



Single-use face masks and their alternatives

Recommendations from
Life Cycle Assessments

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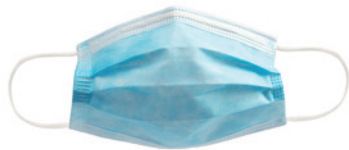
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Abbreviations

TERM	DEFINITION
COVID-19	Coronavirus disease of 2019 ('CO' for corona, 'VI' for virus, and 'D' for disease)
BFE	Bacterial filtration efficiency
EFL	Embedded filtration layer
EEA	European Environment Agency
FFP	Filtering face piece
FU	Functional unit
GWP	Global warming potential
LMA	Laryngeal mask airways
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MCI	Material circularity index
PET	Polyethylene terephthalate
PLA	Polylactic acid
PFE	Particle filtration efficiency
PP	Polypropylene
PPE	Personal protective equipment
UK	United Kingdom of Great Britain and Northern Ireland
UNEA	United Nations Environment Assembly
UNEP	United Nations Environment Programme
WHO	World Health Organisation

A note on terminology around face masks

In this report, face mask refers to a personal protective device covering the face, intended to prevent the transmission of COVID-19. The various types of face masks are commonly referred to in different ways around the world. In this report the term in bold as indicated below is generally applied (noting that it is considered inter-changeable with the other commonly-used terms for that type of mask). The only exception is in Section 2 when the specific findings of each LCA study are considered. There the terminology chosen by the study authors is used. Furthermore, “single-use masks” is taken to broadly cover both surgical masks and respirators in that they are intended for single-use, although it is noted that they may be worn more than once by some consumers. Similarly, “reusable masks” is taken to mean any mask designed to be washed and re-worn, while recognising that there is a possibility of only being worn once.



Surgical/Medical mask
(Single-use)

Multilayer mask made of three layers of non-woven fabric (polypropylene), typically pleated. Type I has a bacterial filtration efficiency > 95% and Type II > 98% (Type IIR is additionally splash resistant)¹. Type II/IIR is used in health care settings, with Type I recommended for use in community settings.



Respirator-type mask (e.g., FFP2/N95)
(Single-use)

Multilayer mask of non-woven fabric, typically cut to give a close fit around the face. Respirator-type masks are known by different names in their different markets, linking to the different national standards regulating the masks. E.g., in the US, masks are classified as N95 (95% particle filtration efficiency), N99 (99% filtration efficiency) and N100 (99.97% filtration efficiency)², and in China as KN95, KN99 and KN100 (with filtration efficiencies matching the US)³. In Europe, masks are classified as FFP1 >80% filtration efficiency, FFP2 >94% and FFP3 >99%⁴.



Fabric/Cloth/Community mask
(Non-medical, Reusable)

Fabric masks and reusable masks particularly intended for use by the general public (community masks) range widely in their design and effectiveness, from simple home-made cotton masks to commercially-produced multi-layer masks made from synthetic fabrics. While many are not tested, some commercially-made masks are certified for a particular filtration efficiency for a specified number of washes. E.g., under EN 14683:2019 (medical masks) or CWA 17553:2020⁵.

¹ In accordance with the European standard EN 14683:2019 Medical face masks. Requirements and test methods

² In accordance with the US federal regulation 42 CFR 84 - Approval of respiratory protective devices

³ In accordance with the Chinese standard GB 2626 -2019 Respiratory Protection—Non-Powered Air-Purifying Particle Respirator

⁴ In accordance with European standard EN 149:2001+A1:2009 Respiratory protective devices. Filtering half masks to protect against particles. Requirements, testing, marking

⁵ CEN Workshop Agreement (CWA) document - CWA 17553 Community Face Coverings - Guide to Minimum Requirements, Methods of Testing and Use. ftp://ftp.cenelec.eu/EN/ResearchInnovation/CWA/CWA17553_2020.pdf

Executive summary

CONTEXT

The widespread wearing of face masks has become a particular feature of the COVID-19 global pandemic, with many countries mandating or encouraging the wearing of face masks to help prevent the spread of the disease. Along with this, the waste disposal and pollution problems associated with single-use face masks are increasingly being highlighted in news articles and scientific research. Developing countries in particular are battling to manage this surge in plastic waste, with the pandemic exposing the fault lines in countries with waste management systems already strained or overwhelmed by single-use plastic products pollution. Globally, an estimated 3.4 to 4.2 billion face masks are discarded daily (Prata *et al.* 2020; Benson, Bassegy and Palanisami 2021). It is not known how many of these face masks are finding their way into the environment, although an increasing number of studies provide evidence this is occurring. A recent report estimates between 4,680 and 6,240 tonnes of plastic pollution arising from face masks entered the marine environment in 2020 (Phelps Bondaroff and Cooke 2020)⁶. It is thus apparent that face masks are a notable source of plastics in the environment. As with other plastic debris, once in the environment, masks pose a range of threats to ecosystems and wildlife, in addition to being an eyesore.

Reusable fabric face masks are a commonly used alternative to single-use face masks. Initially home-made cloth face masks (so-called “community masks”) were encouraged by governments for the general public to ensure sufficient supply of medical-grade face masks would be available for frontline workers. Now that shortages of single-use masks are no longer an issue in most countries, the use of reusable masks is mostly driven by environmental concerns, for some consumers, and affordability, for others.

To assist policy makers in making informed choices about the regulation of single-use face masks and their alternatives, this report is a meta-analysis that summarises current knowledge about the life cycle environmental performance of single-use and reusable face masks. Life cycle assessment (LCA) is a well-established tool for assessing the potential environmental impacts associated with a product or service. Especially valuable is an LCA’s ability to highlight areas of highest potential impact along the value chain and to highlight trade-offs between different impacts. Given that the widespread wearing of face masks globally is a recent phenomenon, only five published LCA studies on single-use and reusable face masks were available at the time of writing this meta-analysis. These studies are summarised in Table E1. To enrich the findings, the meta-analysis also draws on the wider LCA literature on single-use plastic products, textiles and medical equipment.

Important Note

The recommendations from this meta-analysis are limited to face masks used by the general public, that is, masks worn by private persons to limit the spread of the virus in public places (as opposed to masks worn by health professionals in a hospital setting). Furthermore, the meta-analysis covers only face masks and not face shields or other types of hard-plastic masks, and provides no guidance on the effectiveness of different face mask designs with respect to limiting the transmission of COVID-19.



The **waste disposal and pollution problems associated with single-use face masks** are increasingly being highlighted. **Developing countries in particular are battling to manage this surge in plastic waste**, with the pandemic exposing the fault lines in countries with waste management systems already strained or overwhelmed by single-use plastic products pollution.

⁶ This number is calculated from a global production estimate of 52 billion masks manufactured in 2020 and an assumption that 3% of global plastics production enters the oceans (Ritchie and Roser 2018). This amounts to 1.56 billion masks entering the oceans in 2020. Applying an average weight of 3 to 4 g polypropylene per mask, this results in 4,680 to 6,240 tonnes of plastic.

Reusable face masks generally have lower environmental impacts than single-use face masks

In general, reusable fabric face masks, especially those made from synthetic materials (polyester, polypropylene (PP) and/or elastane), have lower environmental impacts than single-use face masks, provided they are reused sufficient times (approximately 10 to 20 times)⁷. Cotton has relatively high environmental impacts due to the high use of water, land and agrichemicals in its cultivation.

The difference in environmental impacts between reusable cotton masks and single-use masks is therefore not as high as between reusable synthetic fabric masks and single-use masks. This means that cotton masks were not shown to have better environmental performance than single-use masks under all scenarios, e.g., if washed by hand. Reusable masks made from synthetic materials can also approach single-use face masks in terms of their effectiveness if they are manufactured in accordance with the WHO guidelines and/or relevant national standards.

Guidelines on reusable face masks

A number of countries and bodies have put together guidelines on the manufacture and use of reusable face masks*. The World Health Organization (WHO) interim guidance provides a synthesis of available national and regional guidance** and recommends that to be effective reusable face masks should be made of three layers of different types of fabrics:

- an absorbent inner layer, e.g., cotton
- a middle-layer with good filtration properties, e.g., spunbond polypropylene (PP)
- a water-resistant outer layer, e.g., polyester

Breathability, filtration efficiency, fit, coating and maintenance are essential considerations in the design and choice of materials for reusable face masks. The WHO recommend a particle filtration efficiency threshold of 70%.

The European committee for standardisation (CEN) Workshop Agreement*** considers two levels of particle filtration efficiency; >70% and >90%. Filtration efficiency must be maintained through the intended number of reuses (minimum of 5) with a minimum washing temperature of 60°C.

* See <https://www.iso.org/covid19-members> for a list of country-specific resources for ISO member countries.

** Mask use in the context of COVID-19: Annex: Updated guidance on non-medical (fabric) masks. Available at: [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](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)

*** CEN Workshop Agreement (CWA) document - CWA 17553 Community Face Coverings - Guide to Minimum Requirements, Methods of Testing and Use. Available at: ftp://ftp.cencenelec.eu/EN/ResearchInnovation/CWA/CWA17553_2020.pdf

⁷ Indicative range based on the relatively small number of studies covered in this meta-analysis. Not all studies do breakeven analyses, or only calculate breakeven on a single metric (most often carbon footprint). Furthermore, the number of reuses to breakeven is strongly related to whether masks are handwashed or machine washed, and whether masks are washed with the general household laundry in full machine loads (the latter is the case for the breakeven range indicated).

What drives the environmental impacts of face masks?

1. Number of reuses and washing practices

The number of times masks are used and how they are washed (e.g., in a fully-loaded machine) determine whether reusable masks are always more eco-friendly than single-use masks. Each time a mask is reused, the quantity of materials consumed per use of the face mask is divided over again, and so is its environmental impact. From the limited evidence available, it seems that **many consumers wear single-use face masks more than once**. Research also suggests it might be possible to decontaminate single-use face masks with low-impact strategies, such as setting them aside in dry air for a week. If such strategies are confirmed to be effective, then **re-wearing (decontaminated) single-use masks is potentially an environmentally competitive option along with reusable fabric masks**.

User behaviour has strong influence over the environmental impacts of reusable face masks. Because of the higher water and energy efficiency of a modern fully-loaded washing machine relative to hand washing, **reusable face masks washed in a fully-loaded washing machine are shown to be environmentally preferred to single-use face masks** (provided they are reused a sufficient number of times, typically around 10 to 20 times). This is not always the case if reusable masks are hand-washed or washed in a partly loaded machine (for the same number of reuses assumed in the studies). Washing temperature typically has a strong influence on the environmental impacts of reusable products. However, in the case of reusable face masks, washing masks in a fully-loaded machine (e.g., mixed with other household laundry) appears, for the time being, to be even more important than the washing temperature used⁸. However, since the WHO and most government and manufacturer guidelines recommend washing fabric face masks with detergent in water above 60°C, only two of the studies evaluated the influence of washing temperature on environmental impacts.

2. Materials used

The **materials used to make the masks and their overall weight are the primary source of their environmental impacts for both single-use and reusable masks**. Using **materials with lower environmental impact⁹** will lower the environmental impacts of face masks. This could be, for instance, the use of repurposed fabrics, in the case of home-made masks, or recycled materials, in the case of polyester used in reusable fabric masks. There is also potential to use recycled polypropylene in single-use and reusable masks; although it would need to be demonstrated that the use of secondary materials does not affect the efficacy of the masks. Two key findings emerge:

- › **Home-made reusable masks** made from repurposed fabric were shown to have the lowest environmental impacts but these are likely to be the least effective and most likely do not meet WHO or national guidelines. **Adding a filtration layer made of non-woven PP to two-layer cotton masks could be a solution for improving the effectiveness of reusable masks made from repurposed fabrics, while only marginally increasing their environmental impacts.**
- › **Commercially available reusable face masks** made from synthetic fabrics are next in terms of lowest environmental impacts. They would more likely comply with national and/or WHO guidelines than simple cotton masks and some might even adhere to other relevant standards and labels, e.g., the French AFNOR label and the Swiss TESTEX label.

3. Guidelines and standards on how to use the masks

As evident from the points above, international standards or government issued guidelines on how reusable (and single-use) masks should be used have important implications on the environmental impact of these products, as they influence users' behaviour. For example, a recommendation that reusable masks be discarded after



International **standards** or **government issued guidelines** on how face masks should be used, especially reusable face masks, **have important implications on the environmental impact of these products**, as they influence users' behaviour.

⁸ Note: this finding might be driven by the fact that only two of the studies considered in the meta-analysis evaluate the influence of washing temperature on environmental impacts, following the instruction of most guidelines that recommend washing fabric face masks with detergent in water above 60°C.

⁹ In LCA models, reused and recycled materials are typically given no or only a low share of emissions and resources, with the majority of emissions and resources attributed to the product that first required the materials.

only five washes does not seem to be rooted in evidence, with different standards having different limits (e.g., 20 times for the AFNOR standard), and testing on some masks showing filtration efficiency is maintained up to 50 washes. A requirement to boil masks is another contradictory example, with some guidelines recommending boiling to sterilise, while others discourage it on grounds that it is likely to degrade the fabric (and thus the filtration efficiency). WHO and most government and manufacturer guidelines recommend washing fabric face masks with detergent in water above 60°C. Such guidelines might need to be reconsidered if studies prove that washing at lower temperatures (e.g., 30-40°C), can guarantee the same level of health and safety.

4. Location of production vs. point of sale (transport)

Where the masks are manufactured and the subsequent transport impacts are also a significant factor in the environmental impacts of single-use face masks, if these are transported by air freight.

5. End-of-life disposal

Emissions from disposal of face masks are found to be, for the time being, a less important contributor to their life cycle impacts. This could be due to the fact that all the life cycle studies considered look only at formal waste treatment processes (incineration and landfill disposal), with none looking at the potential impacts masks would generate if disposed of inappropriately¹⁰. This is more notable for single-use than for reusable masks. The focus on formal waste treatment reflects the geographical context of Europe and Singapore (origin of the studies considered in the meta-analysis), where dumping and open-burning of waste are not prevalent; as well as limitations in data and methods to quantify impacts from litter.

ASPECTS TO CONSIDER IN LCA MODELS OF FACE MASKS

Based on the studies reviewed in the meta-analysis, the following **aspects** are important to consider when undertaking and interpreting LCAs of single-use face masks and their alternatives.

Functional equivalence and face mask options: LCA comparisons of single-use vs. reusable fabric masks are only relevant in a community setting (i.e., for mask wearing by the general public), since fabric face masks are recommended only as a last resort in a health care setting. There is a wide range in efficacy between different designs of reusable masks and between different types of single-use face masks, related both to their materials and their fit, which is not taken into account in LCA studies. Equivalency in function is however an important aspect of LCA studies, and studies should preferably compare masks that meet a stated minimum filtration efficiency (maintained over a specified number of washes) to ensure a reasonable degree of functional equivalence.

Behaviour of consumers: The limited data available suggests that consumer behaviour with regards to washing and wearing masks is far from the ideal or recommended behaviour. This is particularly important since the number of times reusable masks are washed and re-worn is critical in establishing their environmental preference to single-use face masks, as is how they are washed between uses. The fact that many single-use masks are being used multiple times is particularly noteworthy.

Modelling choices and choice of environmental impact indicators: As with behavioural assumptions, LCA modelling choices can have a large effect on the comparison of single-use and reusable face masks. E.g., whether energy credits (avoided emissions) are assigned to single-use face masks incinerated in waste-to-energy plants. The choice of environmental impact indicators against which the masks are assessed should cover all potential environmental impacts. Litter-related impacts, i.e., the environmental impacts of face masks ending up in the natural environment, are currently not covered by the standard suite of life cycle impact assessment indicators¹¹.

Geographical context: The available studies are limited in their geographic scope (UK, Switzerland, Italy and Singapore). Results are affected by factors that differ by geographic region, including electricity grid mix, transport to market, and waste management practices. Considerations of inappropriate waste management – which are not relevant in the geographical context of the studies included – are likely to be very relevant in affecting the potential environmental impacts of single-use face masks.

¹⁰ Only the study by Bouchet et al. (2021) highlighted the high plastic litter potential of single-use face masks through application of a “plastic leakage” indicator.

¹¹ Although research is ongoing to address this gap, E.g., the MarILCA project (<https://www.lifecycleinitiative.org/activities/key-programme-areas/life-cycle-knowledge-consensus-and-platform/marine-impacts-in-lca-marilca/>)

Table E1: Overview of LCA studies included in the meta-analysis

 The option with the lowest climate impact

Publication	Functional unit	Type (face masks used by the general public)		Geographic scope	Main conclusions
		Single-use	Reusable		
<p>The impact and effectiveness of the general public wearing masks to reduce the spread of pandemics in the UK: a multidisciplinary comparison of single-use masks versus reusable face masks</p> <p><i>Allison et al. 2020</i></p> <p>This study <u>compares cotton reusable face masks, with and without a single-use filter, with single-use surgical face masks</u>. Different use scenarios are considered for the cotton masks (2 and 4 masks in rotation, and masks washed by hand and in a washing machine).</p>	One year of face mask usage, with one face mask used per person per day.	Surgical masks	Cotton masks with single-use filter	UK (use and disposal), masks made in China	Reusable face masks without filter and washed in a washing machine have the lowest environmental impacts in all impact categories analysed other than water scarcity. Having a higher number of masks in rotation to allow for machine washing results in lower environmental impacts than having a few reusable masks requiring hand washing. Adding a single-use filter considerably increases the environmental impacts, although if machine-washed, they still have lower environmental impacts than an equivalent number of single-use face masks.
<p>Cotton and surgical masks—what ecological factors are relevant for their sustainability?</p> <p><i>Schmutz et al. 2020</i></p> <p>The aim of this paper is to identify the factors determining the environmental impacts of textile masks so that they can be designed in a more sustainable manner. <u>Surgical masks are compared with two-layered cotton masks</u> in a simplified LCA.</p>	One person wearing face masks during one working week when travelling to work on public transport and when going into a shop (five return public transport trips and three shop visits)	Surgical mask	Cotton masks (two-layered)	Switzerland (use and disposal), global production of masks	User behaviour strongly influences the relative environmental preference for the surgical and cotton masks. In the strict scenario (1 mask/day; lifespan 5 washing cycles) cotton masks are preferred to surgical masks for the carbon footprint (though to a marginal extent), while for the less strict scenario (1 mask/week; lifespan 15 washing cycles) cotton masks have a lower impact than surgical masks (except for water scarcity).
<p>Life cycle assessment of single-use surgical and embedded filtration layer (EFL) reusable face mask</p> <p><i>Lee et al. 2021</i></p> <p>This study <u>compares single-use surgical face masks to reusable face masks with an embedded filtration layer (EFL)</u>. The 3-layer EFL mask was developed in Singapore as an alternative face mask option for the general population.</p>	One month (31 days) of face mask consumption of one person	Surgical mask	Polyester masks with embedded filtration layer (3-layered)	Singapore (use, disposal and manufacturing, with materials sourced from China, Japan and Indonesia)	The reusable EFL mask has lower environmental impacts in all impact categories considered, other than water depletion, eutrophication and human toxicity. The number of uses for the reusable EFL mask to break even ranges from 8 days (fossil fuel depletion) to 20 days (freshwater ecotoxicity). Scenario analyses showed the better performance of the reusable EFL mask is strengthened further if masks are washed in a washing machine (instead of by hand) and both masks are landfilled (instead of incinerated ¹²).

12 The reusable EFL mask scored better than single-use when landfilled than if incinerated, because the study attributes energy credits to single-use masks if incinerated. More details are provided in the study itself and in Section 2.3.

Table E1: Overview of LCA studies included in the meta-analysis (continued)

 The option with the lowest climate impact

Publication	Functional unit	Type (face masks used by the general public)		Geographic scope	Main conclusions
		Single-use	Reusable		
<p>Engineering design process of face masks based on circularity and life cycle assessment in the constraint of the COVID-19 pandemic</p> <p><i>Boix Rodríguez et al. 2021</i></p> <p>The aim of this study is to minimise the negative impact of COVID-19 masks on the environment through developing a design guide outlining environmentally preferred design practices. <u>Three single-use masks (surgical and respirator-type masks) are compared with a fabric reusable mask and a rigid mask</u> with a disposable filter.</p>	<p>The use of a face mask compliant with UNI EN 149:2009 or UNI EN 14683:2019 standards. The face mask must be able to mitigate the release of respiratory droplets during the pandemic environment, for an Italian citizen for the period of one month</p>	Surgical mask	3D-printed mask with removable FFP2 filter	<p>Italy (use and disposal), with global and European production of masks</p>	<p>The reusable cloth face masks have the lowest environmental impacts across all impact categories considered, other than in ozone depletion and water consumption (in which the 3-D printed reusable masks with disposable filters have the lowest impacts). Based on the strengths of the two best-performing masks, the authors develop a prototype mask that has a rigid PP injection-moulded structure, and that, if used with washable reusable filters, has the potential to be the best performer across all environmental impact categories.</p>
		FFP2 masks with valve	<p>Masks made from polyester and PP (3-layered)</p>		
		FFP2 masks without valve			
<p>What is the environmental impact of different strategies for the use of medical and community masks? A prospective analysis of their environmental impact.</p> <p><i>Bouchet et al. 2021</i></p> <p>The aim of the study is to explore and <u>compare</u> the environmental impact of <u>eight different mask types</u> and use strategies used in the community in an attempt to provide recommendations on the best compromise between protection effectiveness and environmental impact.</p>	<p>To equip one person with a mask during a month</p>	Surgical masks used once, transported by sea	Cotton (made in China)	<p>Switzerland (use and disposal), surgical masks made in China, cotton reusable mask made in China, reusable polyester masks made in France or Switzerland</p>	<p>Home-made cotton masks and prolonged use of medical masks (through a wait-and-reuse strategy) have the lowest environmental impacts.</p> <p>Single-use medical masks transported by plane have by far the highest impact on climate change, with a global warming potential (GWP) more than double that of single-use medical masks transported by ship.</p>
		Surgical masks used once, transported by air	Home-made masks from repurposed cotton cloth		
		Surgical mask, reused 10 times, decontaminated by hot drying	Labelled polyester masks (AFNOR)		
		Surgical mask, reused 10 times, decontaminated by “wait-and-reuse”	Labelled polyester masks (TESTEX)		

RECOMMENDATIONS FOR POLICY MAKERS

Policy advice on face masks is particularly sensitive as it might have implications for the health and safety of citizens. It is therefore **imperative that the advice derived from this meta-analysis is only applied for face masks used by the general public, and where mask wearing is only one of a number of infection-control measures that should be followed**, such as social distancing and regular hand washing. Reusable cloth masks are generally not recommended in a health care setting.

Table E2 below plots the results of the LCA studies reviewed in this meta-analysis into an easy-to-read matrix that indicates the relative preference for the different face masks, based on waste management and behavioural contexts.

This meta-analysis recommends that, from an environmental perspective, policies on face masks for the general public (non-high risk individuals) should promote the use of reusable face masks. However, it must be kept in mind that the LCAs from which this recommendation is derived are not able to inform on the relative effectiveness of the face masks. The **environmental impacts of hospitalisation** can be very high, therefore wearing **effective masks**, to protect the wearer and those around them, **is the best option, since it avoids potentially very high environmental impacts of medical treatment.**

Countries deciding to promote reusable masks should work with international organisations (e.g., WHO, ISO, etc.) to **develop a widely agreed set of minimum performance standards for reusable masks to ensure effectiveness of reusable masks.** Such guidelines and standards should require producers of reusable masks to both meet a minimum effectiveness standard for protecting their population and maintain this performance for a specified number of washes¹³. Guidelines and standards on face masks should be regularly reviewed and based on best available scientific information.

With respect to the development of guidelines and standards, **studies on how mask design, maintenance and wearing practices in community settings affect health outcomes are strongly recommended.** Studies should take into account the particular country context and actual user behaviour. This is an urgent need since currently there is little understanding on how mask design and consumer behaviour with regards to the wearing, washing and disposing of masks affects the degree to which masks protect the wearer and those around them.

Studies investigating such aspects are needed in order for policy makers to be able to determine what sort of masks should be recommended in particular settings (with respect to their effectiveness in protecting the wearer and reducing the spread of viruses), and so to be equipped with the necessary information to weigh up the environmental benefits of reusable masks against single-use masks.

Policy makers should be aware of differences in environmental impacts between different fabrics and mask designs. Reusable face masks are shown to have lower environmental impacts under most scenarios, and do not have the high volumes of non-recyclable plastic waste and propensity for littering that single-use face masks have. Using repurposed or recycled fabrics or fibres has the potential to further improve the environmental performance of reusable face masks.

There are also a number of ways to improve the environmental impacts arising from single-use face masks. **Air-freight should be avoided** through better planning and/or local procurement of materials. **Much of the research and advice on improving the circularity of single-use plastic products is relevant also for single-use face masks**, including reprocessing them for reuse; and implementing advanced waste management technologies (e.g., recycling them into wastewater treatment filters, thickening agents and construction materials, or thermochemically converting them into petrochemicals). While advanced waste management options have been shown to be technically feasible, systems for the large-scale collection, transport and processing of masks still require development.

It is recommended to **improve monitoring and gathering of waste data on face masks**, as this would help in determining points of high littering and/or where interventions should be prioritised. For instance, installing waste bins in points of high littering (e.g., touch-free bins in grocery store and hospital parking lots, or waste bins with lids on quaysides in ports) might help reduce the number of masks that enter the environment.

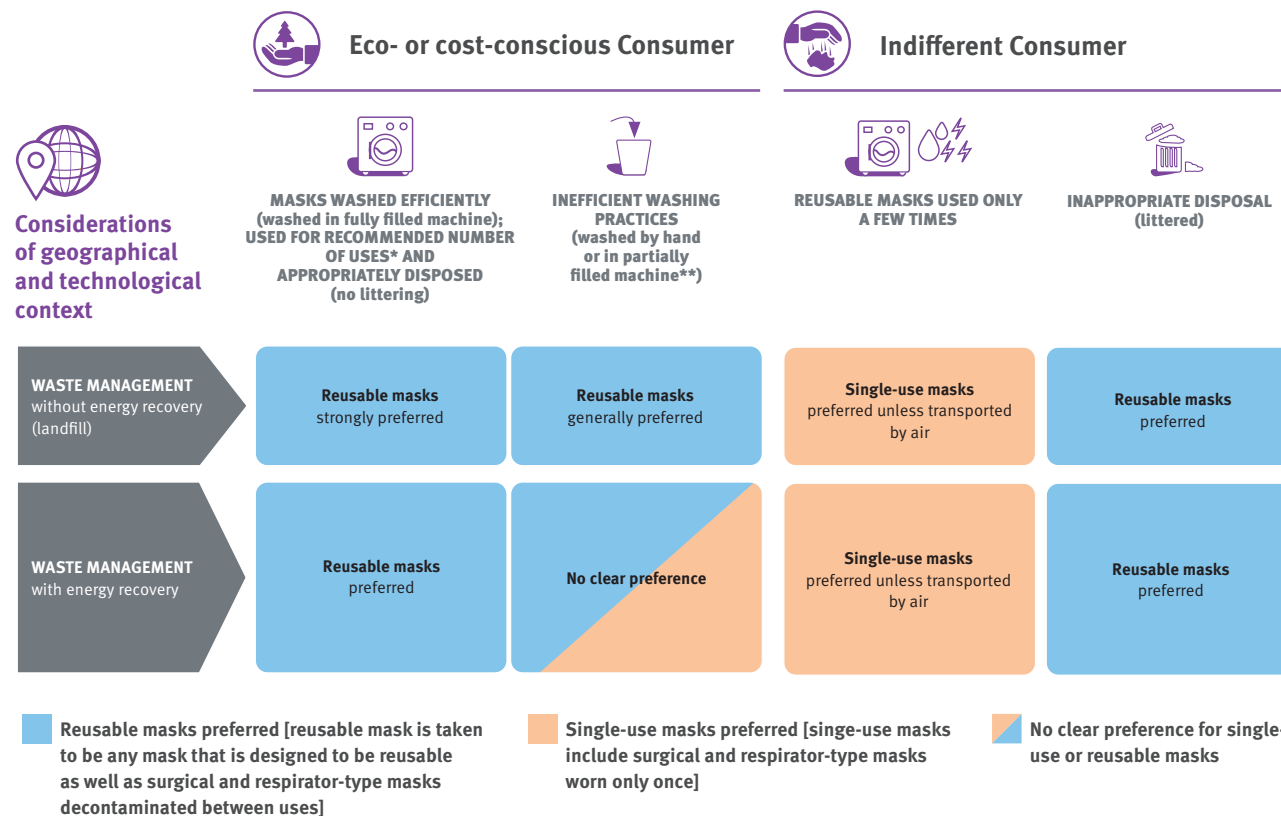
¹³ Noting that reusable masks need to be able to withstand a sufficiently high number of washes to have clear environmental benefits over single-use masks. This number is suggested to be between 10 and 20 uses (from the relatively limited evidence of the LCA studies included in the meta-analysis)

Table E2: Preferred type of face mask (for the general public) depending on behavioural considerations and waste management context

LIFE CYCLE ASSESSMENTS OF FACE MASK: WHAT THE SCIENCE TELLS US

Single-use or reusable face masks depending on waste management context and behavioural considerations

This matrix helps to identify the closest scenario and most environmentally sound options given a certain context and behavioural considerations. The content of the matrix is simplified. Please refer to the full narrative of the meta-study for details.



Very important Notes:

The recommendations in the matrix **are limited to face masks used by the general public**, that is, masks worn by private persons to limit the spread of the virus in public places, and where mask wearing is only one of a number of infection-control measures that should be followed, such as social distancing and regular hand washing. The matrix does not provide recommendations on masks worn by health professionals in a health-care setting.

To compare single-use and reusable masks with reasonably similar effectiveness, the **matrix recommendations should only be applied to reusable masks that conform to a relevant national standard¹⁴** and have a filtration efficiency of 70% or above (noting that home-made cotton masks and many store-bought fabric masks will not meet this requirement and users should be cautious in applying the matrix recommendations to such masks).

¹⁴ For example, EN 14683:2019 Medical face masks. Requirements and test methods and CEN Workshop Agreement (CWA) document - CWA 17553 Community Face Coverings - Guide to Minimum Requirements, Methods of Testing and Use.

- * Many commercially available reusable masks, especially those manufactured according to a standard, have a maximum number of washes specified to which the masks are guaranteed to retain their filtration efficiency.
- ** Regional and national guidelines recommend masks are washed at 60°C. The temperature at which masks are washed is found to be less important to environmental impacts than washing at full loads.



01 Introduction

1.1 BACKGROUND

Mask-wearing, in most parts of the world, has become synonymous with the COVID-19 global pandemic, with many countries mandating or encouraging the wearing of face masks as one of the front-line measures in preventing the spread of the disease (Al Jazeera 2020; Patricio Silva *et al.* 2020). This has resulted in a dramatic rise in the use of face masks by the general public. Alongside this a number of news articles (e.g., OceansAsia 2020; Kassam 2020), and an increasing number of reports and scientific articles (e.g. EEA 2021a; Ammendolia *et al.* 2021; Cordova *et al.* 2021; De-la-Torre *et al.* 2021; Okuku *et al.* 2021), are raising the waste disposal and pollution concerns associated with the wide-scale use of single-use face masks by the general public. For example, riverine debris monitoring data in the Jakarta Bay is finding unprecedented levels of personal protective equipment (PPE) made from plastics, with PPE accounting for 16% of the collected debris (Cordova *et al.* 2021)¹⁵.

This report focuses on single-use face masks and their alternatives, although it is recognised that face masks are just one component of the considerable plastic waste associated with the COVID-19 pandemic (EEA 2021a). Use of other single-use personal protective equipment (PPE) (e.g., gloves, aprons etc.) and medical plastics associated with testing and treating patients have also increased considerably over the pandemic (Haque *et al.* 2021). Furthermore, hygiene concerns have seen precautionary COVID-19 measures suspend or reverse single-use plastic products reduction policies in many countries (Prata *et al.* 2020), all putting an extraordinary strain on plastic waste management systems. Developing countries in particular are battling to manage a surge in plastic waste, with the pandemic exposing the fault lines in countries with waste management systems already strained or overwhelmed by single-use plastic products pollution (Arduzzo *et al.* 2021; Benson *et al.* 2021; Haque *et al.* 2021).

Estimates of the global usage of single-use face masks differ, from 52 billion per year (Phelps Bondaroff and Cooke 2020) to around 129 billion per month (Prata *et al.* 2020). It is not known how many of these face masks are finding their way into the environment, although an increasing number of studies are providing evidence this is occurring (Ryan, Maclean and Weideman 2020; Ammendolia *et al.* 2021; De-la-Torre *et al.* 2021). Around 3% of global plastics production is estimated to enter the oceans (Ritchie and Roser 2018). Applying this loss rate to face masks, it is estimated that 1.56 billion single-use masks could have entered the ocean in 2020, amounting to between 4,680 and 6,240 tonnes of plastic pollution to the marine environment (Phelps Bondaroff and Cooke 2020). This estimate uses a lower estimate of global face mask usage (52 billion per year) than that of the WHO (129 billion per month). It is thus apparent that single-use face masks have the potential to be a considerable source of plastics in the environment. As with other plastic debris, once in the environment, masks pose a range of threats including (De-la-Torre and Aragaw 2021):

- Wildlife can become entangled in the masks
- Wildlife can ingest the masks
- Masks broken down by mechanical and photo degradation processes into micro- and nano-plastics can become bioavailable and have detrimental effects on organisms
- Floating masks can become a vector of invasive species and microbial pathogens
- Masks can serve as a vector and source of chemical contaminants. A specific concern with face masks is that anti-viral coatings, such as textile fibres impregnated with Ag and Cu nanoparticles, could increase their negative impact on marine biota (Arduzzo *et al.* 2021)



It is estimated that **1.56 billion single-use masks** could have **entered the ocean in 2020**, amounting to **between 4,680 and 6,240 tonnes of plastic pollution** to the marine environment. *Phelps Bondaroff and Cooke (2020)*

¹⁵ This equates to over 500 masks per day at the monitoring sites, with face masks accounting for more than 60% of PPE debris.

Reusable fabric face masks are a commonly used alternative to single-use face masks. Initially home-made cloth face masks (so-called “community masks”) were encouraged by governments to ensure sufficient medical-grade face masks were available for frontline workers. Now that shortages of single-use masks are no longer an issue in most countries, the use of reusable masks is mostly driven by environmental concerns, for some consumers, and affordability, for others. Reusable face masks are also now widely commercially available, and come in a range of fabrics and designs.

A further development has been the emergence of performance labels that guarantee a specific filtration performance for a maximum number of washes, e.g., the French AFNOR label and the Swiss TESTEX label. The WHO recommends that to be most effective, a reusable face mask should be made of three layers of different types of fabrics (an absorbent inner layer, e.g., cotton, a middle-layer with good filtration properties, e.g., spunbond PP, and a water-resistant outer layer, e.g., polyester).

There is therefore a clear need to consider the environmental performance of alternatives to single-use face masks. *Resolution 9 of the fourth edition of the United Nations Environment Assembly (UNEA4) in March 2019, on “Addressing single-use plastic products pollution” (UNEP/EA.4/R.9)*, “encourages member states to take actions, as appropriate, to promote the identification and development of environmentally-friendly alternatives to single-use plastic products, taking into account the full life cycle implications of those alternatives” (UNEP 2019, p.2). The UN Environment Programme was requested by UNEP/EA.4/R.9 to make available existing information on the full life cycle environmental impacts of single-use plastic products compared to their alternatives.

Guided by UNEA4 resolution 9, this study aims to provide an insight into how life cycle assessment (LCA) can be used to make informed decisions on single-use plastic products and their alternatives. In particular, it addresses single-use (disposable) face masks and their alternatives. It is part of a *series of meta-analyses covering widespread single-use plastic products and their alternatives, including, bottles, take-away food packaging, beverage cups, tableware, nappies and menstrual products.*¹⁶



The WHO recommends that to be most effective, a **reusable face mask should be made of three layers of different types of fabrics** (an absorbent inner layer, a middle-layer with good filtration properties, and a water-resistant outer layer).

¹⁶ All of these reports are available from <https://www.lifecycleinitiative.org/single-use-plastic-products-studies/>

1.2 PURPOSE, SCOPE AND METHOD

This report aims to provide insights on how LCA can inform policy decisions on single-use face masks and their alternatives. The study is limited to face masks used by the general public, that is, masks worn by private persons to limit the spread of the virus in public places by reducing the range and volume of exhaled water droplets containing viral particles, as opposed to masks worn by health professionals in a hospital setting. Furthermore, the report looks only at face masks and not face shields or other types of hard-plastic masks.

The analysis looks only at the relative environmental impacts of single-use and reusable face masks. It is beyond the scope of this meta-analysis – and LCAs in general – to look at the efficacy of different face mask types and designs. This does not mean to say that understanding the effectiveness of masks in blocking the transmission of COVID-19 is not an essential consideration in any policy decision around face masks. Indeed, the need for a better understanding of how mask wearing in community settings affects health outcomes and the spread of viruses is identified as a critical need in Section 3.3. The evidence

of such studies – taking into account both the efficacy of the masks themselves and the influence of consumer behaviour on the effectiveness of masks – will need to be applied in conjunction with the life cycle environmental impacts of face masks to arrive at sound policy decisions.

The report is based on the review and analysis (meta-analysis) of the literature on single-use face masks and their alternatives available at the time of writing this report. Literature searches were performed on Web of Science, with further searches performed using Google Scholar and Google to ensure the literature search was comprehensive and included both academic literature as well as company- and industry-sponsored studies. Given that the widespread global wearing of face masks is a recent phenomenon, only five LCA studies on single-use face masks and their alternatives were found in the scientific literature. These studies are summarised in Table E1 and in Section 2.

The meta-analysis also draws on insights from the wider LCA literature on single-use plastic products, textiles and medical equipment to enrich the findings (see Section 3).



1.3 LCA METHOD IN BRIEF

Life Cycle Assessment (LCA) is a well-established tool for assessing the potential environmental impacts associated with a product or service, providing a structured framework within which to model its consequences on the natural environment and society. All stages of a product's life cycle are considered, from mining, extraction or growing of raw materials, to its manufacturing, distribution and use, right up to the final disposal of its components. LCAs have a number of benefits including:

- Creating awareness that decisions are not isolated, but that they influence a larger system.
- Promoting decision-making for the longer-term, by considering all environmental issues and potential knock-on effects associated with a decision choice.
- Improving entire systems, and not just single parts of systems, by avoiding decisions that fix one problem but cause another unexpected issue.

An LCA identifies the impacts and significance of each life cycle stage of the product analysed and makes possible comparisons with different products or systems and between different materials. International standards on LCAs (ISO 14040 and ISO 14044) divide LCAs into four main stages:

- **Goal and scope definition:** Objective (goal) and the methodological approach (scope).
- **Inventory analysis:** All raw materials and emissions (inputs and outputs) are considered for each of the unit processes that make up the life cycle of the product. Inputs include the use of natural resources, such as land and water, as well as manufactured materials such as fuels and chemicals. Outputs are released to air, water and land, as well as all products and by-products. Taken together these unit processes make up the life cycle system to be analysed, as defined by the product system boundary. The Life Cycle Inventory (LCI) is a comprehensive list of resources and emissions (inputs and outputs).

- **Impact assessment:** Assesses the life cycle inventory by connecting resources and emissions to their corresponding impacts on the environment and human health. In this way, the inputs and outputs are summed up into common areas of environmental concern, for example, impacts on human health, impacts on ecosystems, etc. This can be done at varying degrees of complexity, and a number of different Life Cycle Impact Assessment (LCIA) methods have been developed to quantify the potential environmental impacts of a product system.
- **Interpretation:** Findings are evaluated in relation to the defined goal and scope in order to reach conclusions and make recommendations.

It is important to note that although the LCA method is standardised, there is still room for a range of methodological choices that affect the results. Additionally, LCAs predict *potential* environmental impacts or damages, as the necessarily global nature of the predictive LCIA models means they do not take the site-specific environmental compartment into account. Life cycle inventory data (the basis for impact assessment) span multiple geographical locations across countries and continents in today's global supply chains, thus LCIA's predictive models are not like environmental impact assessment models that accurately characterise the actual risks associated with emissions at a particular location. Indeed, the value of an LCA study lies not so much with the final numbers, but rather with the exploration and consequent understanding of the system it assesses. **Especially valuable is the LCA's ability to highlight hotspots along the value chain** (i.e., showing the areas of highest potential impact), and also to **highlight trade-offs between different impacts**. It is seldom that one system or decision option performs better than another in all aspects of environmental impact. Understanding these trade-offs is a prerequisite towards improving the sustainability of product systems.



02 Meta-analysis of the studies

This chapter presents the main findings and results of the analysed LCA studies. For each study a short description is provided together with a summary of the results and main conclusions. This is followed by a tabular summary of the study, which presents further details on the products studied and highlights key assumptions. Results are summarised using colour coding to depict the relative performance of products across the impact indicators considered in the study. Note that the colour coding only denotes relative and not absolute impacts and the reader is referred to the original publication to appreciate the range and scale of the impacts calculated by the studies.

2.1 THE IMPACT AND EFFECTIVENESS OF THE GENERAL PUBLIC WEARING MASKS TO REDUCE THE SPREAD OF PANDEMICS IN THE UK: A MULTIDISCIPLINARY COMPARISON OF SINGLE-USE MASKS VERSUS REUSABLE FACE MASKS: ALLISON *ET AL.* 2020

This study compares reusable and single-use face masks in terms of their effectiveness to protect against COVID-19, taking into account behavioural considerations, their environmental impacts and their costs.

Material flow analysis and LCA were applied to explore the potential environmental impact of the whole UK population using either single-use masks or reusable cotton face masks for one year. The following face mask adoption scenarios were modelled:

- Single-use surgical face masks, disposed of at the end of the day
- Reusable cotton face masks, two masks in rotation, washed by hand 50 times
- Reusable cotton face masks with single-use filters, two masks in rotation, washed by hand 50 times
- Reusable cotton face masks, four masks in rotation, washed in machine (full-load wash with bulk household laundry) 30 times
- Reusable cotton face masks with single-use filters, four masks in rotation, washed in machine 30 times

The functional unit applied was one year of face mask usage, with one face mask used per person per day. The number of masks and filters required in each of the different scenarios is given in Table 1. Both the single-use surgical masks and

reusable masks are assumed to be manufactured in China and transported by air freight to the UK. For the reusable masks, the average household size in the UK (2.4 people) was applied to calculate the number of masks washed together (manual washing) and the frequency of a full machine wash (every three days). “Medium” washing machine energy efficiency and detergent use in accordance with manufacturer’s recommendations were assumed in the washing scenarios. An average disposal scenario representative of typical disposal destinations for UK household waste was modelled for both the masks and their packaging (see Table 1).

Summary of results and conclusions

Reusable face masks without a filter and washed in a washing machine generally have the lowest environmental impacts. Having a higher number of reusable face masks in rotation to allow for machine washing results in lower environmental impacts than having a few reusable masks requiring hand washing. The use of filters with reusable face masks adds considerably to their environmental impacts. Nonetheless, **even with a filter, machine-washed reusable cotton masks generally have lower environmental impacts than single-use surgical face masks.**

Wearing a machine-washed reusable mask (without filter) every day for a year generates 85% less waste, has 3.5 times lower impact on climate change and incurs 3.7 times lower costs than wearing single-use surgical face masks (for the particular UK conditions modelled in the study).



Wearing a **machine-washed reusable mask (without filter)** every day for a year **generates 85% less waste**, has **3.5 times lower impact on climate change** and incurs **3.7 times lower costs** than wearing single-use surgical face masks. *Allison et al. (2021)*

Table 1: Summary table: Allison *et al.* (2020) (continued)

		Products considered in study				
		Single-use surgical face masks	Reusable face masks, hand washed	Reusable face masks with single-use filter, hand washed	Reusable face masks, machine washed	Reusable face masks with single-use filter, machine washed
Study scope	Materials	PP (nonwoven) and cellulosic fabric Nose wire: HDPE Ear loops: polyetherimide	Cotton fabric Ear loops: polyetherimide	Cotton fabric Ear loops: polyetherimide Filter: PP (nonwoven), cellulosic fabric, carbon filter	Cotton fabric Ear loops: polyetherimide	Cotton fabric Ear loops: polyetherimide Filter: PP (nonwoven), cellulosic fabric, carbon filter
	Functional unit (FU)	One year of face mask usage, with one face mask used per person per day.				
	Use Scenario	Single-use	Hand washed in tub in warm (60°C) water, 50 washes (2.6 g soap and 2.5 l water per mask per wash)		Machine washed in full load at 40°C, 30 washes (0.16 g soap and 0.12 l water per mask per wash)	
	Number per FU	365	7 masks	7 masks, 365 filters	12 masks	12 masks, 365 filters
	Weight [g per mask]	2.68	14.4	Mask: 14.4 Filter: 1.19	14.4	Mask: 14.4 Filter: 1.19
	Geographic region	UK (use and disposal), masks made in China with air freight to UK				
	Life cycle stages	Cradle-to-grave				
	End-of-life	43% landfill, 41% incineration with energy recovery and 16% incineration without energy recovery				
Indicators	Climate change					
	Acidification terrestrial and freshwater					
	Cancer human health effects					
	Ecotoxicity freshwater					
	Eutrophication freshwater					
	Ionising radiation – human health					
	Land use					
	Non-cancer human health effects					
	Ozone depletion					
	Photochemical ozone formation – human health					
	Resource use, energy carriers					
	Resource use, minerals and metals					
	Respiratory inorganics					
	Water scarcity					
Method	Environmental Footprint (EF) 3.0					
Other comments	The study is modelled in GaBi Software.					
Reviewed	Preprint for open peer review					

■ Highest relative impact
 ■ In-between (neither highest nor lowest)
 ■ Lowest relative impact

The following is found by the study:

- Washing reusable masks in a washing machine has lower impacts than washing by hand, thus having a higher number of masks in rotation to allow for machine washing together with the regular wash loads in the household results in the machine-washed reusable masks having lower environmental impacts than the single-use surgical masks (while this is not the case for the hand-washed reusable masks). An individual can have up to 48 reusable masks in rotation per year before the impact on climate change of the reusable masks exceeds that of the single-use surgical masks. This break-even number (the maximum number of reusable masks in rotation to be equivalent to the impact of single-use masks) ranges from five for non-cancer human health effects to 59 for ionising radiation effects on human health (with an average of 25 across all the impact categories analysed).
- Single-use surgical face masks have the highest potential impacts in four out of 14 impact categories (acidification, ionising radiation, ozone depletion and photochemical ozone formation). Reusable face masks with a single-use filter and manual washing have the highest environmental potential impacts in seven of the 14 impact categories considered in the study (climate change, freshwater ecotoxicity, freshwater eutrophication, land use, resource use of energy carriers, resource use of minerals and metals, and water scarcity).
- Reusable face masks generate significantly less waste, owing to fewer masks being disposed and less packaging required. The use of single-use masks in the UK for one year is estimated to produce 124,000 tonnes of waste. If everyone in the UK were to switch to a reusable masks (without filters) solid waste arising from the use of face masks could be decreased by over 85%, while solid waste could be decreased by half if everyone in the UK switched to reusable masks with single-use filters.
- Reusable face masks are associated with substantial water use, owing to both the high water requirements of cotton textile production and of needing to wash the masks between uses. Hand washing requires significantly more water than machine washing, resulting in the scenarios of two hand-washed masks in rotation having more than double the water requirements of the scenarios of four machine-washed masks in rotation.
- For single-use surgical masks, transport to the UK from China is the highest contributor to climate change by a considerable margin (with masks transported by airfreight). An analysis on manufacturing location found that manufacturing masks in the UK from materials imported from China had relatively little potential to reduce impact on climate change, but that manufacturing masks in Turkey (or in the UK from materials produced in Turkey) could reduce climate change impact by a third. So much so, that single-use surgical masks would then be preferred (in terms of their impact on climate change) to hand-washed reusable masks and to reusable masks used with a single-use filter (with the reusable masks produced in China). The impact of producing reusable masks in the UK and/or other countries was not assessed in the study but the authors surmise that if production was also shifted from China to Europe, the overall environmental impact of reusable masks would reduce and remain lower than single-use surgical masks.
- For the machine-washed reusable masks, mask manufacture and transport to the UK from China contribute the most to climate change. Although not quantified, the authors note that the impacts of reusable masks would decrease if they were made from recycled/repurposed fabric and/or if they were locally produced. If used with a single-use filter, the transport of filters to the UK contributes the most to climate change, followed by mask manufacture and filter manufacture.
- For the hand-washed reusable masks, the highest contributor to climate change is washing masks, with the thermal energy required to supply hot tap water accounting for over 70% of the impact (in the case of hand-washed masks without filters). Transport of single-use filters from China to the UK is also a significant contributor to climate change in the case of reusable masks with filters.
- The contribution to impacts from electricity used in machine washing is low, thus washing at 60°C increases impacts by a maximum of 5% across all impact categories and does not change the ranking amongst the scenarios.
- Waste disposal contributes less than 1% to all impact categories for both single-use and reusable masks (all scenarios). Only the impacts of formal disposal (landfill and incineration) are considered in the study.

2.2 COTTON AND SURGICAL MASKS—WHAT ECOLOGICAL FACTORS ARE RELEVANT FOR THEIR SUSTAINABILITY? SCHMUTZ *ET AL.* 2020

The aim of this paper is to identify the factors determining the environmental impacts of textile masks so that they can be designed in a more sustainable manner. Surgical masks are compared with two-layered cotton masks in a simplified LCA. The masks are compared on a functional unit of one person in Switzerland wearing face masks during one working week when travelling to work on public transport and when going into a shop. No mask is assumed to be worn on Sunday. Five return public transport trips and three shop visits are assumed. In order to evaluate the influence of human behaviour, the cotton masks and surgical masks are compared in two different user behaviour scenarios. The “stricter” scenario follows the recommendations of the Swiss National COVID-19 Science Task Force, while the “less strict” scenario represents potential behaviour users might have, despite this not being recommended from a health perspective.

- Stricter scenario
 - Cotton masks: The person owns (at least) two masks and wears a clean mask every day other than Sunday, resulting in six wears. After each wear, the mask is washed in a half full washing machine at 60°C. The masks are used for a total of two weeks (equates to five use-wash cycles per mask) before being thrown away.
 - Surgical masks: A new mask is worn for every use, resulting in the use of 13 masks over the week. (five return public transport trips and three shop visits).

- Less strict scenario
 - Cotton masks: One cotton mask is worn for the week (same mask every day), and washed in a half full washing machine at 40°C at the end of the week. The mask is thrown away after 15 washes (after 16 uses).
 - Surgical masks: One mask is worn per day, resulting in six masks used over the week (no mask is worn on Sunday).

The number of masks per functional unit for both scenarios is given in Table 2. The masks are used in Switzerland and produced globally (the global markets of theecoinvent database are applied for the various production materials). Both the surgical and cotton masks are assumed to be incinerated at their end-of-life.

Summary of results and conclusions

The cotton masks perform better than the surgical masks against some environmental impacts, but worse in others. **User behaviour strongly influences how the two types of masks perform environmentally** (as indicated by a comparison between the two scenarios). **The lifespan and weight of the cotton masks are the most important factors** when it comes to determining their overall environmental performance.



Table 2: Summary table: Schmutz *et al.* (2020)

		Products considered in study			
		Surgical masks – stricter scenario	Cotton Masks – stricter scenario	Surgical masks – less strict scenario	Cotton Masks – less strict scenario
Study scope	Materials	PP (spunbond and melt-blown) Elastic bands (polyurethane) Nose wire (aluminium)	Cotton Elastic bands (polyurethane)	PP (spunbond and melt-blown) Elastic bands (polyurethane) Nose wire (aluminium)	Cotton Elastic bands (polyurethane)
	Functional unit (FU)	One person wearing face masks during one working week when traveling to work on public transport and going into a shop three times.			
	Use Scenario	New mask every wearing (5x2 travels to work, 3x shopping trips)	One mask worn per day then machine-washed at 60°C; lifespan of 5 washes (0.25 g powder detergent and 0.16 kg water per mask per wash)	One mask worn per day (assume no mask worn on Sunday)	One mask worn for the entire week then machine-washed at 40°C; lifespan of 15 washes (0.25 g powder detergent and 0.16 kg water per mask per wash)
	Number per FU	13	2	6	1
	Weight [g]	2.45 g PP, 0.25 g elastic, 0.18 g aluminium	11.5 g cotton, 0.25 g elastic	2.45 g PP, 0.25 g elastic, 0.18 g aluminium	11.5 g cotton, 0.25 g elastic
	Geographic region	Switzerland (with global production of both masks)			
	Life cycle stages	Cradle-to-grave			
	End-of-life	Incineration			
			Stricter scenario		Less strict scenario
Indicators	Carbon Footprint	Highest relative impact		Lowest relative impact	
	Non-renewable Cumulative Energy Demand	Highest relative impact		Lowest relative impact	
	Water Footprint	Lowest relative impact		Highest relative impact	
	Ecological Scarcity	Lowest relative impact		Highest relative impact	
Method	Three mid-points: Carbon footprint (IPCC method), non-renewable cumulative energy demand (VDI definition) and water footprint (AWARE method); Overall environmental impacts, expressed in ecopoints, according to the Swiss method of Ecological Scarcity.				
Other comments	The calculations were made in Microsoft Excel using the LCIA results from the different materials and/or services of the ecoinvent database version 3.7, recycled-content model.				
Reviewed	Peer-reviewed journal article				



Highest relative impact



In-between (neither highest nor lowest)



Lowest relative impact

The results for the stricter scenario are as follows:

- Wearing cotton masks results in lower cumulative energy demand than wearing surgical masks and has a marginally lower carbon footprint.
- However, wearing cotton masks results in higher water depletion and has a higher overall environmental impact (according to the Swiss Ecological Scarcity method).
- For both the cotton and the surgical masks, their impacts arise mostly from their production.
- Washing the masks plays only a minor role in the impacts of wearing cotton masks, owing to the high impacts of cotton production.
- End-of-life (incineration) has a relatively minor contribution to the life cycle impacts of both masks, except for the carbon footprint of the surgical masks, where burning polypropylene (PP) gives rise to fossil carbon emissions.

The results for the less strict scenario are as follows:

- Wearing cotton masks results in a lower carbon footprint, lower cumulative energy demand and lower overall environmental impacts (according to the Swiss Ecological Scarcity method) than wearing surgical masks. The only environmental impact category in which wearing cotton masks has poorer performance than wearing surgical masks is water depletion.
- As with the strict scenario, the production of the masks (including their raw materials) accounts for the majority of the environmental impacts of both cotton and surgical masks.
- End-of-life also has a significant contribution to the carbon footprint and ecological scarcity of the surgical masks, with incineration accounting for 36% of the carbon footprint of the surgical mask scenarios.
- Washing has only a minor contribution to the life cycle impacts of the cotton masks for all of the environmental indicators considered.

When the masks are considered on their own, i.e., cradle-to-gate, without use or disposal, the following were found:

- The production of cotton fibre accounts for the majority of impacts of the cotton masks in all four impact categories considered.

- Dyeing, fabric production and yarn production are also significant contributors to the carbon footprint and cumulative energy demand of a cotton mask.
- The spunbond nonwoven PP that makes up two of the three layers of the surgical mask contributes the most to its carbon footprint, cumulative energy demand and water footprint. The melt-blown nonwoven PP that makes up the middle layer of the surgical mask is also a significant contributor to these impacts.
- The aluminium nose wire is the most significant component of the surgical mask according to its ecological scarcity, with production of the nonwoven PP also a significant contributor (both spunbond and melt-blown).

Sensitivity analyses were carried out on four key variables affecting the cotton masks with the following scenarios assessed:

- **Lifetime**, the number of washing cycles was varied from five to 35, corresponding to wearing the masks from two to 12 weeks.
- **Weight**, the mass of cotton was varied from 9 g to 20 g, representing the design possibility of adding a third layer to the mask.
- **Washing behaviour**, two possible machine-washing and hand-washing behaviours were investigated: machine washing at 30°C, machine washing at 40°C, washing by hand in three litres of water at 55°C (“long hand-washing” scenario), and washing by hand in one litre of water at 40°C (“short hand-washing” scenario).
- **Mask design**, the possibility of adding a melt-blown PP filter and a nose wire was investigated.

The **higher the number of times you use the same mask** (machine washing it in between uses), the **lower its environmental impact**. **Lifetime of the cotton masks** is the most influential variable that decreases all environmental impacts. The weight of the cotton masks is also very important, with a three-layer mask having substantially higher environmental impacts. However, adding a PP filter and nose wire was found to have little effect on environmental impacts. Washing behaviour was found to be somewhat influential, especially the long hand-washing scenario, but much less influential than the lifetime and weight of the cotton masks.

Break-even points were calculated for the stricter scenario. For the cotton masks to have a lower Ecological Scarcity score than the surgical masks requires them to be used and washed 22 times. For the surgical masks to have a higher carbon footprint than the cotton masks, the cotton masks are required to be hand washed or weigh more than 12 g.

2.3 LIFE CYCLE ASSESSMENT OF SINGLE-USE SURGICAL AND EMBEDDED FILTRATION LAYER (EFL) REUSABLE FACE MASK: LEE *ET AL.* 2021

This LCA study compares the use of single-use surgical face masks to the use of reusable face masks with an embedded filtration layer (EFL).

The EFL reusable face mask was developed in Singapore as an alternative face mask option for the general population to address the shortage of single-use surgical face masks and is widely used there (with nationwide distribution by the Singapore government). The EFL reusable face mask was shown to have a bacterial filtration efficiency of 95% after 30 washes, and as such its filtration performance is comparable with that of a single-use surgical face mask (according to the WHO definition for surgical face masks (WHO 2020b)).

The reusable EFL face mask is comprised of three layers; a layer of polyester fabric with a hydrophobic coating, a layer of melt-blown PP and polyester fabric with hydrophobic coating composite, and a layer of polyester fabric. The three-layer surgical mask is a composite of melt-blown PP sandwiched between a layer of spunbond PP. The materials of each mask and the main assumptions are summarised in Table 3.

The face masks are compared according to the functional unit of a single person's face mask consumption over one month (31 days) (assuming face masks are worn for less than 12 hours each day). This equates to 31 single-use surgical masks and one reusable EFL mask, washed 30 times.

The LCA study is from cradle-to-grave, and includes the production of raw materials, packaging, distribution, use and end-of-life disposal of the masks. Both masks are assumed to be incinerated in a waste-to-energy plant at end-of-life, with residues landfilled. Energy credits (avoided burdens) are applied for electricity production avoided by waste-to-energy. The life cycle of the reusable masks includes the use-phase washing. Masks are assumed to be hand washed in room-temperature water, with the entire household's daily masks assumed to be washed together in one wash (applying the average household size in Singapore of 3.16 this comes out at 1.975 g of liquid detergent and 1.899 l of water per face mask washed). The masks are assumed to be washed 30 times before being discarded, as recommended by the manufacturer.

The two masks are compared against the nine impact categories of the ReCiPe method (Hierarchist perspective), as well as on the amount of waste associated with each of the face masks.

Summary of results and conclusions

The **reusable EFL mask has lower environmental impacts in all impact categories considered, other than water depletion, eutrophication and human toxicity**. The carbon footprint of the reusable EFL mask is 40% lower than the single-use surgical masks, and it generates 90% less waste¹⁷.



The **higher the number of times you use the same mask** (machine washing it in between uses), the **lower its environmental impact**. **Lifetime of the cotton masks** is the most influential variable that decreases all environmental impacts. The weight of the cotton masks is also important. *Lee et al. (2021)*

¹⁷ This figure does not take into account waste generated from raw material production

Table 3: Summary table (baseline scenario): Lee *et al.* (2021)

		Products considered in study	
		Single-use surgical face mask	Reusable embedded filtration layer (EFL) face mask
Study scope	Materials	Composite of melt-blown PP (25 gsm) sandwiched between a layer of spunbond PP (20 gsm); aluminium (nose piece); polyurethane (ear loops)	Layer of polyester fabric with a hydrophobic coating, layer of melt-blown PP and polyester fabric with hydrophobic coating composite, layer of polyester fabric; polyurethane (ear loops)
	Functional unit (FU)	One month (31 days) of face mask consumption of one person	
	Use Scenario	New mask every day	Washed daily by hand with room temperature water with all the household's masks together in one wash (1.975 g of liquid detergent and 1.899 l of water per face mask per wash)
	Number per FU	31	1 (discarded after 30 washes)
	Geographic region	Singapore (use, disposal and manufacturing, with materials sourced from China, Japan and Indonesia)	
	Life cycle stages	Cradle-to-grave	
	Indicators	End-of-life	Incinerated in waste-to-energy plant followed by landfill
Climate change			
Fossil fuel depletion			
Metal depletion			
Water depletion			
Freshwater ecotoxicity			
Freshwater eutrophication			
Marine ecotoxicity			
Marine eutrophication			
Human toxicity			
Waste generated (kg)			
Method		ReCiPe method with Hierachist perspective applied. Nine impact categories considered in addition to the waste generated from each mask. The entire value chain is considered (from acquisition of materials to end of life). Ecoinvent 3.6 database used in LCA study.	
Other comments	Inventory data on the production of raw materials, detergent, transport and incineration is from the ecoinvent database (v 3.6), with water and electricity production modelled with published data for Singapore (alongside supplementary data from the ecoinvent database).		
Reviewed	Peer-reviewed journal article		

Highest relative impact

In-between (neither highest nor lowest)

Lowest relative impact

The main findings of the study are that:

- The reusable EFL face masks have environmental impacts at least 30% lower than that of the single-use surgical face masks in five out of the nine impact categories considered (climate change, fossil fuel depletion, metal depletion, freshwater ecotoxicity and marine ecotoxicity).
- The number of days for a reusable face mask to break even with the single-use face mask was also determined. For those impact categories where the reusable face masks performed better than the surgical face masks for the functional unit considered (one month), the number of days to break even ranged from eight days (fossil fuel depletion) to 20 days (freshwater ecotoxicity). In those impact categories where the single-use surgical masks performed better for the functional unit considered, the number of days required to break even was 595 days for water depletion, 221 days for marine eutrophication and 86 days for human toxicity. The surgical face masks have a negative score for freshwater eutrophication and thus it is not possible for the reusable face masks to ever break even¹⁸.
- The lower environmental impacts of the single-use surgical masks in freshwater eutrophication and human toxicity are owing to the fact that they receive substantial end-of-life credits from the avoided energy associated with incinerating the masks in a waste-to-energy plant at end-of-life (a consequential approach is followed in the study).
- The poorer performance of the reusable EFL mask with respect to water depletion is owing to water used in washing the masks, while the poorer performance with respect to marine eutrophication is owing to the EFL masks' raw materials having higher impacts in this category than the single-use surgical masks' raw materials.
- Across all impact categories other than water depletion, the majority of emissions arise during raw material acquisition. This is the case for both the reusable and the single-use surgical masks. For the single-use masks, this is also the case for water depletion, while for the reusable face masks, usage (washing) accounts for the highest share of water depletion. Production and transportation have negligible shares of emissions for both masks across all impact categories considered, while the end-of-life stage is influential in the life cycle impacts of the single-use face masks in metal depletion, freshwater eutrophication and human toxicity. However, in the latter two impact categories this is owing not to emissions at end-of-life but rather to credits associated with avoided energy production.

- Raw materials acquisition was analysed in further detail in terms of the climate change impact of the two masks. Seven and eight materials need to be acquired for the surgical and EFL masks, respectively. For the surgical masks, the spunbond PP shows the greatest share of climate impact. For the EFL mask, washing detergent shows the greatest share of climate impact, followed by polyester. It therefore follows that in sensitivity analyses that vary the quantities of input materials and the emission factors of the materials, the climate change impact of the single-use surgical mask is most sensitive to the material used in making the mask (in particular to the quantity of spunbond PP). The reusable EFL mask is most sensitive to the emission factors applied for detergent production.

A scenario analysis was carried out to determine how changes in face mask use and waste treatment affected the results. Four scenarios were investigated:

- In Scenario 1, masks were assumed to be worn for a shorter duration, so that two masks are worn per day instead of a single mask for the whole day (applies to both single-use and reusable EFL masks). The scenario was evaluated with reusable masks washed together in one wash or in two separate washes.
- In Scenario 2, masks were assumed to be used for two days, resulting in half the number of single-use masks used over the month, and with the reusable EFL masks only washed every second day. In both Scenario 1 and 2, the impacts change in proportion to the number of masks required and trends between the masks do not change.
- In Scenario 3, it was assumed that masks were sent to landfill instead of incineration. In this scenario, the reusable mask had lower environmental impacts than the single-use mask in the freshwater eutrophication and human toxicity impact categories. This results in the reusable masks having better environmental performance than the single-use surgical masks in all impact categories other than water depletion and marine eutrophication.
- In Scenario 4, it was assumed that the reusable EFL masks were washed in a washing machine rather than by hand. In this scenario the reusable EFL masks were found to have lower environmental impacts in all nine impact categories considered owing to the lower use of water and detergent in this scenario.

The reliability of the results was assessed in a Monte Carlo analysis. The observed differences between the two masks were found to be statistically significant for all nine impact categories¹⁹.

¹⁸ The negative score results from the credit received at end-of-life incineration of the masks (i.e., from avoided energy production)

¹⁹ The *p*-values for the two-tailed form of the *t*-test produces values that are below the predefined significance level of 0.05 for all nine impact categories.

2.4 ENGINEERING DESIGN PROCESS OF FACE MASKS BASED ON CIRCULARITY AND LIFE CYCLE ASSESSMENT IN THE CONSTRAINT OF THE COVID-19 PANDEMIC: BOIX RODRÍGUEZ ET AL. 2021

The aim of this study is to minimise the negative impact of COVID-19 masks on the environment through developing a design guide outlining environmentally preferred design practices. LCA and material circularity indices (MCI) were used to compare different types of face masks available in Italy.

The following face masks are covered in the study:

- **Reusable 3D-printed mask with single-use FFP2²⁰ filters:** This mask has a rigid plastic structure made from the biopolymer polylactic acid (PLA) with single-use FFP2 filters inserted into the mask. The filters require changing after eight hours of use, and the mask requires disinfecting with ethanol between uses.
- **Single-use surgical face mask:** The surgical mask is assumed to be worn for four hours and then discarded (in accordance with best-practice guidelines).
- **Single-use FFP2 mask with valve:** The FFP2 mask is assumed to be worn for eight hours and then discarded (in accordance with best-practice guidelines). The valve facilitates breathing but renders the mask no longer protective of others (i.e., it protects only the user).
- **Single use FFP2 mask without valve:** The FFP2 mask is assumed to be worn for eight hours and then discarded (in accordance with best-practice guidelines).
- **Reusable washable mask:** This mask made from polypropylene and polyester has been tested to maintain its bacterial filtration efficiency (BFE) for up to 50 washes. In accordance with manufacturers' instructions masks are machine washed in a standard washing cycle (temperature between 40°C and 75°C).

The functional unit applied was the use of face masks to protect an Italian citizen in a pandemic situation for the period of one month. The mask should comply with the UNI EN 149:2009²¹ or UNI EN 14683:2019²² standards and be able to prevent the emission of respiratory droplets. An estimated daily need for masks in Italy of 40 million was used to calculate the number of masks and filters required per functional unit (see Table 4).

The LCA study covers the whole life cycle, including mask production (material extraction and, for the reusable 3D masks, the manufacturing process), transportation (mask distribution but excluding transport to disposal at end-of-life), use phase/maintenance of the reusable masks (ethanol used in disinfecting and electricity, water and soap used in washing), and end-of-life disposal (municipal landfill).

Summary of results and conclusions

The reusable washable face masks have the lowest environmental impacts across all impact categories considered, other than in ozone depletion and water consumption (in which the reusable masks with disposable filters have the lowest impacts). As much as 650,000 tonnes CO₂e of greenhouse gas emissions could be avoided per year in Italy if reusable masks instead of FFP2-type single-use masks were used by all citizens.

The reusable masks with single-use filters also show significantly better environmental performance than the single-use face masks. The authors combine the strengths of the two best-performing masks in their study to develop a prototype mask that has a rigid PP injection-moulded structure. If used with washable reusable filters, the prototype has the potential to be the best performer across all environmental impact categories.

²⁰ The "2" in FFP2 indicates the level of protection, with FFP2 masks filtering >94% of particles in a standardized test.

²¹ UNI EN 149:2009 is the Italian standard covering respiratory protective devices - Filtering half masks to protect against particles - Requirements, testing, marking. A requirement of this standard is that masks must be tested for their particle filtration efficiency (PFE), with masks classified into three categories: FFP1 (PFE ≥ 80%), FFP2 (PFE ≥ 94%), and FFP3 (PFE ≥ 99%).

²² UNI EN 14683:2019 is the Italian standard covering medical face masks - Requirements and test methods. A requirement of this standard is that masks must be tested for their bacterial filtration efficiency (BFE), with masks classified into Type I masks (BFE ≥ 95%) and Type II masks (BFE ≥ 98%).

Table 4: Summary table: Boix Rodríguez *et al.* (2021a)

		Products considered in study				
		3D-printed mask with removable FFP2 filter	Surgical face mask	FFP2 mask with valve	FFP2 mask without valve	Washable face mask
Study scope	Materials	3D-printed PLA mask structure; with PP and polyester filter; and synthetic rubber ear loops	Polypropylene PP and polyester; with aluminium nose wire and cotton ear loops	PP; with injection-moulded PP valve, aluminium nose wire, polyurethane (PU) foam nose protection and synthetic rubber ear loops	PP; with aluminium nose wire and synthetic rubber ear loops	PP and polyester with cotton ear loops
	Functional unit (FU)	The use of a face mask compliant with UNI EN 149:2009 or UNI EN 14683:2019 standards. The face mask must be able to mitigate the release of respiratory droplets during the pandemic environment, for an Italian citizen for the period of one month.				
	Use Scenario	Mask disinfected with ethanol before reuse (single-use filters)	Worn for 4 hours (i.e., two required per day)	Worn for 8 hours (i.e., one required per day)		Machine washed with soap in standard washing cycle (between 40°C and 75°C) 50 times
	Number per FU	Mask: 40 million Filter: 600 million	1,200 million	600 million	600 million	40 million
	Weight [g]	0.5 g PP 0.5 g PE 30 g PLA 3.0 g synthetic rubber	1.48 g PP 1.28 g PE 0.44 g aluminium 0.02 g cotton	5.0 g PP 5.0 g PE 0.95 g aluminium 0.05 g PU 3.0 g synthetic rubber	5 g PP 0.95 g aluminium 3.0 g synthetic rubber	2.7 g PP 2.7 g PE 1.0 g cotton
	Geographic region	Italy (use and disposal), global and European production of materials and masks				
	Life cycle stages	Cradle-to-grave				
	End-of-life	Municipal landfill				
Indicators	Global warming potential					
	Ozone depletion					
	Photochemical oxidant formation					
	Particulate matter formation					
	Terrestrial acidification					
	Freshwater eutrophication					

Table 4: Summary table: Boix Rodríguez *et al.* (2021a)

		Products considered in study				
		3D-printed mask with removable FFP2 filter	Surgical face mask	FFP2 mask with valve	FFP2 mask without valve	Washable face mask
Indicators	Terrestrial ecotoxicity	In-between (neither highest nor lowest)	In-between (neither highest nor lowest)	Highest relative impact	In-between (neither highest nor lowest)	Lowest relative impact
	Freshwater ecotoxicity	In-between (neither highest nor lowest)	In-between (neither highest nor lowest)	Highest relative impact	In-between (neither highest nor lowest)	Lowest relative impact
	Marine ecotoxicity	In-between (neither highest nor lowest)	In-between (neither highest nor lowest)	Highest relative impact	In-between (neither highest nor lowest)	Lowest relative impact
	Human toxicity	In-between (neither highest nor lowest)	In-between (neither highest nor lowest)	Highest relative impact	In-between (neither highest nor lowest)	Lowest relative impact
	Fossil fuel	In-between (neither highest nor lowest)	In-between (neither highest nor lowest)	Highest relative impact	In-between (neither highest nor lowest)	Lowest relative impact
	Water consumption	Lowest relative impact	In-between (neither highest nor lowest)	Highest relative impact	In-between (neither highest nor lowest)	In-between (neither highest nor lowest)
	Cumulative energy demand	In-between (neither highest nor lowest)	In-between (neither highest nor lowest)	Highest relative impact	In-between (neither highest nor lowest)	Lowest relative impact
Method	ReCiPe (12 midpoints and three end points) and cumulative energy demand (CED).					
Other comments	Modelled in SimaPro software using datasets from ecoinvent v 3.5					
Reviewed	Peer-reviewed journal article					

■ Highest relative impact
 ■ In-between (neither highest nor lowest)
 ■ Lowest relative impact

In terms of the environmental comparison between the masks, the main findings of the study are:

- The single-use FFP2 masks with a valve consistently have the highest environmental impacts. The FFP2 masks with a valve showed, on average, 20% higher environmental impacts than the FFP2 masks without valves. This is because of the two additional materials and the higher weight of PP required in the manufacture of the mask with the valve.
- The FFP2 mask without a valve is the face mask with the second highest environmental impacts, followed by the surgical mask. The surgical masks have, on average, 40% lower impacts than the FFP2 masks without valves, with substantially lower human toxicity, marine ecotoxicity and freshwater ecotoxicity potentials (85%, 68% and 67% lower, respectively). This is despite double the number of surgical masks being required to fulfil the functional unit (surgical masks are worn for four hours, while the FFP2 masks are worn for eight hours). The lighter weight of the surgical mask relative to the FFP2 masks primarily accounts for this result (i.e., less materials are required per mask).
- Comparing the two reusable options, the washable masks show the best environmental performance, with substantially lower human toxicity, fossil fuel depletion and marine ecotoxicity potentials (69%, 66%, and 66% lower, respectively). Only the ozone depletion and water consumption potentials of the washable masks are higher than those of the 3D-printed masks. The higher water consumption of the washable masks arises from producing the cotton for the ear loops (the washable mask has cotton ear loops while the 3D-printed mask has synthetic rubber ear loops) and the water used in its use phase (ethanol is used to disinfect the 3D-printed masks between uses, while the washable masks are washed in a washing machine).
- With regards to the source of impacts, similar trends were observed for the FFP2 masks (with and without valves) and for the 3D-printed masks with FFP2 filters. For both these masks, materials and manufacturing account for the greatest share of all impact potentials, other than in the freshwater ecotoxicity, marine ecotoxicity and human toxicity potentials. In these three impact categories, end-of-life disposal (landfilling) accounts for the highest share. The aluminium nose wire is a significant contributor to the human health and ecosystem impacts of the single-use face masks.
- The trend in cumulative energy demand (CED) between the masks is the same as that found for the impact potentials, i.e., that the FFP2 masks without valve have the highest CED, followed by the FFP2 masks without valves and the surgical masks. The reusable options have substantially lower CEDs, coming in at 7% and 3% of the CED of the FFP2 masks with valves, for the 3D-printed masks and washable masks, respectively.

The washable mask is also the best performer in terms of material circularity index. While the 3D-printed mask structure was determined to have a circularity index of 1, the single-use filters have a circularity index of 0.1 (the same as the single-use masks). The washable masks were determined to have a circularity index of 0.9.

2.5 WHAT IS THE ENVIRONMENTAL IMPACT OF DIFFERENT STRATEGIES FOR THE USE OF MEDICAL AND COMMUNITY MASKS? A PROSPECTIVE ANALYSIS OF THEIR ENVIRONMENTAL IMPACT: BOUCHET *ET AL.* 2021

This study provides an environmental assessment of eight different mask type and use strategies according to three indicators (global warming potential, ecological scarcity and plastic leakage). The aim of the study is to explore and compare the environmental impact of different masks used in the community in Switzerland in an attempt to provide recommendations on the best compromise between protection effectiveness and environmental impact.

Eight scenarios were constructed of mask use by the general population, distinguishing the typology of masks, modalities of reuse and mask origin and transport. The eight scenarios are summarised in Table 5. Three types of masks intended for use by the general public are considered:

- **Medical masks** (or surgical masks) are usually constituted of three different layers of non-woven PP fabric. In Europe, medical masks must meet the requirements of EN 14683 and must comply with the Medical Devices Directive (EU) 2017/745. The majority are produced in China and imported to Europe via ship. Medical masks are originally intended for single use but, driven by the needs of the pandemic, numerous strategies have emerged evaluating their potential for reuse. These include various physical treatments, such as treating them with microwaves or dry heat. Another such reuse strategy – that is yet to be validated – is the wait-and-reuse strategy. Tests on surgical masks that show a decline in the

virus load over time suggest that surgical masks can be stored at room temperature for seven days before being reused (by the same user).

- **Community masks** encompass all non-professional masks intended to protect the general public, and range from home-made cotton masks to more sophisticated textile masks. Community masks are not subject to legal requirements so their effectiveness can vary greatly, although some countries have developed quality labels that specify minimum performance requirements (e.g., the French AFNOR label and the Swiss TESTEX label). Since community masks do not have any legal requirements and are designed with the intention to be used by the general public, their washing is assumed to follow that of the average home (washing in a home washing machine at 60°C).
- **Labelled community masks** are much less common and produced in smaller numbers owing to their higher technical requirements and costs. They are typically made of polymers, such as polyester. Masks adhering to the AFNOR and TESTEX labels are produced in France and Switzerland, respectively. To maintain the performance specified by their label, labelled community masks are assumed to be washed the number of times specified by the standard (20 and five washes for the AFNOR and TESTEX labels, respectively).

The LCA considers all the life cycle stages of the different masks including production, transport, use (decontamination) and end-of-life. The functional unit chosen for the comparison is the number of face masks required by one person over a one month period.

The number of masks required to fulfil the reference flow of 30 masks in each of the eight scenarios, along with the decontamination assumptions for the reusable masks, are given in Table 5.

The masks are compared against three indicators of potential environmental impact:

- Potential contribution to **climate change**, expressed as global warming potential (measured as emissions of greenhouse gases in kgCO₂ eq. applying a 100-year timeframe).
- Potential contribution to **ecological scarcity**, expressed as eco-points (the German UBP method encompasses such impacts as water footprint and biodiversity loss).
- **Plastic leakage** expressed as the amount of plastic leaving the technosphere and accumulating in the environment (measured as the quantity of plastic ultimately released into the ocean or into the other compartments (freshwater, soils and other terrestrial environments) including both microplastics and macroplastics²³). In the Swiss context of the study, a plastics leakage rate of 2% was applied in the study.

Summary of results and conclusions

Home-made cotton masks and prolonged use of medical masks (through a wait-and-reuse strategy) have the lowest environmental impacts. A 50 to 90% reduction in climate change impact and a 60 to 100% reduction in plastic leakage can be achieved by switching from single-use masks to reusable masks. If just 10% of the Swiss population made the shift²⁴, 4,000 tonnes CO₂ eq. and 17 to 19 tonnes plastic leakage could be avoided.



A 50 to 90% reduction in climate change impact and a 60 to 100% reduction in plastic leakage can be achieved by switching from single-use masks to reusable masks. If just 10% of the Swiss population made the shift, 4,000 tonnes CO₂ eq. and 17 to 19 tonnes plastic leakage could be avoided. *Bouchet et al. (2021)*

²³ Plastic leakage is a result of both loss and release and is described by the following equation: Plastic leakage mass = Plastic waste mass x Leakage rate (with Leakage rate = Loss rate x Release rate, and Loss rate = mismanaged rate + littering rate)

²⁴ Considering a shift from single-use medical masks (transported by boat) to either home-made cotton masks or extended use of medical masks using wait and reuse.

Table 5: Summary table: Bouchet *et al.* (2021)

		Products and reuse strategies considered in study							
		Medical mask				Unlabelled community mask		Labelled community mask	
		Single-use, boat transport	Single-use, plane transport	Reused, hot drying	Reused, wait and reuse	Cotton, made in China	Cotton, home-made from old cloth	AFNOR (French)	TESTEX (Swiss)
Study scope	Materials	PP, nylon and aluminium (nose strip)				Cotton	Cotton, old cloth	Elastane and polyester	
	Functional unit (FU)	To equip one person with a mask during a month							
	Use Scenario	Single-use		Hot drying in oven, 30 min at 70°C (5 masks per batch)	Wait and reuse	Washing machine at 60°C (full load) (water use of 67.6 per cycle and soap consumption of 65 g per cycle, allocated to masks on mass basis with full load taken as 6 kg of dry clothes)			
	Number per FU	30		3 (one mask used each weekday, reused 10 times)		2	2	2	6
	Weight [g per mask]	3.2 g (2.5 g PP, 0.5 g nylon, 0.2 g aluminium)				5 g	5 g	6.3 g (0.13 g elastane, 6.17 g polyester)	
	Geographic region	Switzerland, made in China				Switzerland, made in China	Switzerland	Switzerland, made in France	Switzerland
Indicators	Life cycle stages	Cradle-to-grave							
	End-of-life	Incineration with energy recovery							
	Global warming potential								
	Ecological scarcity								
	Plastic leakage								
Method	Global warming potential (GWP100, IPCC), ecological scarcity (UBP method from German 'Umweltbelastungspunkte') and plastic leakage (Boucher <i>et al.</i> 2020)								
Other comments	A proprietary Excel tool developed by the authors was used to perform the LCA based on ecoinvent datasets.								
Reviewed	Peer-reviewed article								



Highest relative impact



In-between (neither highest nor lowest)



Lowest relative impact



The main findings of the study with respect to climate change impact include:

- Single-use medical masks transported by plane have by **far the highest impact on climate change**, with a GWP more than double than that of single-use medical masks transported by ship (the mask with the next-highest GWP).
- The **home-made community mask made from old cloth has the lowest global warming potential, followed by reusing medical masks with a “wait-and-reuse” strategy.**
- The low environmental impacts of the home-made community mask are **owing to the use of second-hand cloth in their production**, i.e., they have no impacts from their production, as well as the relatively low impacts of their use phase (owing to their being washed in a fully-loaded washing machine).
- Medical masks with decontamination using dry heating, commercial cotton reusable masks made in China, and polyester reusable masks reused only six times have similar GWPs, and are the next-highest contributors to GWP after the single-use medical masks. **The poor performance of medical masks with dry heat decontamination is owing to the energy use during decontamination**, while the poor performance of the commercial masks (both cotton and polyester) is owing to the impacts of producing their materials.
- The AFNOR masks (French label) are the third-best option, having a GWP only somewhat higher than the extended use of medical masks with wait and reuse. **The poor performance of the TESTEX masks is owing to its relatively low number of recommended uses.**

The main findings with respect to ecological scarcity include:

- The relative performance of the masks when measured against the ecological scarcity indicator is similar to that obtained when measuring against GWP. **The home-made cotton mask and the extended use of medical masks with wait and reuse remain the best options.**
- The **use phase becomes relatively more important in all the reusable options when measured against ecological scarcity.**
- The higher importance of the use phase results in the extended use of medical masks decontaminated with **dry heat becoming a higher impact option than single-use medical masks** (with masks transported by boat).

The main findings with respect to plastic leakage include:

- The **cotton masks do not generate plastic litter** and are therefore, not surprisingly, the best-performing option with respect to plastic leakage.
- The **single-use medical masks are associated with 1.8 g plastic leakage per person per month** of mask use. This can be reduced by a factor of ten if extended use strategies are employed.

The effect of the number of reuses on GWP was also evaluated, with the following key insights:

- **Commercial cotton masks have a higher GWP than single-use medical masks** (transported by boat) if used less than eight times.
- **Increasing the number of reuses decreases the gap** between the two most advantageous scenarios, that of home-made cotton masks and extended use of medical masks through wait and reuse.



Single-use medical masks transported by plane have by **far the highest impact on climate change**, with a Global Warming Potential (GWP) more than double than that of single-use medical masks transported by ship. *Bouchet et al. (2021)*



03 Discussion and conclusions

The conclusions are split into three sections. The first section provides a synthesis of the findings of the meta-analysis in terms of the environmental impact of single-use face masks and their alternatives. The second section is relevant for life cycle assessment practitioners and discusses the aspects to be considered when developing or interpreting LCA studies on these products. The third section provides specific guidance for policy makers when using LCA to develop policy that addresses the environmental concerns associated with single-use face masks.

3.1 ENVIRONMENTAL IMPACT OF SINGLE-USE PLASTIC FACE MASKS AND THEIR ALTERNATIVES

In general, reusable face masks have lower environmental impacts than single-use face masks, although the number of times they are used and how they are washed or decontaminated determine whether this is always the case. Reusable face masks that are used only a few times and washed inefficiently (e.g., by hand in hot water) are likely to have higher environmental impacts than single-use face masks in some or all environmental impact categories.


Being lighter and with lower environmental impacts in some impact categories, **reusable masks made from synthetic materials tend to show more definitive improvements in environmental performance relative to single-use masks than do reusable masks made from cotton**. Only the study by Bouchet *et al.* (2021) includes reusable masks made from both cotton and polyester in their option suite, with the polyester reusable masks shown to have better environmental performance even when used fewer times than their cotton counterparts. The potential for masks originally intended to be single-use to be used more than once was only evaluated by Bouchet *et al.* (2021). If it is deemed safe to decontaminate medical masks – as early research suggests (Liao *et al.* 2020; Ou *et al.* 2020; Pascoe *et al.* 2020; Chu *et al.* 2021) – then rendering “single-use” masks “reusable” by extending their life span appears a very promising option for low environmental impacts and high efficacy. This is especially the case where the decontamination step does not introduce additional environmental impacts, such as, if a “wait-and-reuse” strategy can be employed to decontaminate them.

Another important aspect of reusable masks made from synthetic materials is that they are more likely to conform to performance guidelines for face masks, with most guidelines on reusable face masks recommending they be made up of three layers and that the different layers be made of different fabrics (Bhattacharjee *et al.* 2020; WHO 2020b). Cotton (or an equivalent absorbent fabric) is only

recommended for the inner-most layer, with water resistant fabrics (such as nylon and polyester) recommended for the outer-most layer, and a blend of fibres with good filtration properties (such as spunbond PP) recommended for the middle layer. In the study by Schmutz *et al.* (2020), adding a third layer of cotton was found to add considerably to the environmental impacts of the reusable mask (to the extent that reusable masks were no longer preferred to single-use masks in any environmental impact category), whereas adding a filtration layer of nonwoven PP increased the environmental impacts by only a negligible degree. This suggests that adding additional layers of synthetic fabrics rather than cotton is preferable with regards to both environmental performance and increasing the filtration performance. Designs of reusable masks with single-use filters added are evaluated in Allison *et al.* (2020) and Boix Rodríguez *et al.* (2021a) and these partially reusable systems were shown to be advantageous to fully disposable masks, i.e., to an equivalent number of single-use masks (although reusable filters would improve environmental performance further).

Increasingly, commercially available reusable face masks are marketed as conforming to some sort of standard or performance label that guarantees their filtration performance for a maximum number of washes. This development allows a better equivalence between single-use and reusable face masks in the LCA comparisons, taking into account the tested filtration efficiency of the reusable masks (e.g., as in Lee *et al.* 2021) or requiring conformance with European standards and labels (e.g., as in Boix Rodríguez *et al.* 2021a and Bouchet *et al.* 2021).

The **materials from which face masks are manufactured are in most cases the main source of their life cycle environmental impacts**²⁵. It thus stands to reason that the number of times masks are reused, and the weight of the materials they are made of, are important in determining

 The **number of times masks are reused**, and the **weight of the materials they are made of**, are important in determining their environmental impacts.

²⁵ Exceptions are cases of inefficient washing practices, where the use phase can dominate, or air-transport of masks, where transport can dominate.

their impacts. This accounts for the findings of the LCA studies that the life span of reusable masks (i.e., the number of times they can be used and washed/decontaminated before discarding) is a highly influential variable in their life cycle environmental impacts. It thus also follows that the more impactful the materials, the more important the weight and number of reuses will be. For example, since the production of cotton has high environmental impacts, the weight and number of reuses was found to be very important in studies evaluating cotton masks (e.g., as in Schmutz *et al.* (2020)). It also follows that masks made from recycled materials²⁶ or second-hand fabrics will have lower environmental impacts than those made from virgin materials (e.g., as in Arpe (2020) and Bouchet *et al.* (2021)).

This is supported by the wider LCA literature, with a review study finding there is strong evidence that recycling, and especially repurposing of textiles reduces their life cycle impacts (Sandin and Peters 2018). The evidence from wider LCA studies is less clear when it comes to different fibre types, with no clear “winners” when it comes to sustainable fibres (Sandin, Roos and Johansson 2019). Rather, the range in environmental performance within each fibre type (representing differences in manufacturing practices) is often larger than the differences between fibre types, thereby making it impossible to draw clear conclusions around relative performance. Furthermore, different fibres have different environmental impacts, so which textile is deemed more advantageous depends on which impact one focuses on (EEA 2021b). Material improvements are also relevant to other masks components, such as the aluminium nose wire, which was found to have a high contribution to the life cycle environmental impacts of single-use masks.

Alongside their weight and life span, **the manner in which reusable masks are washed or decontaminated strongly influences their environmental impacts.** Allison *et al.* (2020) find washing behaviour to be the most influential variable, with machine-washed masks found to have the lowest environmental impacts even when machine washing is assumed to decrease the mask’s life span relative to washing by hand (Allison *et al.* 2020). Lee *et al.* (2021) also find machine washing to be strongly preferred to hand washing. Furthermore, in those LCA studies that considered only machine washing of masks, the washing stage was found to be relatively less important.

The finding that **reusable masks are generally environmentally preferred to single-use masks if used a sufficient number of times, and with the impacts from reusable masks strongly dependent on user behaviour, is consistent with findings on a range of reusable vs. single-**

use products (UNEP 2021). This finding is also consistent with findings on reusable vs. single-use PPE and medical equipment. For example, an LCA study on laryngeal mask airways (LMAs) found a 40-use reusable LMA mask to perform significantly better than a disposable LMA across all impact categories considered, with potential to further decrease its impacts by improving the efficiency of autoclave sterilisation of the masks (which is the most significant contributor to the impacts of the reusable LMA) (Eckelman, Mosher and Sherman 2012). Similarly, an LCA on isolation gowns found reusable isolation gowns to have significant environmental benefits relative to single-use isolation gowns in non-renewable energy use, climate change, water use and solid waste generation (Vozzola, Overcash and Griffing 2020).

For single-use masks, the production of masks, including the production of raw materials, are the most significant contributors to their environmental impacts. An exception is when masks are transported by air freight, such as in emergency situations at the start of the COVID-19 pandemic. **Where single-use masks are made in China and transported to Europe by air rather than by sea, transport strongly dominates their environmental impacts** (Allison *et al.* 2020; Bouchet *et al.* 2021).

Formal waste disposal of face masks (incineration and landfill) was generally shown by the LCA studies to be a less important contributor to environmental impacts, with carbon emissions arising from burning fossil-based plastics at end-of-life found to be somewhat significant for the carbon footprint of single-use masks in some studies. An exception is where the LCA took into account the electricity and heat generated from incinerating single-use face masks (as in Lee *et al.* (2021)), with the energy credits allocated to the single-use face masks playing an influential role in certain impacts. It is however important to note that only Bouchet *et al.* (2021) looked at potential for littering of face masks, although littering and mismanagement (e.g., dumping or open burning) is known to be occurring (see for e.g., Haque *et al.* (2021) and Selvaranjan *et al.* (2021) and EEA (2021a)). Single-use face masks were found by Bouchet *et al.* (2021) to have a high plastic leakage potential even in the Swiss context of the study where mismanaged waste is not a factor. The study estimated that an equivalent of 570,219 plastic bottles (1.5 l) entering the ocean per year could be avoided if just 10% of the Swiss population switched from using single-use face masks to cotton face masks.

End-of-life disposal was not a particular focus of any of the LCA studies, although Lee *et al.* (2021) evaluated landfill disposal relative to incineration in a scenario and found landfill disposal to increase the environmental

²⁶ A mask made from 100% post-consumer recycled PET was found to have a carbon footprint seventeen times lower than a single-use mask made from polypropylene (covering materials, transport, manufacture, distribution, use and end-of-life, and assuming 50 machine washes at 60°C) (Arpe 2020).

preference for reusable face masks (owing to the single-use face masks having higher end-of-life emissions when landfilled since they no longer receive waste-to-energy credits as when incinerated). An LCA of the disposal of

PPE kits (including face masks) found that decentralised incineration is the preferred disposal option compared to landfill or centralised incineration (Kumar *et al.* 2020).

3.2 IMPORTANT ASPECTS OF LCAS OF SINGLE-USE FACE MASKS AND THEIR ALTERNATIVES

Based on the studies reviewed in the meta-analysis, the following aspects are identified that should be considered when undertaking and interpreting LCAs of single-use face masks and their alternatives.

Face mask design and options considered: A wide array of different designs of face masks have emerged over the COVID-19 pandemic, thus care should be taken not to generalise the findings of LCAs on single-use vs. reusable masks without a thorough exploration of the possible options. The various LCAs covered different types of face masks, without significant overlap between the option sets of the studies. Reusable face masks are made out of a variety of fabrics and only home-made masks are likely to be made from 100% cotton. Indeed, guidelines for reusable face masks recommend they be made from a combination of natural and synthetic fabrics for good filtration performance. Face masks can also be made from repurposed or recycled fabrics. The only type of face mask common to all the LCA studies is the surgical face mask (also known as a medical mask), although these are not the only single-use face masks worn by the general public. Filtering facepiece respirators (FFPs) – of which the N95 mask is a well-known example – are also widely used, despite being recommended only for health care providers and high-risk individuals (WHO 2020a). Only Boix Rodríguez *et al.* (2021b) include the higher efficacy respirator-type masks²⁷ in their analysis. Boix Rodríguez *et al.* (2021b) is also the only study to include a rigid-type reusable mask disinfected

with ethanol. The potential for single-use masks to be used multiple times, as assessed in Bouchet *et al.* (2021), is an additional factor needing consideration.

Functional equivalence: the LCA comparisons of single-use vs. reusable masks covered in the meta-analysis are all only intended to be relevant in a community setting (i.e., for mask-wearing by the general public). There is evidence to suggest that reusable fabric face masks are less effective at stopping the transmission of viruses (and other airborne diseases) than respirators (Bhattacharjee *et al.* 2020; O’Kelly *et al.* 2020; WHO 2020b). For this reason, fabric face masks are recommended only as a last resort in a health care setting. There is also a wide range in efficacy between different designs of reusable masks (Geddes 2020), from relatively ineffective home-made cotton masks to labelled fabric face masks that guarantee a filtration efficiency similar to that of surgical masks. Perhaps even more importantly, incorrect face mask usage – of both single-use or reusable masks – results in little or no infection control. It should be noted that all advice on the wearing of face masks recommends this be in addition to – and never in place of – other infection-prevention measures, such as social distancing and regular hand washing (Javid, Weekes and Matheson 2020; WHO 2020b). This implies that in a community setting, at least, the inability of LCA to take the functional equivalency of the masks into account in terms of their efficacy is perhaps less significant.

²⁷ FFP2 mask and N95 masks – popular in different parts of the world - are roughly equivalent in their efficacy although not identical (FFP2 masks have a filtration efficiency of 94% and N95s a filtration efficiency of 95%).



Behaviour of consumers: There is currently little data on user behaviour to support assumptions on how masks are being used by the general public. Ideal or recommended behaviour, as tends to be assumed in the studies, could be far from how consumers are actually behaving. This is significant since the number of times reusable masks are washed and re-worn is critical in evaluating their environmental performance relative to single-use masks, as is how they are washed and/or sterilised between uses. To date there is little data on how masks are being used by the general public, but changes in the behavioural assumptions can greatly affect the results of the comparison between single-use and reusable face masks. For example, **a survey by YouGov found that only 32% of those wearing reusable masks in the UK wash them after every use, and of this, only 41% wash them in accordance with UK government guidelines** (i.e., using soap or detergent in water 60°C or above) (YouGov 2020). The duration for which consumers retain their reusable masks is also critical. Guidelines recommend reusable face masks be designed for a minimum of five uses and/or that manufacturers indicate the number of times masks should be worn before being discarded (CEN Workshop Agreement 2020; WHO 2020b). However, given the evidence on washing behaviour, it is doubtful whether consumers take note of such guidelines. The number of face masks a consumer has in rotation is also likely to vary considerably between consumers. It is recommended, to have at least two reusable face masks in rotation to ensure adequate cleaning and drying of masks before use, although the number is dependent on personal preference and economic feasibility (MacIntyre *et al.* 2020).

Non-ideal consumer behaviour is not limited to reusable masks, with the YouGov survey finding **only 44% of those wearing single-use masks in the UK dispose of them after a single use, with most users wearing them multiple times before throwing them away** (YouGov 2020). This is very significant since in the LCA studies (with the exception of Bouchet *et al.* (2021)), single-use masks are assumed to be disposed of after a single or daily use. Furthermore research suggests that **single-use face masks can – and are – being decontaminated and reused** despite this being against manufacturers' recommendations (Bhattacharjee *et al.* 2020). Although the research still needs validation, simple strategies for decontaminating single-use face masks

– such as dry heat in an oven, or even just leaving them for a sufficient length of time in the open air – can render masks safe for reuse (by the same user). This substantially lowers their environmental impacts and makes them a competitive choice relative to reusable masks with regards to their environmental impacts (Bouchet *et al.* 2021).

Modelling choices: Similar to behavioural assumptions, modelling choices can also have a large effect on the comparison of single-use and reusable face masks. In particular, the LCA studies differ on the importance of the washing stage – owing to modelling choices around the washing, such as the washing machine energy efficiency, the size of the load and how many masks are washed together – and on the importance of transport to market (owing to the assumption of whether masks are transported by air or by sea).

Geographical context: The available studies are limited in their geographic scope (all Western European other than one study covering Singapore). The results are very likely to be affected by factors that differ by geographic region, including electricity grid mix and washing and waste management practices. Manufacturing location (including where materials are sourced from and components are made) and the subsequent transport to market was found to be a very significant parameter if air freight is required. The likelihood of mismanaged waste and littering is also very significant with regards to the potential environmental impacts of single-use face masks.

Choice of environmental impact indicators: The intention of LCA is to assess environmental impacts across all types of environments so as to better understand trade-offs and avoid burden shifting. There is however a tendency to focus on climate change due to its relevance and priority to policy makers. Notable in this regard is the current limitation of the environmental impact category indicators applied in LCAs to fully consider the impacts from plastics, such as single-use face masks and filters ending up in watercourses, and microplastics generated when manufacturing and washing synthetic fabrics. Bouchet *et al.* (2021) include an indicator of the relative plastic leakage potential of the masks considered in their study, acknowledging this limitation of current LCIA methods.



To date there is **little data on how masks are being used** by the general public, but changes in the **behavioural assumptions** can greatly **affect the results of the comparison** between single-use and reusable face masks.

3.3 IMPORTANT ASPECTS IN POLICY MAKING

Policy advice on face masks is particularly sensitive as it has implications for the health and safety of citizens. It is therefore **imperative that the advice derived from this meta-analysis is only applied in the context for which it is relevant; that of mask-wearing in a community setting, and where mask-wearing is clearly communicated to be only one of a number of infection-control measures that should be followed**, such as social distancing and regular hand washing. Reusable cloth masks are generally not recommended in a health care setting.

This meta-analysis recommends that – when considering the environmental impacts of face masks – policies on face mask-wearing in a community setting, i.e., by the general public and non-high-risk individuals, should promote the use of reusable face masks. These are shown to have lower environmental impacts under most scenarios, especially when they are used for a number of weeks and washed in a washing machine together with the regular wash loads in the household. They also do not have the high propensity for littering that single-use face masks have (Ammendolia *et al.* 2021) and avoid the production of non-recyclable plastic waste. However, it must be kept in mind that the LCAs from which this recommendation is derived are not able to inform on the relative effectiveness of the face masks. The environmental impacts of hospitalisation can be enormous, therefore wearing effective masks, to protect the wearer and those around them, is ultimately the best option, since it avoids potentially very high environmental impacts of medical treatment.

Ideally the comparison should only be between masks of similar filtration efficiency, which is only possible for masks that have been tested and/or adhere to some sort of standard or label. This is not the case for many

community masks, especially home-made varieties. It is therefore recommended that countries deciding to promote reusable masks **develop minimum performance standards for reusable masks**, as has already been done in some countries²⁸. Countries should work with international organisations (e.g., WHO, ISO, etc.) to **develop a widely agreed set of minimum performance standards** that require producers of reusable masks to both meet a minimum effectiveness standard for protecting their population and maintain this performance for a specified number of washes²⁹.

It is however imperative to note that there is currently **insufficient evidence on how mask wearing in community settings affects health outcomes and the spread of viruses** to support the development of standards and policies on face masks. There is no clear evidence for what level of filtration efficiency is relevant in a community setting. There is also little understanding on how mask design and consumer behaviour with regards to the wearing, washing and disposing of masks affects the degree to which masks protect the wearer and those around them. Such studies are urgently needed in order for policy makers to be able to determine what sort of masks should be recommended in particular settings (with respect to their effectiveness in protecting the wearer and reducing the spread of viruses), and so for policy makers to be in a position to weigh up the environmental benefits of reusable masks against the higher filtration efficiency of single-use masks.

Guidelines and standards on face masks should be regularly reviewed and based on best available scientific information. While the health and safety of citizens need to remain central in any policy around face masks, it is important to consider the effect of central government



While the health and safety of citizens need to remain central in any policy around face masks, it is important to consider the **effect of government advice** and regulations on the environmental impacts of face masks.

²⁸ For example, the French Standardization Association (AFNOR Group), The European Committee for Standardization (CEN), Swiss National COVID-19 Task Force, the American Association of Textile Chemists and Colorists (AATCC), the South Korean Ministry of Food and Drug Safety (MFDS), the Italian Standardization Body (UNI) and the Government of Bangladesh (WHO 2020b).

²⁹ Noting that reusable masks need to be able to withstand a sufficiently high number of washes to have clear environmental benefits over single-use masks. The LCA studies in this meta-analysis suggest that reusable masks need to be used around 10 to 20 times to have lower environmental impacts than single-use masks.

advice and regulations on the environmental impacts of face masks. For example, standards and guidelines on reusable masks, such as washing them at temperatures of above 60°C, boiling to sterilise them, washing them in isolation and advice to dispose of them after five uses, might make sense from a precautionary standpoint, but have the potential to significantly increase their environmental impacts. Furthermore, many guidelines are not supported by scientific evidence as governments rushed to put together resources for consumers at the start of the COVID-19 pandemic.

There is also evidence that many consumers do not follow the guidelines, and **education and awareness raising around the correct handling of masks** – the number of reuses and acceptable washing/decontamination strategies – is needed. Education around the correct disposal of masks and litter awareness campaigns are also needed.

While the overarching recommendation of this meta-analysis is to favour reusable face masks (in the appropriate setting), there are also a number of ways in which policies can improve the environmental impacts arising from single-use face masks³⁰. As a single-use plastic product, much of the research and advice on improving the circularity of single-use plastic products is relevant also for single-use face masks, such as using bio-based rather than fossil-based plastics, reprocessing for reuse, and implementing advanced waste management technologies (Patrício Silva *et al.* 2020; Rowan and Laffey 2021). Advanced waste

management options that have been suggested (but not yet proven at scale) include using single-use face masks in wastewater treatment filters, as thickening agents and in construction materials (Asim, Badiei and Sopian 2021; Selvaranjan *et al.* 2021). There is a lack of information on the application of bio-based plastics specifically to face masks and research is needed. Similarly, there is a lack of studies on the use of recycled materials in face masks, specifically if this has any impact on the effectiveness of the masks. Other design elements of the face masks also have potential to decrease their environmental impacts, such as replacing the aluminium nose wire with a lower-impact material.

Determining points of high littering of single-use face masks, and/or where littering has potential for high impact will allow interventions to reduce the impacts of single-use face masks to be prioritised. For example, touch-free waste bins in grocery store and hospital parking lots (Ammendolia *et al.* 2021) and waste bins with lids on quaysides in ports (WWF Italy 2020). Furthermore, wherever mask wearing in a community setting is mandated, especially in cases where single-use masks are handed out, provision for the regulated disposal method should be made. For example, bins provided at the exit points of public transport.

This meta-analysis is not intended to provide definitive environmental guidance on the “best” face mask and in so doing promote policies that prohibit or limit the use of alternatives. Rather, this report serves to highlight important aspects that policy makers should consider when

³⁰ UNEP's COVID-19 waste management factsheets are a useful resource here: <https://www.unep.org/resources/factsheet/covid-19-waste-management-factsheets>



evaluating the limited life cycle environmental information available on face masks, and in so doing, to inform policy development that is context specific and locally relevant. In particular, the following are recommended:

- **Policies on face masks should take a systems perspective. With face masks, health concerns and the effectiveness of the masks need to be balanced with their environmental impacts.** LCA studies employ a systems perspective in that they consider the life cycle of a product from resource extraction, production, through to use and end-of-life disposal. The use phase is highly influential in determining the environmental impacts of reusable face masks (how often and in what manner they are washed), while the potential for littering and adding to single-use plastic products waste are notable factors in the single-use face mask system. The materials from which they are manufactured are important for both single-use and reusable masks. It is therefore necessary to consider the whole life cycle system in a policy on face masks. In addition to the life cycle system, it is critical to recognise that the use of face masks sits within a wider socio-economic system. There are thus additional factors that need to be considered in designing an appropriate policy on face masks, including those related to health and safety, affordability and attitudes to reusable options (including perceptions on efficacy and behaviour change required). Additional considerations include waste management infrastructure, implementation costs and related implementation barriers. Many of these factors are not only country specific, but they also vary with time.
- **Policy makers should be made aware of differences in environmental impacts between and within material categories** and the reasons for these differences. There are currently insufficient LCA studies to gauge the likely range in environmental impacts. This is especially true for reusable face masks, since these can be made from a range of different materials, with

potential to use repurposed and/or recycled materials. Further LCA studies are required to assess the wide range of materials from which reusable masks are being manufactured, and especially of masks which comply with guidelines for manufacturing reusable face masks. Most notably, that reusable face masks be comprised of three layers of fabrics with different properties (most likely requiring a mix of synthetic and natural fabrics)³¹.

- **Policy makers should be aware of the potential for likely future developments in face mask designs, materials and related systems.** Given the dramatic rise in the use of face masks since the start of the COVID-19 pandemic, new designs and materials are constantly emerging, as is scientific evidence as to what are the most effective materials and designs. Emerging evidence of effective decontamination strategies allowing reuse of “single-use” masks is an additional factor. Policy makers need to keep abreast of developments, but also to be aware that a rapidly developing field makes decision-making more difficult. More recently developed technologies may be at a disadvantage to other more established technologies due to their scale. Where possible, learning rates should be included in terms of environmental performance. Current LCA results may also change if future developments in energy, transport and waste management systems are incorporated.
- **Policies must be geographically adapted.** Many of the aspects that impact environmental performance are geographically dependent, such as the carbon-intensity of the electricity generation mix, available waste management systems and end-of-life practices. It is critical that policy makers understand and appreciate the implications and feasibility of proposed policies in the context of geographical constraints. Water and energy infrastructure is notable in the case of reusable face masks, with citizens requiring clean, hot water to care for these. Waste management infrastructure is especially notable in the case of single-use face masks, which produce large volumes



It is critical that policy makers **understand and appreciate the implications and feasibility of proposed policies in the context of geographical constraints.** Water and energy infrastructure is notable in the case of reusable face masks, with citizens requiring clean, hot water to care for these.

31 See for example, WHO (2020b) Mask use in the context of COVID-19: Interim guidance and the WHO video: The Three layer fabric mask: <https://youtu.be/iYEOA-5wd14>

of non-recyclable plastic waste. As with any single-use plastic products waste, there are a number of advanced or future waste management technologies that have the potential to reduce the environmental impacts associated with disposing single-use face masks. Nonetheless, limited infrastructure and challenges around the safe and effective collection of face masks are a barrier to implementation of advanced recycling technologies in many countries.

- **Policies must be culturally adapted.** In the same way that policies need to take into account country or region-specific characteristics, they also need to take into account the characteristics of the consumer population that will be impacted on by the policy. In particular, washing practices and the potential for inappropriate disposal of single-use masks are important factors influencing the relative environmental preference for reusable face masks over single-use face masks.
- **Policies must recognise and manage the trade-offs and risks of burden-shifting between environmental, health and socio-economic impacts.** Care must be taken to recognise and manage the trade-offs between other quantified and unquantified environmental impacts such as the issue of macro- and micro-plastic pollution which is important to include in the context of face masks. Inappropriate disposal of single-use face masks is contributing to this ever-growing problem, while reusable face masks made from synthetic materials are also a potential contributor to microplastic pollution (noting this is dependent also on the wastewater treatment practices of the particular country). Related to the above, **policies must be based on several sources of information for environmental, health and socio-economic impact.** In addition to macro- and micro-plastic pollution as noted above, other issues to consider include health and safety aspects, such as potential use of chemicals for antiviral coatings and disinfecting masks.



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