product use extension

COVID-19 PPE products offered

Forsta Medtech is an Indian biotechnology company that makes microwave-based sterilizers. It provides innovative proprietary microwave-based infection and epidemic control solutions for patient safety and for preventing hospital-acquired secondary infections.

Forsta Medtech's SterilSmart is based on the innovative "microwave-assisted cold 70°C sterilization" (MACS) technique, which uses microwaves to treat and disinfect different types of PPE at the point of generation so that they can be reused.

Product technical features in terms of circularity

SterilSmart offers a dry process, enabling sterilization of moisture-sensitive products. Key features of SterilSmart include its low-temperature sterilization, between 60°C and 80°C, without affecting material qualities; quick throughput of 7–30 minutes depending on the type of PPE; and low consumption of energy (3 kilowatts vs. 18 kilowatts for autoclaves) and water (8 liters vs. 900 liters per day). SterilSmart also has a higher sterilization efficacy (in terms of kill rate) than autoclaves (Log^{10} compared with Log^{6}).

The system is available in three models. Based on the number of health-care facility beds, it can cater to 75, 250, and 500 beds with a capacity volume of 150, 400, and 500 liters, respectively. A 500-liter system can disinfect over 60 PPE kits per cycle. On average, this accounts for a load-handling capacity of 80–380 kilograms per day.

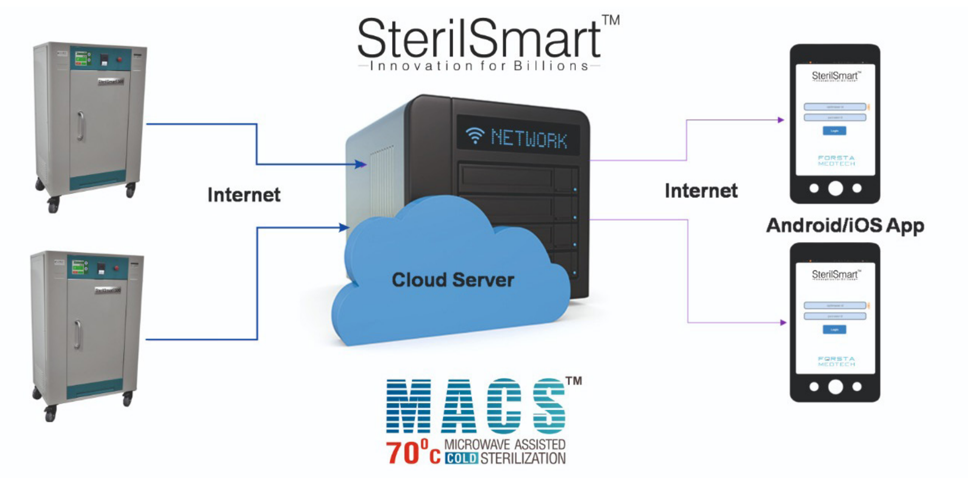
Each model has an easy-to-install plug-and-play unit with nine programmable applications. The models are also Internet-of-Things-enabled with hub connectivity. This allows the user to control the disinfection process through an app, which provides reports and alerts throughout the process.

SterilSmart meets several requirements of the Indian government, along with worldwide quality accreditations from the European Union, ISO 13485, Good Manufacturing Practice, Department of Scientific and Industrial Research, WHO-GMP, OHSAS 18001:2007, and NABL. In addition, it meets several international regulatory guidelines, including the Basel and Stockholm international conventions on managing medical waste.

Circularity mapping

Forsta Medtech's SterilSmart is an innovative decontamination technology that can be used for large-scale sterilization of PPE, at a high throughput, to make them reusable.

FIGURE 3.5: STERILSMART IS INTERNET-OF-THINGS-ENABLED



Source: Adapted from Forsta Medtech's website material.

TABLE 3.3: CIRCULAR DESIGN PRINCIPLES ADOPTED BY FORSTA MEDTECH

CIRCULAR PRINCIPLES	FEATURES	IMPLEMENTATION
Resource recovery and product use extension: SterilSmart makes PPE products reusable by sterilizing them	Decontamination technology	PPE kits and N95 masks can be sterilized and disinfected in bulk within a cycle time of 7–30 minutes

Circular inputs

COVID-19 PPE products offered

Biodegradable Packaging for Environment Public Company Limited was established in Thailand under the brand “Gracz” by Dr. Weerachat Kittirattanapaiboon, the Chief Executive Officer, who recognized the negative environmental impacts of single-use virgin plastic-based food packaging. Today’s conventional food containers may leach dangerous substances and chemicals into food that may cause health problems in the long run. The company produces biodegradable food and non-food containers, as well as health-care products such as kidney and urinal trays made of 100 percent natural fibers. It operates in a vertically integrated manner where agricultural waste is turned into natural fibers and then into the end product. In March 2020, Gracz began a new business line, applying its knowledge of the biodegradable packaging industry to PPE manufacturing. The company started producing biodegradable masks to respond to the market demand for non-medical masks and to address the problem of increasing waste from non-woven disposable masks.

Technical features of Gracz’s biodegradable masks

Mask production for non-medical use was initiated without seeking any medical-grade certification. As the market became saturated with non-medical masks, Gracz began researching how to produce N95-equivalent medical-grade masks, targeting hospitals and medical clinics as its main consumer group. The certification process to verify the masks’ filtration and breathability is in progress. Both Gracz’s non-medical masks and medical-grade masks are made of bagasse—a dry, pulpy fibrous material that remains after crushing sugar cane or sorghum stalks—which gives them a suitable texture for filtration and breathability. The medical-grade masks are single use while the non-medical masks can be sprayed with alcohol and reused up to five times. The masks are compostable in a natural environment and in landfills under humidity, up to a temperature of 40°C. Decomposition begins after 30 days, and the product is fully biodegraded within 60 days. Gracz avoids using polylactic acid—eco-friendly bioplastic—in its PPE production, as PLA is only compostable under industrial conditions requiring chemical additives and a higher temperature (68°C).

Circular economy feature: Circular inputs

Gracz uses 100 percent virgin agricultural waste that would otherwise have been burned or dumped as its material input to produce the fibers. The waste is treated in airflow halls in the factory to remove all bacteria before it is turned into natural fibers. In addition to using bagasse, the company is researching the use of other agricultural inputs to diversify its raw material supply, including rice straw, palm, and pineapple fiber.

The company adopts a clear circular economy model by using circular inputs. When disposed of or discarded in a landfill, its masks decompose naturally in 60 days under normal humidity and a temperature of up to 40°C and with the existence of bacteria, without requiring any extra efforts or additives. Through this decomposition, the masks are fully converted back into their natural elements, becoming a fertilizer for plants (see Figure 3.7).

Scalability

The availability of a long-term supply of agricultural feedstock is key to Gracz’s business model. This requires having bilateral, long-term supply agreements with vendors to source, pre-process, and transport the raw material to the manufacturing locations. Gracz was initially planning to expand its operations to other countries but securing the raw material supply proved to be a challenge. The company’s presence outside of Thailand is limited to technology partnerships in design and innovation with customers in France, New Zealand, and Poland. Gracz is developing sample masks for customers in these three markets that will be mass produced overseas.

Gracz aims to distribute its masks in Thailand as soon as it obtains the required certifications from the Thai standards authorities. The standards set forth by Thailand comply with 80 percent of the international standards. By improving the required performance of its masks, Gracz plans to meet the remaining 20 percent of requirements to be eligible to export its masks to the European Union and the United States.

FIGURE 3.6: GRACZ'S CIRCULAR ECONOMY APPROACH TO CONTAINERS

Source: Adapted from Gracz internal documents.

TABLE 3.4: CIRCULAR DESIGN PRINCIPLES ADOPTED BY GRACZ

CIRCULAR PRINCIPLES	FEATURES	IMPLEMENTATION
Circular inputs: Gracz masks are biodegradable	The masks are made of natural fibers derived from agricultural waste	The masks are naturally compostable under certain conditions without the addition of any chemicals

Lindström

Product as service

Product use extension

COVID-19 PPE products offered

Based in Finland, Lindström offers a wide range of textile rental services for different industries, including workwear, patient clothing, bed linen, and mats for health-care workers, as well as other products for pharmaceutical companies and food industries. The company has more than 80 laundry services in 24 countries across Europe and Asia, as well as its own manufacturing facilities. Lindström's unique workwear manufacturing concept, "Prodem," produces workwear based only on customer demand, helping to fight textile waste. With production being located close to customers, transporting and storing stock is also minimized.

In March 2020, when demand for specific health-care products suddenly spiked, the company was able to respond in a short period of time through Prodem. Prodem delivered over 30,000 additional health-care garments above its normal production rate during March and April 2020. In the same period, the facility also played a central role in Lindström's launch of a reusable face mask service.

Product technical features in terms of circularity

Lindström's rental service covers all stages—from sourcing the textiles (90 percent of its garments are Öko-Tex 100 certified), to design, garment laundry and maintenance, delivery to its customers, storage, and disposal, where the products are recycled at the end of their life.

A special laundry process is followed for infected workwear using special handling procedures, as well as thermal and chemical disinfection for microbes to ensure that the products are hygienic and sustainable. The company's products also comply with several ISO certifications.

The cleanroom garments are reusable, made of washable materials that generate minimal lint, and can be autoclaved. The company's standardized cleanroom service ensures that these garments are hygienic and properly washed and packed in an ISO-certified area.

Circularity mapping

Lindström is focused on creating a circular economy and reducing the negative impact on the environment that its products can have. To slow down the resource loops, the company minimizes textile waste by producing only on demand, providing digital solutions, and cross-using regional inventories. The company also works closely with companies to produce and use recyclable textiles—a sustainable and long-term solution—and is committed to reducing textile overconsumption.

In addition, Lindström is conserving natural resources by (i) optimizing laundry operations (by minimizing energy, water, and detergent consumption); (ii) recycling water in its laundry systems; (iii) optimizing delivery routes and loads; and (iv) recycling textile waste. For example, in the United Kingdom, Lindström opened a new sustainable laundry service in early 2021—the first of its kind in the region. The laundry service uses advanced technology to recycle all used water back into the water system to eliminate the discharge of wastewater.

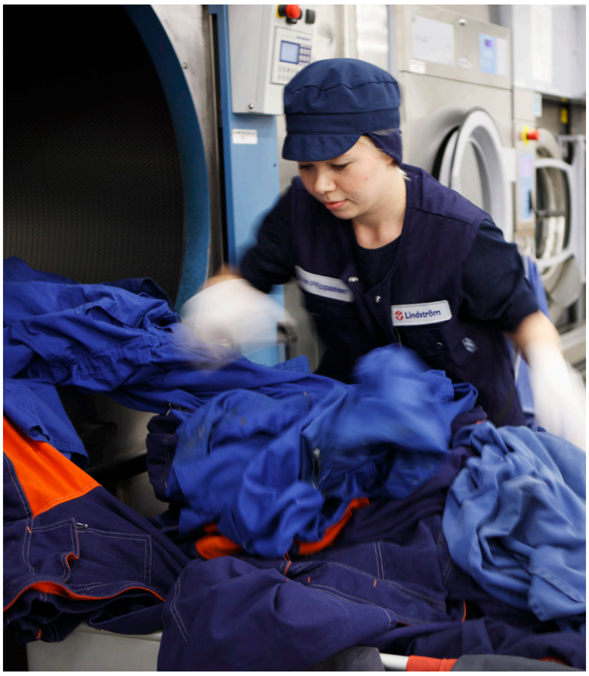


TABLE 3.5: CIRCULAR DESIGN PRINCIPLES ADOPTED BY LINDSTRÖM

CIRCULAR PRINCIPLES	FEATURES	IMPLEMENTATION
Product as service	• Providing laundry service for PPE • Providing rental service for PPE and industrial wipers	• The company offers laundry services and applies special disinfection methods to remove bacteria and dirt from workwear so that it can be reused • The workwear rental service allows Lindström to acquire the workwear, but also wash, maintain, repair, renew, and even store it on behalf of the client. The company also provides a rental service for industrial wipers and provides products to clients for the handling of industrial dirt and hazardous waste, and cleaning them after use
Product use extension	• Durable materials as input • Repairing and reusing garments	• The company uses durable materials to maximize a product's life • The company repairs and reuses garments for additional orders and for other customers. The company repairs over 4.5 million garments each year

BOX 3.3: FROM MARINE POLLUTION TO PPE PRODUCTION

Resource recovery

Cyrill Gutsch was running a design firm in the United States focused on brand strategy and innovation when he began to notice how climate change and pollution—particularly as a result of plastic waste—around the world was destroying the most important ecosystem on this planet: our oceans. In 2012, Parley for the Oceans was created from the understanding that we—creators, brands, think tanks, and consumers—all have a role to play in collaboratively addressing environmental problems for both present and future generations.

Parley tackles marine plastic pollution, which it is intercepting in the Maldives and 30 other countries around the world, through two methods.

The **shield method** entails intercepting plastics before they enter the marine environment by installing shields in areas where plastic is being mismanaged and ends up in the ocean.

The **rescue method** entails removing plastic such as discarded fishnets and cargo nets from the marine environment, beaches, and reefs, including by conducting floating and underwater cleanups.

Face shields made from plastic debris

During the pandemic, to respond to the immediate PPE shortages for health-care workers, Parley designed face shields made from plastic debris collected from remote islands, coastlines, and beaches. In this way, the plastic waste is repurposed to protect human health and wildlife instead of polluting marine environments. It selected 3D printing as the production method due to its speed and ability to make products on a small scale.

Parley collaborates with Nagami Design, a Spanish 3D printing company that had put its furniture production on hold to focus on supplying health-care workers with PPE. Parley and Nagami Design distributed the face shields to hospitals in Spain and the United Kingdom as a pilot project. Nagami Design has continued with the project in Spain. It currently prints around 500 protective face shields a day in Spain, or one every five minutes, for security forces and health-care workers on the frontline. The latest version of the open-source shield is created from polyethylene terephthalate (PET) plastic intercepted in the oceans and made into plastic sheets, before being shaped and finally paired with a 3D printer.

Conventional technology methods of production can be slow and often require creating mold forms, installing machinery, and large-scale investments. Nagami Design, on the other hand, has integrated a circular economy approach in the design phase by avoiding the use of multiple materials, making it easier to shred and recycle the face shields at the end of their life.

Parley's future vision is to establish local manufacturing sites that can convert trash rapidly into items of need. Once the sites are established, the organization will be able to print standardized product designs.

Closing the loop

The common challenge that organizations like Parley face in closing the loop and adopting full circular economy approaches is ensuring that collected plastic products are taken to recycling facilities.

To ensure the end-of-life recycling of the face shields, Parley and Nagami Design are working on a new project to adopt a systematic approach to reverse logistics. This involves introducing a QR code on each product that would provide a unique identification number. To complement the QR code, they are also releasing a software application where anyone who buys the item can register it and send it back after use. Eventually, this system will ensure that the loop is closed by integrating a systemic recycling process.

In addition, more manufacturers are exploring using recycled materials in production rather than virgin plastic. Many brands are investing in research and development to produce primarily durable but also recyclable products.

Thus far, the focus has been on providing PPE for health-care workers, security staff, educational staff, and other professionals who are exposed to potential risks due to their line of work in the Caribbean, Europe, and South Asia. However, this method of 3D printing products from plastic waste can be replicated in any country in the world where waste debris is close to the areas in need. Speed is the main advantage in producing this PPE. Although Parley started PPE production with face shields, it is possible to produce other types of PPE using 3D technology. It is also feasible to establish production sites with additional investments in key regions and government support. In fact, the establishment of an end-to-end collection system with government support will make it much easier to upcycle plastic waste feedstock for 3D printing at production sites.

Parley's other partnerships

In addition to making face shields from marine plastic waste, Parley for the Oceans is a parallel financing partner of the World Bank's International Development Association and the South Asia Co-operative Environment Programme on a first-of-its-kind $50 million regional project, "Plastic free Rivers and Seas for South Asia," which aims to combat marine plastic pollution and scale eco-innovation across South Asia. The project, which is organized around the avoid, intercept, redesign strategy, will coordinate and accelerate South Asia's transition to a circular economy through investment and collaboration between the public and private sectors, and regionally across countries.

NANOSAFE

Product use extension

COVID-19 PPE products offered

Launched in October 2019, Nanosafe Solutions Pvt Ltd is a technology start-up that strives to develop cost-effective nanotechnology-based innovations in collaboration with the Indian Institute of Technology Delhi. Following the outbreak of COVID-19, it applied its AqCure technology (patent pending), which uses active copper to kill microbes, to develop an anti-viral and reusable mask: NSafe. NSafe was developed in April 2020 and launched in the COVID-hit market just one month later.

Nanosafe Solutions launched three types of COVID-19 reusable masks: two that are washable and reusable up to 50 times, and a low-cost version that can be washed and reused 20 times.

Product technical features in terms of circularity

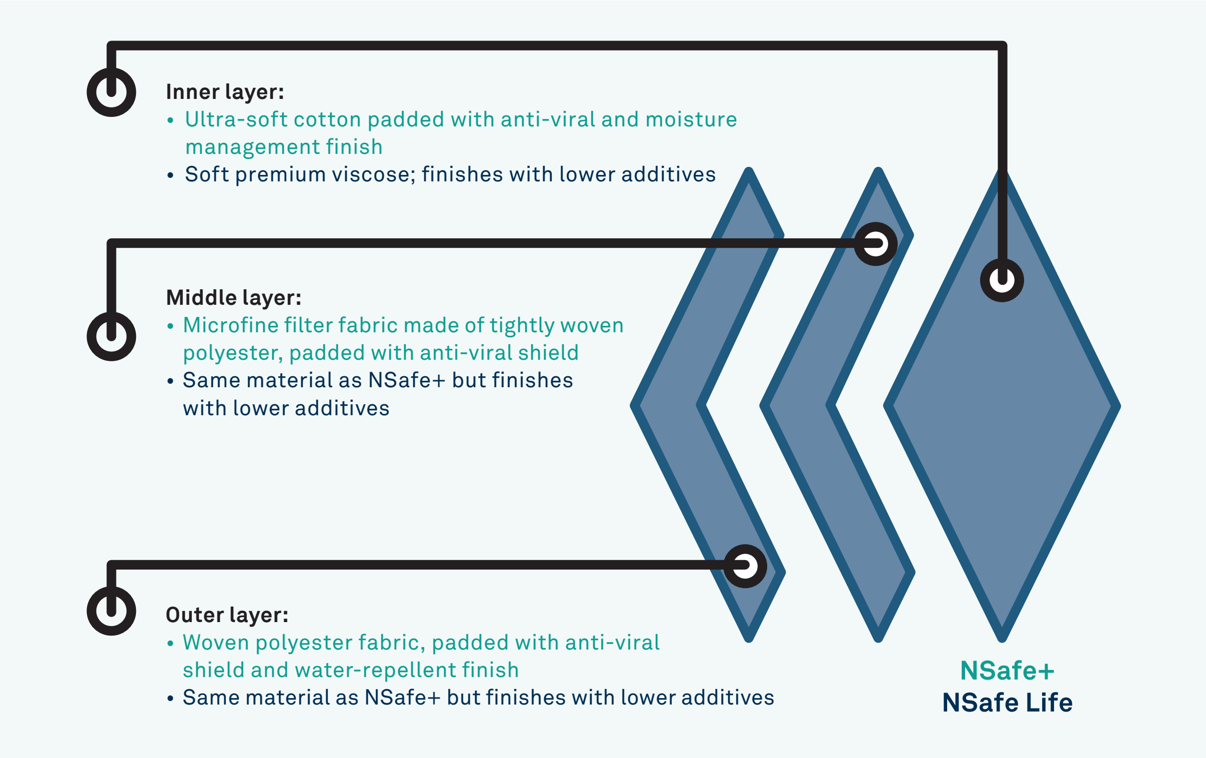
A key feature of the three masks is their self-sanitizing ability, using active copper technology. While the more expensive masks have the anti-viral finish on all three layers, the low-cost version only has it on the outer layer. A padding technique is used to apply the finishing on both sides of the fabric layers. Another feature of the masks is their reusability, which is made possible by using 100 percent woven polyester and cotton fabrics. All products fit tightly due to an additional elastic band (patent pending) in the chin region, with a supplementary neck adjuster.

All products are certified by the South India Textile Research Association, with bacterial filtration efficiency of 99.7 percent at 3 microns (ASTM F2101) and particulate filtration efficiency of 98.2 percent at 0.3 microns (ASTM F2100). Furthermore, the incorporated anti-viral finish is 98.23 percent effective against viruses, tested on the H1N1 flu strain, as per ISO 18184:2019. It is also more than 99 percent effective at inactivating SARS-CoV-2 within one hour and more than 95 percent effective within 30 minutes according to a modified ISO 18184 method.

Circularity mapping

Nanosafe products are reusable owing to their material choice, product design, and innovative self-sanitizing technology.

FIGURE 3.7: COMPOSITION OF NSAFE+ AND NSAFE LIFE MASKS



Source: Adapted from Nanosafe Solutions product brochure.

TABLE 3.6: CIRCULAR DESIGN PRINCIPLES ADOPTED BY NANOSAFE SOLUTIONS

CIRCULAR PRINCIPLES	FEATURES	IMPLEMENTATION
Product use extension: NSafe products are durable	• Designed for durability and efficiency while in use	• Better fit is ensured by an elasticated band in the chin region
Product use extension: NSafe products are reusable	• Self-sanitizing property • Washable material chosen to avoid single use	• The non-static, 100% woven polyester and cotton/viscose fabric makes the masks washable between 20 and 50 times

MAGNUM
MASKS & RESPIRATORS

Product use extension

COVID-19 PPE products offered

Based in India, Magnum Health and Safety manufactures surgical masks and National Institute for Occupational Safety and Health (NIOSH) approved N95 masks. During the COVID-19 pandemic, Magnum developed the Designo mask, which uses a specific fabric for the filter media that makes it reusable for up to seven washes.

Product technical features in terms of circularity

The design of the Designo masks, combining polyester in the outer layer and spunbond polypropylene in the inner layer, makes them reusable. The filter media in the middle layer—made through in-house research and development—is a melt-blown fabric combining polypropylene and polyester. The outer polyester layer is also splash resistant and available in various colors and designs to suit a variety of end user needs. The Designo masks have a filtration efficiency of more than 94 percent (FFP2 standard). They can also be reused after washing at 70°C without compromising the filtration efficiency for between five and seven washes.

Although no specific standards for reusability of masks have been developed yet, Magnum follows IS 9473:2002 (complying with EN 149)—related to particle filtration efficiency, breathability, and fit testing—for its reusable masks. All products are tested in a certified in-house testing facility.

FIGURE 3.8: EXAMPLES OF MAGNUM'S DESIGNO MASKS

Source: Magnum's product brochure.

Circularity mapping

Magnum's Designo masks are reusable owing to their material choice and product design.

TABLE 3.7: CIRCULAR DESIGN PRINCIPLES ADOPTED BY MAGNUM

CIRCULAR PRINCIPLES	FEATURES	IMPLEMENTATION
Product use extension: Designo masks are reusable	• In-house research and development of filter media made of a combination of melt-blown polypropylene and polyester • Outer layer is splash resistant and available in various print designs	• These breathable masks can be washed 5–7 times and reused without losing particle filtration efficiency or comfort

Product use extension

COVID-19 PPE products offered

Vadodara-based Sure Safety (India) Ltd was set up in 2004. Comprising four business verticals, the company provides over 5,000 customers with more than 2,200 PPE products, 20 services, and 15 safety, health, and fire training programs. With a research and development facility and presence in the PPE e-commerce sector through its own e-store, Sure Safety is a one-stop PPE solution provider. Building on its technology and expertise, it developed a first-of-its-kind reusable PPE kit during the COVID-19 pandemic in early July 2020: "Saviour."

Saviour is a full body protective coverall suit made of multi-laminated fibers and anti-static materials, along with exhalation valves. It has a battery-powered air protection system (PAPS) with a minimum battery life of four hours—a COVID-19-specific version of a powered air protection respirator originally designed for industrial use. The whole system is lightweight (about 3 kilograms) and compact (including the powered air purifier), so it can be easily transported. Another lightweight version, a powered air protection hood, designed only for head coverage, is also available.

Product technical features in terms of circularity

The key feature of Saviour reusable kits is the PAPS, which consists of a complete suit including a hood (with optically clear wide-vision visor) and booties, thereby providing complete body protection. The system has an in-built air pass or purifier system powered by a battery and operates with three P3 filter cartridges (a type of high-efficiency particulate air, or HEPA, filter), which take up air from the affected environment and purify it. The reusable suits are made of non-woven thermoplastic polyurethane and polyethylene-laminated breathable fabric, with seam joints ultrasonically welded and overlapped with sealing tapes. This makes Saviour, along with the visors, autoclavable after the purifier system is removed.

The P3 filters have a high filter efficiency (99.95 percent), tested in accordance with EN 143:1991. In addition, the fabric is tested according to IS 7016 Part I, II, and IV or ISO 2411 and ISO 811, ensuring viral non-penetration (equivalent to ASTM 1670 for synthetic blood penetration test and ASTM 1671 (ISO 16604:2004) for viral penetration).

Circularity mapping

Sure Safety's kit is reusable because its material choice makes it possible to autoclave, and the retrofitted PAPS ensures a long service life. Its filters are also replaceable.

FIGURE 3.9: QUALITIES OF THE SAVIOUR KIT

Source: Adapted from Sure Safety product brochure.

TABLE 3.8: CIRCULAR DESIGN PRINCIPLES ADOPTED BY SURE SAFETY

CIRCULAR PRINCIPLES	FEATURES	IMPLEMENTATION
Product use extension: Saviour kits are durable	• High air quality for users • Designed for durability and efficiency while in use	• In-built, mobile air pass and purification system • User-friendly, breathable fabric used, with indication system for filters
Product use extension: Saviour kits are reusable	• Material chosen to avoid single use	• Suit, including the visor, can be autoclaved for 100% disinfection • P3 filter cartridges are replaceable

THAI TAFFETA.CO.,LTD.
www.thai-taffeta.com

Resource recovery | Product use extension

Company profile

Thai Taffeta was established in Thailand 35 years ago as a vertically integrated textile facility involved in everything from raw material polymerization, to spinning, weaving, dyeing, and finishing. Twenty years ago, the company established partnerships with European textile mills to produce functional textiles for uniforms, including medical uniforms. The textiles are made from anti-static, anti-flammable, water-repellant, and high-tenacity fabrics. Currently, half of the company's output is sportswear fabrics, while the other half is textiles for uniforms.

Fifteen years ago, Thai Taffeta began using 100 percent Global Recycled Standard-certified yarn in response to demand for sustainable sportswear products from customers. This knowledge has been transferred to the production of medical textiles, with the main customer groups being hospitals and medical PPE wholesalers.

COVID-19 PPE products: Medical gowns

As a result of the COVID-19 pandemic, demand significantly increased for AAMI PB70 level-2 and level-3 medical gowns providing fluid droplet and virus penetration protection (see Table B.3, Annex B). Thai Taffeta produces both AAMI PB70 level-2 and level-3 surgical and isolation gowns that are washable and reusable. The gowns can be washed at 40–60°C with detergent and sodium hypochlorite, and sterilized or autoclaved at 121°C for 15 minutes. They must then be tumble dried at 80°C for 45–60 minutes (depending on the machine cycle) to avoid compromising the waterproof function.

The PPE gowns are made of two layers of high-density woven fabric and finished with a water-repellant coating that prevents any liquid leakage. The gowns can filter particles smaller than 0.1 microns at a 79 percent efficiency rate. In addition, there is an air barrier between the two layers to avoid penetration through the second layer of fabric if liquid or blood leaks through the first.

Design: Plan for product circularity

The PPE gowns are made of polyester from 100 percent recycled PET bottles and can be recycled back into polyester once they are washed and sterilized under pressurized steam. Level-2 gowns can be washed and reused up to 50 times and level-3 gowns up to 100 times because detergent with water effectively dissolves the fat membrane of the coronavirus and inactivates it for the gown's next use. However, to adopt this model, hospitals must have an efficient laundry system or a service provider to ensure used gowns are washed systematically. After they have been washed and reused by primary

TABLE 3.9: CIRCULAR DESIGN PRINCIPLES ADOPTED BY THAI TAFFETA

CIRCULAR PRINCIPLES	FEATURES	IMPLEMENTATION
Resource recovery: Product composition	• Use of recycled components • Choice of alternative, less resource-intensive, and non-toxic materials • Choice of materials that are recyclable at the end of the product's life	• Using recycled PET as input to produce polyester, the main material of the garment • 100% polyester design; no accessories; easy to recycle after reaching end of life
Product use extension	• Designed for durability and efficiency while in use • Designed to avoid single use • Deployment of circular business models and design of the products for sharing and second life	• A durable design that allows the product to be washed and reused 50–100 times • Reuse of product by secondary critical workers after it has been washed and reused 50 times

FIGURE 3.10: PPE SUIT PRODUCTION PROCESS

medical workers, level-2 and level-3 PPE gowns can be used by non-critical medical workers, clinic officers, and hospital technicians. As a pilot, one Thai hospital distributed washed and sterilized level-3 gowns to waste collection truck drivers to be used as anti-contaminate and dirt covers. Once the gowns reach their end, they are sent to a recycling facility to produce polyester again.

This circular model has been a compelling approach for hospitals to adopt during the pandemic. Through its gown design, Thai Taffeta is applying two circular design principles (Table 3.9).

A conservative cost-benefit analysis comparing the least expensive level-3 disposable PPE gown to the most expensive reusable one affirms that the reusable PPE gown is $6 cheaper after having been washed and used 50 times.

Success factors

Less Plastic Thailand, a private organization, has initiated a community campaign, “Separate PET Bottles to Help Doctors,” to increase PET bottle separation and collection rates among households. Thai Taffeta has joined forces with Indorama Ventures Public Company Limited—the world’s largest producer of PET with a substantial network of recycling units for post-consumer PET bottles—to contribute to this campaign by producing polyester for isolation gowns and coveralls.

Indorama Ventures’ factory processes the PET bottles into flakes and spins them into polyester yarn. Thai Taffeta then weaves the fabrics for the PPE gowns. Raising public awareness with support from Less Plastic Thailand and having the sector expertise and infrastructure in place were success factors for Thai Taffeta in relieving the PPE shortage and implementing a circular design during the pandemic.

Scalability

To implement Thai Taffeta’s circular model, it is crucial that (i) hospitals have an in-house laundry system or a service provider in place, (ii) there is a central or effective system for collecting plastics for raw material supply, and (iii) there is a recycling facility to produce yarn from the plastic bottles. A major challenge for producing recycled polyester from plastic waste is lack of knowledge on which product is recyclable. The gown itself can be reused and recycled over and over again, which is far easier than producing yarn from PET bottles. Closing the loop will depend on the end user’s preference: whether to send the gown to a recycling facility or dispose of it in a waste bin.

THERMAISSANCE
Smart Medical Clothing

Product use extension

COVID-19 PPE products offered

Started in India in 2016, Thermaissance specializes in nanotechnology in health-care textiles. It creates smart fabrics with anti-viral, anti-fungal, and anti-bacterial properties. In 2020, Thermaissance used its nanotechnology to develop self-sanitizing fabric that has been proven to inactivate coronavirus 229E (surrogate of COVID-19) by over 93 percent in five minutes and over 99.99 percent in less than an hour, thus reducing the risk of contact transmission.

Thermaissance used its technology to launch a complete range of reusable COVID-19 PPE products that include scrubs, coveralls, and surgical gowns for health-care professionals, doctors' lab coats, gloves, head covers, track jackets, and innovative patient suits. These products maintain a 99.99 percent kill rate efficacy even after 60 commercial washes, while the non-medical gloves and face masks can be gently washed up to 150 times.

Product technical features in terms of circularity

The key feature of Thermaissance's COVID-19 PPE products is their self-sanitizing ability using nanoparticles embedded in the yarn. When the coronavirus comes into contact with the fabric, Thermaissance's nanotechnology penetrates and ruptures the virus membrane, hindering its ability to thrive. In a similar way, the nanotechnology disrupts the membrane of bacteria, eventually killing the bacteria.

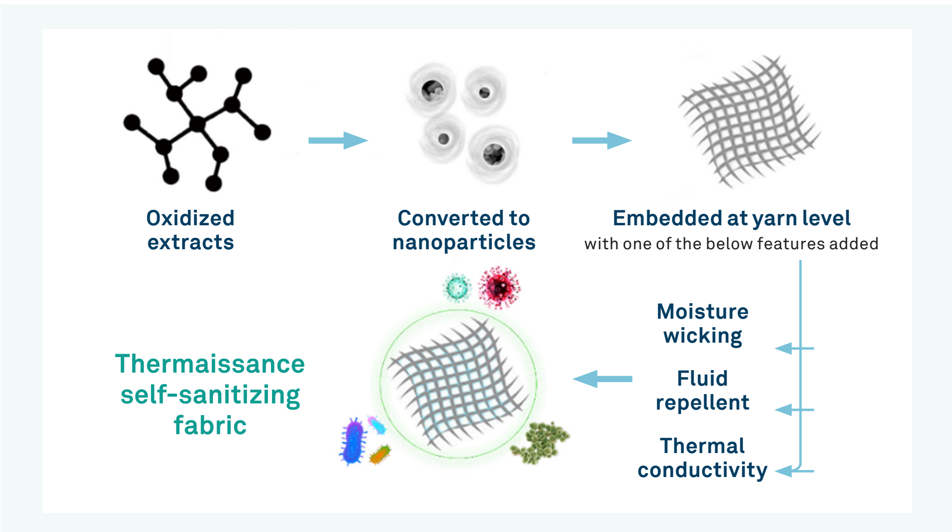
The self-sanitizing fabric is tested and approved for efficacy against coronavirus 229E as per ISO 18184 standards by US-based A2LA, an ISO 17025 accredited lab as mandated by WHO. This fabric is also tested and approved for efficacy against highly resistant bacteria such as MRSA, VRE, and CRE.

Made of diverse blends of polyester, nylon, and spandex, Thermaissance's fabrics (and thus their COVID-19 PPE) are washable. The fabric's anti-bacterial efficacy remains over 99 percent even after 60 commercial washes (or 150 gentle washes), with no dimensional change. In addition, its fabric is breathable at 26 pa/cm2 as per IS 16289, non-toxic, anti-fungal (< 1 CFU/gm) after 150 gentle washes, and splash resistant at 160 mm/Hg (as per ASTM F1862), as verified by the Indian-based NABL Laboratories. Other properties include moisture wicking, fluid repellence, and thermal conductivity. Thermaissance products are also autoclavable, as confirmed by NABL Laboratories.

Circularity mapping

Thermaissance's products are reusable owing to their material choice, product design, and innovative self-sanitizing technology.

FIGURE 3.11: PROCESS INNOVATION IN MAKING SELF-SANITIZING FABRIC



Source: Adapted from Thermaissance internal document.

TABLE 3.10: CIRCULAR DESIGN PRINCIPLES ADOPTED BY THERMAISSANCE

CIRCULAR PRINCIPLES	FEATURES	IMPLEMENTATION
Product use extension: Products are durable	• Designed for durability and efficiency while in use	• Fabric is breathable, anti-fungal, pH neutral, splash and pilling resistant, and dimensionally stable
Product use extension: Products are reusable	• Self-sanitizing property • Material used to avoid single use	• The non-static, polyester-nylon-spandex materials make the PPE washable up to 60 commercial/150 gentle washes and autoclavable • Active nanoparticles at the yarn level make the fabric anti-viral and anti-bacterial

Collective action toward sustainability and circularity in PPE manufacturing

PPE waste and pollution will continue to increase with growing demand

Despite vaccination rates going up, PPE remains critically important—especially for low- and middle-income countries where vaccination rates are slower. The emergence of virus variants will sustain demand for medical PPE across all countries in the short term. In the medium to long term, use of medical PPE will continue to increase[59] given its importance in protecting health workers. Demand for non-medical PPE (particularly masks) is also expected to remain higher than before, due to growing consumer awareness of hygiene.[60]

Most PPE is made of plastics and designed for single use: the manufacturing process generates greenhouse gas emissions and PPE waste can pollute waterways and other environments if not correctly disposed of. In "Transforming the Medical PPE Ecosystem,"[61] various global health organizations point to the urgent need for more innovation in PPE manufacturing to address the environmental impact and for improved PPE waste management to help transform the PPE ecosystem globally.

> "Today, there is no systemic approach for catalyzing PPE innovation that meets health-care workers' needs, and approaches to improving wearability, fit, and environmental impact are still rudimentary."
>
> —Rethinking PPE. 2021. "Transforming the Medical PPE Ecosystem."

[59] UK Foreign, Commonwealth & Development Office (FCDO). 2020. "COVID-19—PPE Demand and Supply Perspectives." Updated in March 2021. https://www.ifc.org/wps/wcm/connect/1d32e536-76cc-4023-9430-1333d6b92cc6/210402_FCDO_GlobalPPE_Final+report_v14updated_gja.pdf?MOD=AJPERES&CVID=nyiUnTU.

[60] FCDO. 2020. "COVID-19—PPE Demand and Supply Perspectives": In 2025, demand is estimated to reach about 185–235 billion units, from about 105 billion in 2019 (that is, almost doubling since the year before the pandemic), driven by enduring PPE use among the general public, an increasing global population, and continuing improvements in sanitary systems.

[61] Rethinking PPE. 2021. "Transforming the Medical PPE Ecosystem: Joint Action Can Protect Healthcare Workers with Effective and High-Quality Personal Protective Equipment." https://www.theglobalfund.org/media/11243/publication_ppe-synthesis_paper_en.pdf.

Urgent need for joint action

In moving toward more sustainable PPE, this report has presented examples of the various circularity approaches PPE manufacturers are adopting, including rethinking design for recyclable products and material substitution. These innovations are still at an early stage and face barriers to scale, including financial barriers to invest in research and development and business expansion; limited facilities to test whether "greener" products meet quality standards; policy gaps to limit the production and procurement of disposable PPE; general infrastructure shortages such as lack of adequate collection, decontamination, and recycling facilities; and lack of PPE waste management systems.

Joint action by all stakeholders—manufacturers, governments, municipalities, financial institutions, health sector and technology providers, standard institutions, and the general public—is needed to transition from small-scale innovation to widespread production and use of more sustainable PPE.

Creating demand for sustainable PPE

Moving toward sustainable PPE starts with a clear demand for it. During the COVID-19 outbreak in Europe, contracts totaling €12.6 billion were awarded to procure PPE.[62] By using their purchasing power to choose goods and services with reduced environmental impact, governments and health sector players can make an important contribution to shifting away from single use, plastic-based PPE. In OECD countries, an average of 29.3 percent of public procurement was spent on the health sector in 2019.[63] Similar to procurement incentives that are intended to support domestic PPE production, governments could include sustainability criteria to help generate more demand for sustainable PPE. This would further spur innovation efforts among PPE manufacturers, including in materials development.

Standardization efforts for sustainable PPE

When replacing plastics with alternative materials, manufacturers must ensure that the materials meet all scientific quality standards that are set by standards institutions and enforced by governments. Standards institutions play an integral role in improving standards that meet both technical requirements for medical and non-medical use. They can introduce guidelines for collecting, handling, and sorting used PPE and contribute to the adoption of national standards for PPE recycling and reuse. Governments can improve testing capacity to test and verify adherence to the standards.

Mobilizing finance to scale up innovation

The company profiles in this report illustrate ongoing innovation in the materials industry to use plastic substitutes and increase the durability and recyclability of PPE. Governments and foundations can support innovation, including through competitions to develop proof of concept and move from small-scale initiatives to scalable approaches. Financial institutions can finance companies to scale up proven solutions.

Integrated waste management systems

PPE waste puts pressure on current infrastructure capacities and causes contaminants to leak into the environment. Government investment in advanced waste technologies is needed to complement conventional systems with decontamination and recycling steps to maximize the value from discarded PPE. In addition, procedures for segregation, collection, transportation, and disposal of waste require regulatory frameworks that provide clear accountability for hospitals, businesses, households, and municipalities.

Commitment from all stakeholders

The case for transforming the medical PPE ecosystem is clear. Some initiatives are already under way, but it will require commitment from all stakeholders and sustained investments in the entire value chain, from procurement to waste management. Joint action will require decision-makers in the public and private sector to come together to design, procure, manufacture, and use PPE that protects health-care workers, the public, and our planet.

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62 https://www.occrp.org/en/coronavirus/europes-covid-19-spending-spree-unmasked.

63 OECD. 2021. *Government at a Glance 2021*. Paris: OECD Publishing. https://doi.org/10.1787/18dc0c2d-en.

Annex A:
Overview of circular economy approaches applied by PPE manufacturers[64]

Table A.1 outlines PPE manufacturers that have adopted a circular input approach.

TABLE A.1: PPE MANUFACTURERS USING CIRCULAR INPUT APPROACH

MANUFACTURER	HEADQUARTERS	PRODUCT	CIRCULAR INPUT	HOW?
Ahlstrom-Munksjö	Finland	Medical textile	PLA, manmade cellulose	TenderGuard BioBased and BioFilter for medical and non-medical face masks. TenderGuard BioBased is made of PLA and is biodegradable and compostable under controlled conditions according to European Norm EN 13432. The fibers used in the filter media are 100% bio-based. These single-use filter media are used for reusable face masks and are composed of three combined layers that meet EN 14683:2019 Type I & II standards and offer 98% bacterial filtration efficiency
Biodegradable Future, Filtech	South Africa (Biodegradable Future), China (Filtech)	Masks	Bio-degradable plastic	Biodegradable Future developed an additive for plastic that makes it naturally biodegrade when it comes into contact with microbes in landfills, the ocean, or soil. Initial production rollout focused on surgical, FFP2, and FFP3 masks while moving to a full biodegradable offering of PPE https://biodegradablefuture.com/blog-post/filtech-collaborates-with-biodegradable-future-to-produce-biodegradable-ppe/
Eco Gloves, Digital Media Vending	United States	Gloves	Cornstarch and vegetables such as cassava, sugar cane, and other bio-based proprietary components	The biodegradable gloves are made from 100% home-compostable and eco-friendly material, which can decompose in 90 days. An embossed surface prevents pathogens from quickly adhering to the glove, which is latex-free, BPA-free, and powder-free https://ecogloves.co https://www.digitalmediavending.com
E-TEX KAWACH	India	Masks	Cotton	The masks' outer and inner layers are made of a fine gauge bio-washed cotton fabric, which makes the product about 95% biodegradable

[64] The tables in Annex A provide an overview of the 11 companies included in Chapter 3 and other companies that take a similar circular economy approach. The companies included in the annex that are not profiled in Chapter 3 were not interviewed for this publication. The information on their circular economy approaches was retrieved from publicly available sources (such as their websites, brochures, and blogs). IFC does not endorse or recommend any products, processes, or services without undertaking technical assessments of them.

TABLE A.1: PPE MANUFACTURERS USING CIRCULAR INPUT APPROACH *cont...*

MANUFACTURER	HEADQUARTERS	PRODUCT	CIRCULAR INPUT	HOW?
Géochanvre	France	Single-layer masks	Hemp	The biodegradable single-layer mask is made primarily from compressed hemp. It has a corn-blend lining for comfort and a recyclable elastic band https://www.geochanvre.fr https://www.geochanvre.fr/masque
Gracz	Thailand	Masks	Bagasse	The bagasse masks are compostable in a natural environment and in landfills under normal humidity, at a temperature of up to 40°C, in 30 to 60 days
Plastic Planet, Reelbrands, Transcend Packaging	United Kingdom	Face shields	Wood pulp	Reelbrands' face shields (produced in partnership with Plastic Planet) are made from FSC-certified paper board and cellulose extracted from PEFC-certified renewable and sustainable wood pulp. The face shields are both recyclable and home compostable and certified to circular economy standards. In collaboration with TerraCycle, the face shields are collected from dedicated disposal bins and recycled or composted https://aplasticplanet.com https://reelbrands.co.uk https://transcendpackaging.com
Welmed	United States	Isolation gowns	Bio assimilative polyethylene	GoGreen Biodegradable Thumb Loop isolation gowns are made of polyethylene that bio assimilates (breaks down into organic elements without remaining microplastics) naturally and fully decomposes in six months in landfills. They meet Association for the Advancement of Medical Instrumentation (AAMI) Level 3 standards for spray impact penetration of less than 1 g and hydrostatic pressure over 50 (cm water) https://welmed.us

Table A.2 outlines PPE manufacturers that have adopted a resource recovery approach.

TABLE A.2: PPE MANUFACTURERS USING RESOURCE RECOVERY APPROACH

MANUFACTURER	HEADQUARTERS	PRODUCT	RECYCLE/ UPCYCLE/ DOWNCYCLE/ ENERGY RECOVERY	HOW?
Marion Förster	Netherlands	Isolation gowns	Upcycle/Recycle	The recyclable gown is made of polyester from recycled PET
Shayya	India	Bedrolls	Upcycle	Shayya produces eco-friendly bedrolls, mattresses, and pillows for COVID-19 patients in first-line treatment centers. The products are made by upcycling industrial scraps of the material used to make PPE gowns http://shayya.in
Thai Taffeta	Thailand	Isolation gowns	Upcycle/Recycle	PET is recycled at a recycling facility to produce polyester and then yarn for isolation gowns (upcycling). The used isolation gowns can be collected and sent back to the recycling facility to produce polyester again. This has been piloted but remains limited due to the lack of a take-back mechanism

Table A.3 outlines PPE manufacturers that have adopted a product use extension approach.

TABLE A.3: PPE MANUFACTURERS USING PRODUCT USE EXTENSION APPROACH

MANUFACTURER	HEADQUARTERS	PRODUCT	HOW?
Ahlstrom-Munksjö	Finland	Medical textile	The company integrates innovative technologies in its design and production to extend the service life and performance of its products
Ascend Performance Materials	United States	Masks	Acteev Protect non-woven masks are reusable general-purpose masks with active zinc ion-based anti-microbial technology with anti-bacterial, anti-mold, and anti-odor properties. These durable and breathable masks can be washed 50 times https://www.ascendmaterials.com
Bioinicia, 4C Air, DiPole Materials	Spain, United States	Masks	Use of nanofibers makes the masks more comfortable, allowing them to capture aerosol droplets more effectively while providing additional breathability with the same filtration efficiency https://bioinicia.com https://4cair.com https://www.dipolematerials.com
Marion Förster	Netherlands	Isolation gowns	The gown is coated with a nanotechnology chemical that inactivates SARS-CoV-2 viruses and provides level-4 protection. It can be used up to 100 times by applying a chemical disinfectant
Nanosafe Solutions	India	Masks	The masks are made of a non-static, 100% woven polyester and cotton/viscose fabric that allows them to be washed between 20 and 50 times
Open Standard Industries	United States	Respirators	Consisting of a medical-grade plastic filter compartment and a silicone facepiece, the respirator can be dissembled and recycled at the end of its service life
Thai Taffeta	Thailand	Isolation gowns	The isolation gowns are designed to be autoclaved and reused up to 100 times by health-care workers

Table A.4 outlines PPE manufacturers that have adopted a product-as-service approach.

TABLE A.4: PPE MANUFACTURERS USING PRODUCT-AS-SERVICE APPROACH

MANUFACTURER	HEADQUARTERS	SERVICE OFFERED	HOW?
Lindström	Finland	Reusable face mask service	Reusable face mask service for non-medical PPE guarantees microbiologically clean textiles as per European Union standard EN 14065. Infected workwear is laundered using special handling procedures and thermal and chemical disinfection to ensure that the products are hygienic and sustainable
SDI	Netherlands	Digital supply chain technology platform: PPE as a service	SDI's ZEUS supply chain technology platform enables the company to offer PPE as a service by partnering with various PPE manufacturers (for example, SDI partners with Ascend Performance Materials to offer the Acteev Protect non-woven mask) https://www.sdi.com

Annex B:
COVID-19 PPE products

B.1 Raw materials of PPE products

COVID-19 PPE products are primarily made of plastics or other derivatives of plastics.

TABLE B.1: MAIN RAW MATERIALS OF PRIMARY PPE

MAIN COVID-19 PPE PRODUCTS	RAW MATERIALS REQUIRED FOR CONVENTIONAL MANUFACTURING
Masks and respirators	Spunbond non-woven fabrics[a]
	Melt-blown non-woven fabrics[b]
Coveralls, aprons, and isolation gowns	Coated or laminated polyethylene fabrics
	Composite fabrics[c]
Nitrile gloves	Nitrile rubber
Eye protectors	Polyethylene terephthalate (PET) and polyvinyl chloride (PVC)

a. Spunbond non-woven fabrics are made by spinning continuous filament fibers onto a moving belt in one continuous process. The continuous fibers come from polypropylene, polyester, and polyethylene raw materials that have been dried, melted, and extruded into a flowing polymer melt. After the spinning process, the polyester emerges as numerous thin filaments, which are then cooled, stretched, and solidified to consistent dimensions before being laid on the moving belt to form a mat.

b. Melt-blown non-woven fabrics are produced by extruding melted polymer fibers through a spin net or die consisting of up to 40 holes per inch to form long, thin fibers. These fibers are then stretched and cooled by passing hot air over them as they fall from the die. The resulting web is collected into rolls and subsequently converted into finished products.

c. Composite fabrics are fabrics produced from two or more materials.

Source: UK Foreign, Commonwealth & Development Office (FCDO). 2020. "COVID-19—PPE Demand and Supply Perspectives." Updated in March 2021. https://www.ifc.org/wps/wcm/connect/1d32e536-76cc-4023-9430-1333d6b92cc6/210402_FCDO_GlobalPPE_Final+report_v14updated_gja.pdf?MOD=AJPERES&CVID=nyiUnTU.

B.2 PPE product types and their certification standards

Masks

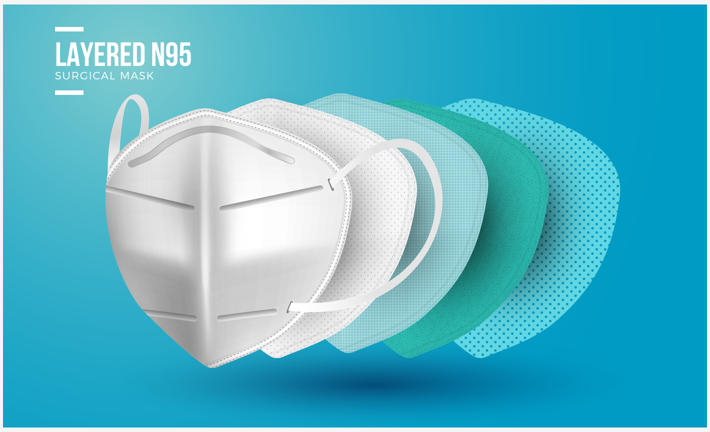
Three types of masks have been used during the COVID-19 pandemic (Figure B.1):

- **Three-layer single-use masks.** These masks are generally designed for non-medical use. They come in many varieties and vary in quality of fit and filtration. An effective mask should have two layers of tightly woven material fabric, such as cotton or linen. The third, middle layer should be a filter-type fabric, such as non-woven polypropylene fabric.
- **Three-ply surgical masks.** These masks are intended for medical use. They consist of three layers and filter out large particles. The outer layer typically has a non-toxic, water-repellent chemical polypropylene woven into it to protect against large droplets. The middle, melt-blown layer has an anti-bacterial filter. The inner layer is designed to absorb moisture from one's breath and to minimize skin irritation.
- **Respiratory masks (N95).** These masks are tight-fitting and create a facial seal that provides two-way protection. They are designed to efficiently filter airborne particles.

FIGURE B.1: TYPES OF MASKS USED DURING COVID-19 PANDEMIC

Three-layer single-use mask

Three-ply surgical mask



Respiratory mask

Some countries and regions have adopted certain standards that each mask type must conform to in order to be used (Table B.2). The standards focus on the filtration efficiency of each mask type and the size of the particles that each mask can filter.

TABLE B.2: A SAMPLE OF STANDARDS APPLIED BY CHINA, EUROPE, AND THE UNITED STATES FOR DIFFERENT MASK TYPES

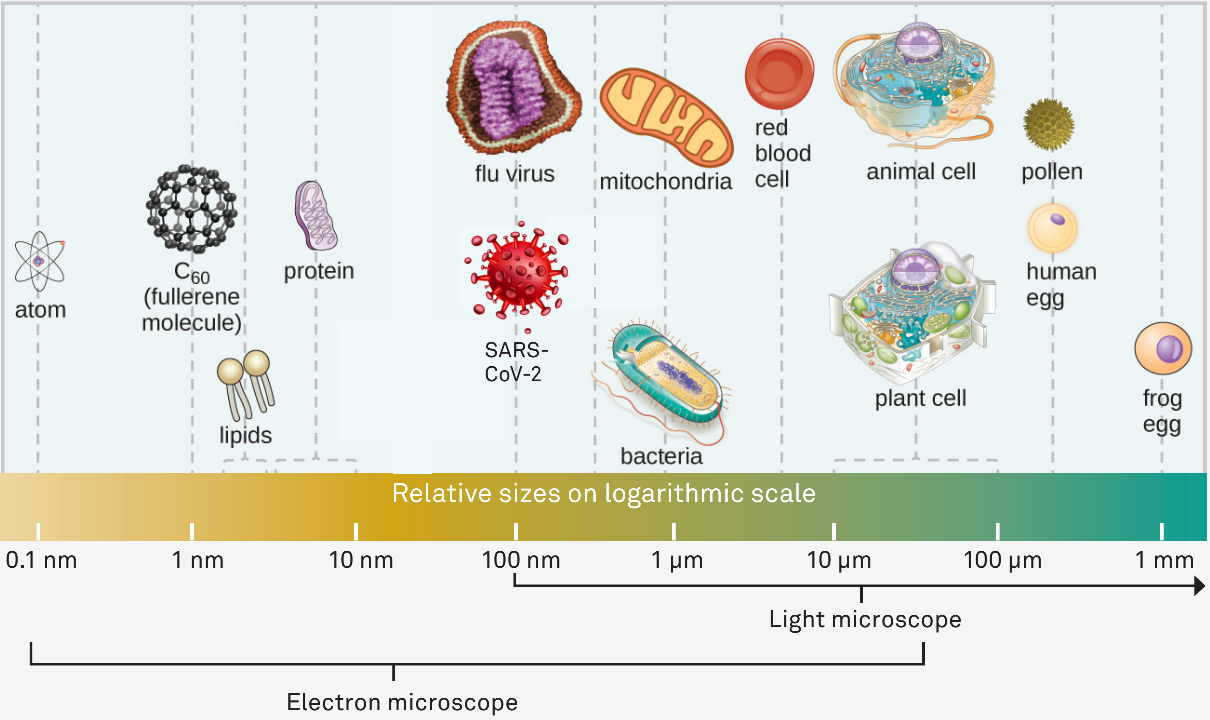
MASK TYPE	STANDARDS	FILTRATION EFFICIENCY		
Single-use masks	**China: YY/T0969**	3.0 microns: ≥ 95%		
		0.1 microns: ×		
Surgical masks	**China: YY 0469**	3.0 microns: ≥ 95%		
		0.1 microns: ≥ 30%		
	United States: ASTM F2100	**Level 1**	**Level 2**	**Level 3**
		3.0 microns: ≥ 95%	3.0 microns: ≥ 98%	3.0 microns: ≥ 98%
		0.1 microns: ≥ 95%	0.1 microns: ≥ 98%	0.1 microns: ≥ 98%
	Europe: EN 14683	**Type I**	**Type II**	**Type III**
		3.0 microns: ≥ 95%	3.0 microns: ≥ 98%	3.0 microns: ≥ 98%
		0.1 microns: ×	0.1 microns: ×	0.1 microns: ×
Respiratory masks	**United States: NIOSH (42 CFR 84)**	**N95/KN95**	**N99/KN99**	**N100/KN100**
	China: GB 2626	0.3 microns: ≥ 95%	0.3 microns: ≥ 99%	0.3 microns: ≥ 99.97%
	Europe: EN 149:2001	**FFP1**	**FFP2**	**FFP3**
		0.3 microns: ≥ 80%	0.3 microns: ≥ 94%	0.3 microns: ≥ 99%

3.0 microns: Bacteria filtration efficiency
0.1 microns: Particle filtration efficiency
0.3 microns: The most penetrating particle size—the most difficult particle to capture
x: No requirements

Source: Robertson, Paddy. 2021. "Comparison of Mask Standards, Ratings, and Filtration Effectiveness." *Smart Air* (blog), July 27, 2021. https://smartairfilters.com/en/blog/comparison-mask-standards-rating-effectiveness/.

Figure B.2 compares the size of various microscopic and non-microscopic objects. A typical virus measures around 100 nanometers (0.1 microns)—10 times smaller than a typical bacterium—and thus requires higher filtration abilities from masks.

FIGURE B.2: THE SIZE OF DIFFERENT TYPES OF PARTICLES



Source: Adapted from Parker, N., et al. 2017. *Microbiology.* OpenStax, Rice University, pp. 30.

Isolation and surgical gowns, coveralls, and aprons

Isolation gowns, surgical gowns, coveralls, and aprons protect the wearer from the spread of infection or illness if the wearer comes into contact with potentially infectious liquid or solid material. They are also used to help prevent the gown-wearer from transferring micro-organisms that could harm vulnerable patients. While isolation gowns are generally used for routine patient care in health-care settings, surgical gowns provide a higher level of protection and are generally used for surgical and other sterile procedures.

In 2004, the US Food and Drug Administration (FDA) recognized the American National Standards Institute/Association for the Advancement of Medical Instrumentation (ANSI/AAMI) PB70 standard, which classifies protective apparel and drapes intended for use in health-care facilities based on their liquid barrier performance. Table A.3 outlines the levels of protection, as well as the standards for each level.

TABLE B.3: CLASSIFICATION OF BARRIER PERFORMANCE OF SURGICAL GOWNS, ISOLATION GOWNS, AND OTHER PROTECTIVE APPAREL

LEVEL	DESCRIPTION	TEST CONDUCTED			EXPECTED BARRIER EFFECTIVENESS
Level 1	• Used for **MINIMAL** risk situations: Basic care, standard hospital medical unit • Provides a slight barrier to small amounts of fluid penetration	**Test**	**Liquid challenge**	**Result**	Minimal water resistance (some resistance to water spray)
		AATCC 42 impact penetration	Water	= 4.5 g	
Level 2	• Used in **LOW** risk situations: Blood drawn from a vein, intensive care unit, pathology lab • Provides a barrier to larger amounts of fluid penetration through splatter and some fluid exposure through soaking	**Test**	**Liquid challenge**	**Result**	Low water resistance (resistant to water spray and some resistance to water penetration under constant contact with increasing pressure)
		AATCC 42 impact penetration	Water	= 1.0 g	
		AATCC 127 hydrostatic pressure	Water	= 20 cm	
Level 3	• Used in **MODERATE** risk situations: Arterial blood draw, inserting an intravenous line, emergency room, trauma • Provides a barrier to larger amounts of fluid penetration through splatter and more fluid exposure through soaking than level 2	**Test**	**Liquid challenge**	**Result**	Moderate water resistance (resistant to water spray and some resistance to water penetration under constant contact with increasing pressure)
		AATCC 42 impact penetration	Water	= 1.0 g	
		AATCC 127 hydrostatic pressure	Water	= 50 cm	
Level 4	• Used in **HIGH** risk situations: Pathogen resistance, infectious diseases (non-airborne), large amounts of fluid exposure over long periods • Prevents all fluid penetration for up to 1 hour • May prevent virus penetration for up to 1 hour • In addition to the other tests conducted under levels 1–3, barrier-level performance is tested with a simulated blood containing a virus. If no virus is found at the end of the test, the gown passes	**Test**	**Liquid challenge**	**Result**	Blood and viral penetration resistance (2 psi)
		ASTM F1670 synthetic blood penetration (for surgical drapes)	Surrogate blood	No penetration at 2 psi (13.8 kPa)	
		ASTM F1671 viral penetration (for surgical and isolation gowns)	Bacterio-phage Phi-X174	No penetration at 2 psi (13.8 kPa)	

Note: AATCC = American Association of Textile Chemists and Colorists; cm = centimeter; g = gram; kPa = kilopascal; psi = pounds per square inch
Source: World Health Organization, COVID-19 Technical Specifications for Personal Protective Equipment and Related IPC Supplies.

In addition, the American Society for Testing and Materials (ASTM) F3352-19 provides standard specifications for isolation gowns intended for use in health-care facilities, while ASTM F2407 describes testing surgical gowns for tear resistance, seam strength, lint generation, evaporative resistance, and water vapor transmission. The standard specifications for each test are as follows:

- Tensile strength: ASTM D5034, ASTM D1682
- Tear resistance: ASTM D5587 (woven), ASTM D5587 (non-woven), ASTM D1424
- Seam strength: ASTM D751 (stretch woven or knit)
- Lint generation: ISO 9073 Part 10
- Water vapor transmission (breathability): ASTM F1868 Part B, ASTM D6701 (non-woven), ASTM D737-75

Gloves

Gloves are the most common type of PPE used in health-care settings. Most patient-care activities require the use of a single pair of non-sterile gloves made of latex, nitrile, or vinyl. Some facilities have eliminated or limited latex products, and now use gloves made of nitrile or other material.

Rubber surgical gloves must meet the ASTM D3577-19[65] standard requirements in the United States, while protective gloves must meet the ASTM D5250-19[66] requirements for polyvinyl chloride and rubber examination gloves.

Face and eye protection

Face and eye protection includes face shields, goggles, and visors. Face shields are used to protect the user's eyes and face from body fluids, liquid splashes, and potentially infectious materials. They should cover the forehead, extend below the chin, and wrap around the side of the face. Goggles, on the other hand, should fit tightly over and around the eyes or personal prescription lenses, be indirectly vented (to prevent penetration of splashes or sprays), and have an anti-fog coating to help maintain clear vision. According to ANSI/ISEA Z87.1-2020, lenses marked as having anti-fog properties must remain free from fogging for a minimum of eight seconds. The lens is typically made of plastic, commonly polycarbonate, and there is an adjustable elastic strap to allow a snug fit around the eyes.

Face shields intended for medical use in the United States are regulated by the FDA under 21 CFR 878.4040—Surgical apparel. These devices are classified as class I (general controls): devices that are not intended for use in supporting or sustaining life or of substantial importance in preventing impairment to human health. They may not present a potential unreasonable risk of illness or injury.

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65 ASTM D3577-19, Standard Specification for Rubber Surgical Gloves, ASTM International, West Conshohocken, PA, 2019, www.astm.org.

66 ASTM D5250-19, Standard Specification for Poly(vinyl chloride) Gloves for Medical Application, ASTM International, West Conshohocken, PA, 2019, www.astm.org.

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