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Research Article

The environmental impacts of different mask options for healthcare settings in the UK

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A B S T R A C T

During the COVID-19 pandemic, different strategies emerged to combat shortages of certified face masks used in the healthcare sector. These strategies included increasing production from the original manufacturing sites, commissioning new production facilities locally, exploring and allowing the reuse of single-use face masks via various decontamination methods, and developing reusable mask alternatives that meet the health and safety requirements set out in European Standards. In this article, we quantify and evaluate the life-cycle environmental impacts of selected mask options available for use by healthcare workers in the UK, with the objective of supporting decision- and policy-making. We investigate alternatives to traditional single-use face masks like surgical masks and respirators (or FFP3 masks), including cloth masks decontaminated in washing machines; FFP3 masks decontaminated via vapour hydrogen peroxide, and rigid half masks cleaned with antibacterial wipes. Our analysis demonstrates that: (1) the reuse options analysed are environmentally preferential to the traditional "use then dispose" of masks; (2) the environmental benefits increase with the number of reuses; and (3) the manufacturing location and the material composition of the masks have great influence over the life-cycle environmental impacts of each mask use option, in particular for single-use options.

1. Introduction

The COVID-19 global pandemic drew attention to the vast amount of single-use personal protective equipment (PPE) required within the healthcare sector to prevent, and protect against, the spread of airborne infections. The use of medical face masks, better known as surgical masks (EN14683 Type IIR grade), and respirators (EN149 FFP3 grade) by the UK National Healthcare Service (NHS) increased 70 times, from approximately 20 million units in 2019 to 1.4 billion units in 2020 (Department of Health &amp and Social Care, 2021). The resulting increase in waste, partly observed through increased littering on the streets, caused great environmental concerns. Furthermore, the demand for surgical masks and respirators from healthcare systems far outstripped their availability, causing global shortages especially in the earlier months of the pandemic. This led some governments, like the UK Government, to advise the general public to use reusable cloth masks to make conventional certified masks available for healthcare workers. To tackle global mask shortages, government bodies, industry and research institutes began exploring ways to prolong the use of single-use masks and investigating reusable alternatives for healthcare use (see Section 2). According to their findings, recommendations were also made for extended use or reuse of masks in cases of shortages (Toomey et al., 2021).

Masks shortages have now become less frequent due to a combination of suppliers increasing their manufacturing capacity and the easing of the pandemic, but the experience provided the healthcare system with multiple options for procuring and managing masks. These include how masks are sourced (i.e. where they are produced and how they are transported to users), the types of masks to employ (i.e. single-use or reusable, or materials of construction), and the method for decontamination (if reuse is possible). Indeed, there is also increasing pressure on the healthcare sector to become more environmentally sustainable. A survey showed that 66.2 % of UK healthcare workers agree that employing reusable masks would provide environmental benefits in healthcare settings (MedSupplyDriveUK, 2021). The National Healthcare System (NHS) in England (UK) has pledged to become carbon-neutral by 2040 (NHS, 2020). Reducing clinical waste, including masks, that is likely sent to incineration can significantly reduce carbon emissions. Nonetheless, reducing masks sent for incineration does not necessarily guarantee lower impacts from a life-cycle perspective because other processes must also be considered. For instance, Allison et al. (2021)

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found that when reusable masks are hand-washed, they can generate higher impacts than employing surgical masks, especially if these are sourced more locally (i.e. from Turkey instead of China, to the UK).

Life Cycle Assessment (LCA) is a well-established, standardised (ISO, 2020; ISO, 2006) methodology for assessing the environmental impacts of products from cradle-to-grave, i.e., including materials extraction, product fabrication, use, and final disposal. Considering all life cycle stages and multiple environmental impact categories enables comprehensive comparisons between options, showcasing their merits and trade-offs, highlighting areas for improvement and providing a robust framework to support decision-making. Several Authors have investigated the environmental performance of face masks for use by the general public, covering single-use and reusable alternatives, design characteristics, manufacturing and transport scenarios and users' behaviours. Allison et al. (2021) compared the environmental impacts of several scenarios for single-use and reusable face masks use in the UK, whilst similar options were evaluated by Schmutz et al. (2020) and Bouchet et al. (2021) for Swiss conditions. Lee et al. (2021) investigated the environmental performance of a three-layer embedded filtration layer (EFL) for reusable face masks that was developed in Singapore. Rodríguez et al. (2021) developed eco-design guidelines to support the design of low-impact face masks. UNEP (2022) critically reviewed these studies, and summarised their key findings, as part of a study commissioned by the United Nations Environment Programme and the Life Cycle Initiative.

Our work builds upon the above studies but extends the investigation to face masks certified for use by healthcare workers, which to the best of our knowledge is yet to be covered in the scientific literature; notably, our study covers medical devices like surgical masks and protective devices like respirators. The objective is to identify the best performing available options, pinpoint key environmental hot-spots, and support policy- and decision-making, in the UK and worldwide.

2. Mask Options for the Healthcare Sector

Like in many European countries, face masks intended for use in the UK healthcare sector are regarded as personal protective equipment (PPE) because they are essential for preventing the spread of diseases. Under the EU Regulation 2016/425 (as incorporated into UK law) on Personal Protective Equipment ("the PPE Regulation"), masks must meet the essential health and safety requirements set out in European Standards. Masks used in healthcare are certified as either medical or protective devices under two standards: EN14683:2019 and EN149:2001, respectively. Table 1 summarises conventional and emerging mask options within the healthcare sector, including compliance requirements and recommended use. The surgical mask and the respirator are respectively the best-known medical-grade and protective-device-grade masks. Both were designed as single-use, most likely due to hygiene and contamination risks arising from reuse, particularly in healthcare.

Respirators generate higher levels of protection than surgical masks. When tested on their efficacy for filtering viral-sized nanoparticles, respirators have 87 % efficacy compared to 76 % for surgical masks (Table 1). For this reason, the UK Health Security Agency (2021) recommended FFP3 respirators for use in areas with higher risks of infection to protect healthcare professionals, whilst surgical masks should be used for preventing the spread of airborne diseases in lower-risk areas. To provide a fair comparison, in our study we consider the functionality provided by masks. We distinguish between "medical-grade" (M) and "protective-device-grade" (P) according to whether masks perform similarly to conventional surgical masks and respirators (see Section 3).

Mask options do not limit to material composition and the decontamination process that will be employed (if applicable), but they also include how masks will be supplied. In the UK, both surgical masks and respirators are typically sourced from China and were imported via air freight during global shortages. This formed the base case of our study. However, efforts were made to combat shortages and to secure supplies by increasing production capabilities, for example in China and locally in Europe and the UK. Greater production and supply of masks from China can mitigate mask shortages for extended periods; this entails that ship freighting could be a viable option. When masks are manufactured in the UK, materials are likely to be sourced from Europe (e.g. Turkey – a larger exporter of textiles) and transported by road. Our previous work showed that ship freighting from China and relocating surgical masks from China to the UK or Turkey would generate lower environmental impacts than air freighting surgical masks from China for general public use (Allison et al., 2021). In this study we assess different combinations of production locations (China and the UK) and likely transportation mode for supplying conventional single-use masks to the UK healthcare settings to identify envirionmental preferable options (see Section 3.1).

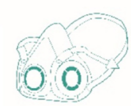
Health authorities recommend surgical masks for extended use of up to 6 h provided that they are used and stored correctly during any breaks in usage and if they are not soiled or damaged, but they should not be decontaminated for reuse (Toomey et al., 2021). The reusable alternative to surgical masks is cloth masks. Research has shown that they can provide similar performances to surgical masks, depending on the materials of construction (Allison et al., 2021). Commercial cloth masks compliant with EN14683 are now available on the market. It must be noted that for healthcare use, Public Health England (2020) specifies that cloth masks must maintain their properties after 60 °C launderings.

For respirators, health authorities advise that their use could be extended up to 8 h and that they could be decontaminated for reuse (Toomey et al., 2021). The most effective decontamination methods include vapourised hydrogen peroxide (VHP), ultraviolet germicidal irradiation and thermal sterilisation (Côrtes et al., 2021; Kumar et al., 2021; Sarkis-Onofre et al., 2021; Toomey et al., 2021). In the UK, a joint effort by the Institute of Chemical Engineers (IChemE) and the International Society for Pharmacoepidemiology (ISPE) suggested that the use of VHP for decontamination is most viable based on literature studies (Côrtes et al., 2021; ECDC, 2020; Sarkis-Onofre et al., 2021). Studies have shown that masks can be decontaminated up to 20 times before mask integrity fails (Laatikainen, 2020; Sherwood et al., 2011). In addition, it was found that this technology could meet UK health and safety regulations for deployment.

Another alternative to conventional respirators is reusable rigid half masks, which are conventionally used in construction settings. A survey conducted through MedSupplyDrive UK (MSD UK) revealed that 80 % of 487 healthcare professionals were supportive of reusable half masks (MedSupplyDriveUK, 2021). Furthermore, Gillian Higgins (2021) indicated that half masks provide greater protection than disposable FFP3 masks whilst being substantially cheaper in the long run for the healthcare setting. Rigid half masks certified under either EN140:1999 or EN1827:1999 are known as "facepieces" and are graded as protective devices. The face seal requirements for both standards are equal to those for EN149 (i.e. protective devices) but are tested to protect against a wider range of substances typically found in construction settings, e.g. dust particles and solvents. Unlike conventional respirators, half masks must be equipped with disposable filters that are certified under EN143:2000 to provide full functionality (i.e. to meet EN140 or EN1827 standards) and equal particle filtration efficiencies to EN149.

Rigid half masks typically have a shelf-life of 5 years, and EN143 compliant filters are often reusable filter cartridges with a lifespan of up to 6 months in construction settings (3M, 2007; GVS, 2015; Moldex, 2016a). Notably, the long lifespan suggests lower waste arising from expired products; but their manufacturing and maintenance are more material-intensive, which may introduce additional environmental impacts. In addition, it is understood that six-monthly changes may not meet healthcare settings' health and safety and hygiene requirements. This is because rigid half masks with filters, like FFP3 masks, were initially designed to protect users from fine particulates in

Table 1
Summary of conventional face masks used in healthcare and emerging reuse/reusable alternatives.

	Medical Device Grade (EN14683 compliant)	Protective Device Grade (EN149 compliant)
Compliance requirements	**Classifications:** Type I - >95% BFE[a] Type II - >98% BFE[a] Type IIR - >98% BFE[a] and splash resistant	**Classifications:** FFP1 - >80% PFE / 22% MIL[b] FFP2 - >94% PFE / 8% MIL[b] FFP3 - >99% PFE / 2% MIL[b]
Recommended use situation in healthcare[c]	Use of Type II and IIR for **PREVENTION** in areas with lower risks of infection. i.e. to limit the spread of diseases.	Use of FFP3 (and FPP2 in cases where FFP3 is unavailable) for **PROTECTION** in areas with a higher risk of infection.
Mask conventionally used in the UK healthcare	 Common name: Surgical Mask **Viral filtration efficiency: 76%[d]** Use mode: **single-use**, disposed of as clinical waste Source: China	 Common name: Respirator **Viral filtration efficiency: 87%[d]** Use mode: **single-use**, disposed of as clinical waste Source: China
Reusable Alternatives	 Common name: Cloth mask Reuse method: laundered via 60C machine washes†	 Common name: Respirator Reuse method: decontamination via vapourised hydrogen peroxide[e]  Common name: Reusable half mask[f] Reuse method: wipe clean using antibacterial wipe with straps and filter replacements.

[a]**BFE =** bacterial filtration efficiency – efficiency of the mask body in filtering organisms and/or particle-sized 1 μm.
[b]**PFE** = particle filtration efficiency – efficiency of the mask body in filtering particle-sized approximately 0.6 μm; **MIL** = maximum inward leakage – the percentage of particles that can leak through the mask via the mask body, facial seal and exhalation valve.
[c]Sources: CCOHS (2022), CDC (2018), UK HSA (2022)
[d]Source: Konda et al. (2020); the type class of surgical mask tested was not specified, the respirator tested was an N95 (FFP2 equivalent) mask.
[e]The decontamination (or reprocessing) process that is assumed most viable - logistically and hygienically, by the authors. Other decontamination methods for single-use masks include thermal sterilisation and UV irradiation.
[f]Compliance:
Mask Body: EN140 or EN1827 – has the same MIL** as EN149 - FFP3 compliant masks (2%)
Replaceable filters – EN1827 – P1-3 classifications have the same PFE** as EN149 FFP1-3 compliant masks

a = BFE = bacterial filtration efficiency – efficiency of the mask body in filtering organisms and/or particle-sized 1 μm.
b = PFE = particle filtration efficiency – efficiency of the mask body in filtering particle-sized approximately 0.6 μm; MIL = maximum inward leakage – the percentage of particles that can leak through the mask via the mask body, facial seal and exhalation valve.
[c]Sources: CCOHS (2022), CDC (2018), UK Health Security Agency (2022).d = Source: Konda et al. (2020); the type class of surgical mask tested was not specified, the respirator tested was an N95 (FFP2 equivalent) mask.
e = The decontamination (or reprocessing) process that is assumed most viable - logistically and hygienically, by the authors. Other decontamination methods for single-use masks include thermal sterilisation and UV irradiation.
f = Compliance:
Mask Body: EN140 or EN1827 – has the same MIL** as EN149 - FFP3 compliant masks (2 %)
Replaceable filters – EN1827 – P1–3 classifications have the same PFE** as EN149 FFP1–3 compliant masks.

manufacturing and construction industries; the suggested six-month filter lifespan is a guide for industries where airborne microorganisms are unlikely. Bioaccumulation tests and risk assessments must first be carried out to determine the lifespan of filters used in healthcare settings. Current guidelines on the use of reusable PPE in preventing and controlling seasonal respiratory infections in healthcare settings are limited to ensuring products are “decontaminated after each use following manufacturer's or agreed local guidance” (UK Health Security Agency, 2021). We assumed single-use antibacterial wipes are sufficient for cleaning half-masks as per manufacturers' guidance (3M, 2020; USA Dust Guard, 2020)(Table 1); notably, we assess the potential waste arising from each mask option in Section 4.

3. Methods

The LCA study was conducted following the ISO standards 14,040:2006 and 14,004:2006 (ISO, 2020; ISO, 2006) and the Product Environmental Footprint (PEF) guidelines (EC-JRC, 2012), particularly on the guidance for the compilation of inventory data (known as Resource Use and Emission Profile) and the method for environmental impact assessment. The study was performed in GaBi Software (Sphera, 2020a), using a mixture of GaBi (Sphera, 2020b) and EcoInvent v.3.6, cut-off model (Ecoinvent, 2019; Wernet et al., 2016) databases. These databases provide life-cycle inventory data covering materials manufacturing (e.g. for polypropylene, PP), energy generation, transportation and disposal of end-of-life waste.

3.1. Goal and Scope Definition

This study aims to evaluate the environmental impacts associated with different mask options within the healthcare sector (Section 2), which can potentially combat mask shortages in the future. Table 2 summarises the LCA scenarios that we investigated, whilst Fig. 1 illustrates the system boundaries for each scenario (i.e. the life cycle stages and processes considered). The system boundaries include material sourcing and manufacturing, transportation, mask use and reuse (if applicable), and waste processing at the end-of-life (EoL). In addition, the life cycle includes activities associated with sourcing, using and disposing of packaging and cleaning materials. The functional unit (FU) corresponds to “one year of mask use per healthcare professional”.

For each scenario, the number of masks required to fulfil the FU was calculated based on the assumption that a professional works an

Table 2
Summary of scenarios investigated. Scenarios are compared on the basis of the mask grade, i.e. medical (M) or protective (P) device. Note that M and P Scenarios cannot be compared as their functionalities within the healthcare setting are different.

Mask Grade	Scenario	Mask Type	Mask Materials	Material Source	Manufacturing Location	Transport to the UK	Number of Uses	Decontamination method	Number of masks/year	Number of wipes/year	Number of straps/year	Pairs of filters/year
Medical (M)	M1	Surgical mask	PP non-woven	China	China	Air	1	N/A	480	N/A	N/A	N/A
	M2	Surgical mask	PP non-woven	China	China	Shipping	1	N/A	480	N/A	N/A	N/A
	M3	Surgical mask	PP non-woven	Turkey	UK	Road	1	N/A	480	N/A	N/A	N/A
	M4	Reusable cloth mask	Polyester	Portugal	UK	Road	16	60 °C machine washes	30	N/A	N/A	N/A
	M5	Reusable cloth mask	Polyester	Portugal	UK	Road	31	60 °C machine washes	15	N/A	N/A	N/A
Protective device (P)	P1	FFP3	Polypropylene and PET	China	China	Air	1	N/A	480	N/A	N/A	N/A
	P2	FFP3	Polypropylene and PET	China	China	Ship	1	N/A	480	N/A	N/A	N/A
	P3	FFP3	Polypropylene and PET	Turkey	UK	Road	1	N/A	480	N/A	N/A	N/A
	P4	FFP3	Polypropylene and PET	Turkey	UK	Road	5	Hydrogen peroxide	96	N/A	N/A	N/A
	P5	FFP3	Polypropylene and PET	Turkey	UK	Road	21	Hydrogen peroxide	23	N/A	N/A	N/A
	P6	GVS	TPE (body), PTFE and carbon fiber (filters)	China	UK	Shipping	1 year life-span	Wipes	1	480	4	12
	P7	GVS	TPE (body), PTFE and carbon fiber (filters)	China	UK	Shipping	1 year life-span	Wipes	1	480	4	2

average of 240 shifts per year, each lasting between 7.5 and 12 h (NHS Fife, 2021; NHS Professionals, 2020). According to NHS guidelines, 30 min breaks are required for shifts above 6 h in length (NHS Fife, 2021). For textile-based masks (surgical masks, respirators and cloth masks), we assumed that two individual masks are required per shift; this is because they are recommended to be changed between 3 and 8 h of use as they lose breathability and integrity due to moisture builds up (Kobayashi et al., 2020). As noted in Section 2, authorities state that textile-based masks should not be reused once donned unless they are decontaminated. Scenarios M1 to M3 and Scenarios P1 to P3 describe the requirements for the conventional single-use medical-grade mask (i.e. surgical mask) and protective-device-grade mask (i.e. FFP3 respirator). The differences among these scenarios include the source of materials, manufacturing location, and the mode of transport to the UK (see Section 3.2.1 and Table 2).

Scenarios M4 and M5 investigate the environmental performance of reusable cloth masks in place of single-use ones. We considered two different numbers of reuses before disposal, based on data provided by multiple suppliers as described in Allison et al. (2021). Although masks are washable up to 40 times (Revolution-ZERO, 2021), their filtration efficiency may reduce after a certain number of washes. Considering potential breakage and loss rates, Allison et al. (2021) assumed that cloth masks would likely be usable between 15 and 30 washes. Similarly, Scenarios P4 and P5 and Scenarios P6 and P7 evaluate respectively the environmental performance of reusing FFP3 respirators and using rigid half masks instead of single-using FFP3 respirators. Scenarios P4 and P5 represent the lower and upper bounds for the number of possible reuses of FFP3 masks when decontaminated via vapourised hydrogen peroxide (VHP). Literature studies suggest that VHP does not affect significantly mask integrity for up to 20 decontamination cycles (21 total uses - Scenario P5), but that it diminishes the elasticity of straps, thus affecting mask fit from four cycles onwards (5 total uses - Scenario P4) (Laatikainen, 2020; Mackenzie, 2020; Sherwood et al., 2011).

For rigid half masks (Scenarios P6 and P7), there are no recommendations on the duration of mask use, most likely because the mask body is not textile-based, and thus its integrity is not affected by moisture build-up. According to the manufacturers' guide and UK Health and Safety Executive (HSE), to ensure masks operate effectively users should ensure any straps provided have good elasticity for securing masks, and mask surfaces should be disinfected using clean damp cloths soaked in the solution, e.g. antibacterial wipes (3M, 2020; Health and Safety Executive, 2022; USA Dust Guard, 2020). Since straps can lose their elasticity over time, we assumed they are replaced every 3 months. We also assumed that once mask surfaces are wipe-cleaned adequately, there should be no issue for reusing rigid half masks in healthcare settings, provided that they are securely stored between uses. The filtering component of the mask should be changed once mask breathability lowers. Our reference product – GVS P3 masks – states that filters have a lifespan of 6 months (GVS, 2015). However, since it is unclear whether a six-month filter change frequency can meet health and safety requirements for use in the healthcare sector (Section 2), we considered an additional scenario where the filter is changed monthly. This enabled investigating the environmental trade-offs between reusing FFP3 via VHP decontamination and employing half masks. Due to lack of data, we assumed that the lifespan of rigid half-masks is 1 year. Additional scenarios were explored as part of this study, including FFP3 respirators manufactured using different material compositions and multiple lifespans for rigid half masks (see Supplementary Information – Table S1 for details).

3.2. Life Cycle Inventory – Assumptions and Calculations

3.2.1. Mask Compositions and Manufacturing, and Packaging Requirements

For each scenario, we identified a reference product on the market that formed the basis of our investigation. In Table 3, we report the reference product and the assumed mask composition for each mask type,

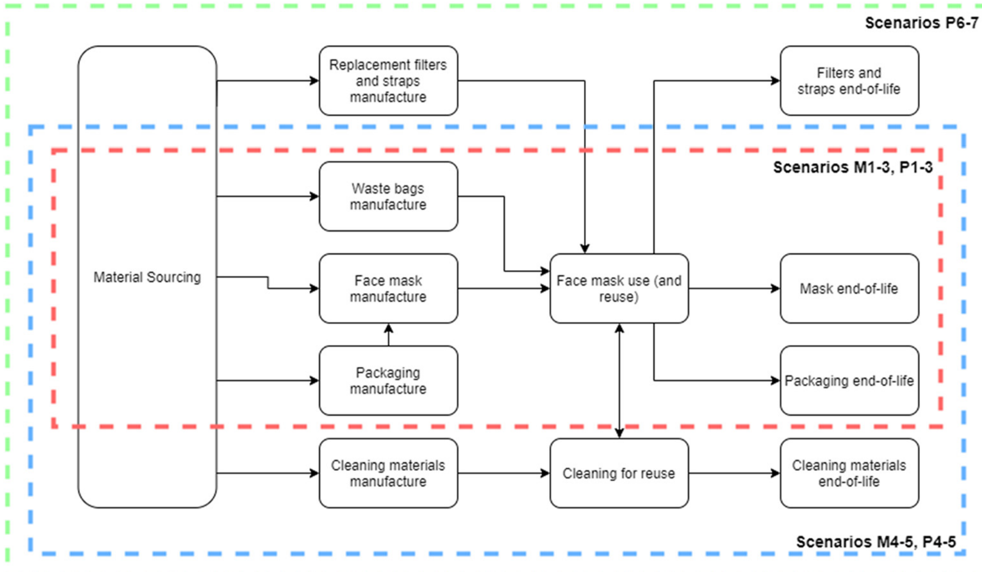


Fig. 1. System boundaries of investigatedmask options, including the use and disposal of conventional masks (Scenarios M1–3 and P1–3) and reuse strategies for both conventional and alternative masks (Scenarios M4–5 and P4–7). Note that "Cleaning for reuse" represents the laundering of cloth masks in M4–5, decontamination of FFP3 masks using vaporised hydrogen peroxide (VHP) (P4–5) and wipe cleaning rigid half masks with antibacterial wipes (P6–7). Additionally, note that the impact of disposing of waste bags was evaluated as part of mask end-of-life, and the replacement of straps was only considered for rigid half masks (P6–7) (although there is potential for replacing straps for FFP respirators, this is not evaluated in this study). [Colour required for print].

whilst in Table S2 and S3 in the Supplementary Information, we include manufacturing and packaging requirements respectively. Materials for surgical masks and FFP3 respirators were based on publicly available data, which was released during global shortages of mask supplies (Q1 2020) following calls from the European Apparel and Textile Confederation (EURATEX) to increase local production (EURATEX, 2020) (see Supplementary Information). In addition, we also used data from Henneberry (2020) and MM Material (2016) for materials components and dimensions of surgical masks. For the FFP3 respirator, the materials components and dimensions correspond to the respirator produced by Moldex (2016b), but the thicknesses of the materials used information provided by EURATEX (2020). In addition, an alternate material composition was evaluated for FFP3 respirators, where the PET layer was replaced with a cotton layer, to understand the impacts associated with material choices (see Supplementary Information - Table S4).

For the reusable cloth mask in Scenarios M4 and 5, the reference product is the Revolution-ZERO mask (EN14683:2019 Type IIR certified) developed by Rutherford Research Ltd. (Revolution-ZERO, 2021). This product was trialled at multiple NHS trusts, including the Yorkshire Ambulance NHS Trust (personal communication, 2021). Notably, the Revolution-ZERO mask looks particularly favourable from an environmental perspective because the supplier provides a service for taking back waste masks for recycling and repurposing (see Section 3.2.4). Lastly, the rigid half mask (Scenarios P6 and P7) was modelled against the reference product: the GVS Elipse P3 mask. The company provided the material composition; the weight of each material component was assumed based on the overall weight of the product as specified in product technical specification sheets (GVS, 2015).

For all scenarios, our study did not include the treatment of wastes from manufacturing due to limited data, and the construction and decommissioning of factory machines. Both are deemed to have minor contributions to the overall environmental impacts.

3.2.2. Transport – Materials Sourcing and Production Locations

As shown in Table 2, face masks were assumed to be manufactured in either China, Portugal, Turkey or the UK. In Supplementary Information Table S5, we report the mode of transport and the transport distances applied to the different scenarios.

3.2.3. Mask Decontamination Assumptions

In Scenarios M4–5 and P4–7, masks are assumed to be decontaminated for reuse. Table S6 in Supplementary Information highlights the machine-washing requirements for reusable cloth masks (M4–5), which were drawn from Walser et al. (2011). In this study, the Authors evaluated the environmental impact of t-shirts, with considerations of the environmental awareness (low, medium or high) of wearers, which influences the choice of washing machine category, the quantity of detergent used and the temperature of the wash. We assumed that reusable cloth masks would be washed at healthcare workers' own homes. Since surgical masks are employed in low-risk situations, infection risks to workers when washing masks at home should also be low. We also assumed low-to-medium efficient machines would be employed on average. We used the parameters associated with "low" machine efficiency and a 60 °C full-load wash scenario to allocate the cleaning resources required to clean each cloth mask.

Table S7 in Supplementary Information reports the requirements for decontaminating FFP3 masks using VHP (Scenarios P4–5). The decontamination unit, which would be purpose-built (Duckett, 2020), was envisaged to be a 20 ft. streel-framed container with dimensions of 6.1 m × 2.44 m and a volume of 38.5 m^3. This unit could decontaminate up to 10,000 masks per batch, utilising 1.5 L of hydrogen peroxide and an average HVAC system for pumping and removing vapours in the units (IChemE, personal communication, 2020). An average consumption of 475 $kWh/m^2/yr$ was used for the HVAC system; this was taken from Knight (2012) and considers chiller, chilled water, air handling units, processing pumps, lighting and other "undefined electricity usage". We also assumed that the average operational days are 340 and that the decontamination unit runs two batches per day; this results in a consumption of 10.4 kWh per batch. For transportation to decontamination units, masks were assumed to be triple bagged using 70 L clinical waste LDPE bags, which can fit approximately 150 masks. We also assumed that masks were individually wrapped and packaged into a corrugated box for returning to hospitals; the packaging requirements were assumed the same as its original supply without the card box packaging shown in Table S3. Lastly, the decontamination of rigid half masks (P6 and P7) was assumed via antibacterial wipes. As shown in Tables 2, 480 wipes would be required per healthcare worker

Table 3
Materials of construction for each mask type.

(Scenario) Mask type/Component	Material	Area (m2)	Length (m)	Mass (g)	Source/Reference
(M1–3) Surgical mask					Surgical mask components and their dimensions were taken from: EURATEX (2020), Henneberry (2020) and MM Material (2016)
Mask body					
Layer	PP (non-woven)	0.029	–	0.638	
1Layer	Cellulosic fabric	0.029	–	0.725	
2Layer	PP (non-woven)	0.029	–	0.638	
3Nose wire	HDPE	–	0.098	0.231	
Earloops	Polyetherimide (elastic material)	–	0.185 (each)	0.444	
Total				**2.68**	
(M4–5) Cloth mask					Rutherford Research Ltd. (personal communication, 2021) provided details of the reusable cloth mask components and mass.
Mask body	PET	–	–	9.14	
Nose wire	Aluminium	–	–	0.33	
Earloops	Elastodiene	–	–	0.44	
Total				**9.91**	
(P1–5) FFP3 respirator					The dimension used to calculate the mask body surface area corresponds to the FFP3 respirator produced by Moldex (2016b). The GSM of materials required were obtained from EURATEX (2020).
Mask body					
Layer	PP (non-woven)	0.0513	–	2.31	
1Layer	PET	0.0513	–	2.31	
2Layer	PP (non-woven)	0.0513	–	2.57	
3Layer	PP (non-woven)	0.0513	–	2.57	
4 Layer	PP (non-woven)	0.0513	–	2.57	
5Straps	Polyamide fiber	–	0.9 (2 straps)	1.08	
Staples	Steel	–	–	0.399	
Nose foam	Polyurethane	–	–	0.072	
Nose wire	Aluminium	–	–	1.22	
Valve	PP (rigid)	–	–	5.00	
Total				**20.1**	
(P6–7) Rigid half mask					The reference product for the rigid half mask is the GVS P3 mask. Details of the masks were provided by GVS (personal communication, 2021)
Mask body	TPE (Butadiene/Styrene 60:40)	–	–	78.1	
Straps and support					
Material 1	Raffia, injection PPCP	–	–	17.6	
Material 2	Resin	–	–	1.95	
Filter capsule					
Filtering layers – outer	HESPA	0.00514		4.11	
Filtering layers - inner	PTFE	0.00514		3.60	
Casing	Glass fiber shell			26.7	
Total				**132**	

per year. Material composition and packaging assumptions for the wipes are highlighted in Supplementary Information Table S8. As the wipes are assumed to be non-woven polypropylene materials, they are assumed to be produced in Turkey which is a large exporter of non-woven fabrics (Euratex, 2019).

3.2.4. Waste Management in Healthcare Settings

The end-of-life (EoL) for conventional surgical and FFP3 masks (Scenarios M1–3 and P1–5) follows standard practices for waste disposal in healthcare. Facemasks are classified as “offensive” or “infectious” waste depending on the procedures healthcare workers take whilst wearing the mask (NHS England, 2021, UCLH, personal communications, 2021). This implies that masks must be discarded in yellow or orange clinical bags which are typically triple-bagged for transport to incinerators. In Scenarios M4–5, we modelled a circular scheme for reusable cloth masks (currently being trialled in NHS trusts) whereby the masks are collected via a takeback scheme and then dismantled for recycling. In the case of Scenarios P6–7, filters and wipes for decontamination were assumed to be treated as clinical waste and incinerated, while the mask body and straps were assumed disposed of via general waste. For this, we assumed the UK treatment mix consisting of 43 % landfill, 41 % and 16 % incineration with and without energy recovery, respectively (DEFRA, 2020). Although cardboard is widely recycled, we assumed it is disposed of as general waste because of insufficient data from GaBi (Sphera, 2020b) and Ecoinvent (Wernet et al., 2016) databases. Plastic film, which is used as wrapping for various masks, and straps and films for the rigid half mask, is also not recycled but disposed of as general waste.

3.2.5. Allocation

Recycling and incineration with energy recovery are EoL strategies that provide additional functionalities (i.e. production of recycled materials and energy) to the product system. Multi-functional systems present a methodological challenge in LCA because environmental impacts need to be allocated between the different functions. For the recycling of polyester and aluminium components of the reusable cloth masks in Scenarios M4–5, we use the Circular Footprint formula developed by the Joint Research Center of the European Commission (EC-JRC, 2012) which envisages the allocation of environmental impacts based on price ratios between recycled and virgin materials (see Supplementary Information – Table S9). For wastes that are assumed to be incinerated with energy recovery, we adopt the “crediting” approach which entails considering the benefits of energy recovery by subtracting the environmental impacts associated with the conventional technologies for generating energy, i.e. the grid mix for electricity and natural gas for heat (ISO, 2020).

Table 4
Waste arising per healthcare professional fromf employing medical-grade masks.

	Surgical masks – one use	Reusable cloth masks	
	(M1 to M3)	(M4) 16 uses	(M5) 31 uses
Waste arising per FU (kg)			
Masks	1.29	0.297	0.153
Packaging	0.382	0.0579	0.0299
Disposal bags	0.0781	0.0180	0.00931
Total	1.75	0.373	0.192

Table 5
Waste arising per healthcare professional from employing protective-device-grade masks.

	FFP3 masks – one use	FFP3 masks (from the UK) – decontaminated via VHP		Rigid half masks with replaceable P3 filters	
	(P1 – P3)	(P4) 5 uses	(P5) 21 uses	(P6) Filters replaced monthly	(P7) Filters replaced six monthly
Waste arising per FU (kg)					
Masks (and components)	9.65	1.93	0.459	0.569	0.225
Packaging	2.77	1.95	1.53	0.241	0.180
Wipes (and containers)	–	–	–	0.720	0.720
Disposal bags	0.585	0.702	0.613	0.0781	0.0574
Total	13.0	4.58	2.60	1.61	1.18

3.3. Life Cycle Impact Assessment (LCIA)

The Environment Footprint (EF) 3.0 impact method – a collection of impact categories and indicators developed by the JRC - was used to translate emissions and resources used into environmental impacts (EC-JRC, 2012); here we report results for all environmental categories. A description of each environmental category can be found in Rosenbaum et al. (2018) or in the Supporting Information of Paulillo et al. (2020). Normalisation and weighting were not carried out as part of life cycle impact assessment (LCIA) because impact assessment results alone are sufficient to present the differences in the environmental footprint associated with each mask scenario, and enable recommendations to be drawn.

4. Results and Discussions

4.1. Waste Arising

Alternatives to conventional face masks were not only proposed to tackle global supply shortages but also to allay public concerns regarding waste arising. Table 4 and Table 5 summarise the waste arising from each mask scenario. Only solid wastes were accounted for; wastewater arising from machine washing cloth masks and emissions of water vapour from decontaminating FFP3 masks via VHP were not tallied because waste collections are not required. Our estimations are obtained on a functional unit (FU) basis using data reported in Table 2 and Table 3; for example, the amount of waste surgical masks is estimated considering a mask mass of 2.68 g (Table 2) and the number of uses per year equalling 480 (Table 3).

Table 4 and Table 5 show that single-use surgical and FFP3 masks (Scenarios M1 to M3 and P1 to P3) generated the greatest amount of solid waste requiring treatment. Switching from surgical masks (M1 to M3) to reusable cloth masks (M4 to M5) reduces waste arising from 79 % to 89 %. Similarly, reusing FFP3 masks via VHP decontamination (P4 and P5) leads to reductions ranging from 65 % to 80 % when compared to single-using FFP3 masks. Reusable rigid half masks (P6 and P7) generate even less waste, with reductions corresponding to 88 % and to 91 % compared to conventional scenarios.

As expected, our results show that waste generation is minimised in the scenarios with the highest mask reuses (Scenarios M5 and P7). Equally, the longer lifespan of filters results in less waste arising from rigid half masks (P7 compared to P6). It must be noted that our results are to be viewed as potential ranges as actual mask reuse frequency depends on several factors, including individual healthcare professionals' tendency to lose masks and exposure to environments that may cause mask/filter clogging. In our study, rigid half masks generate less waste

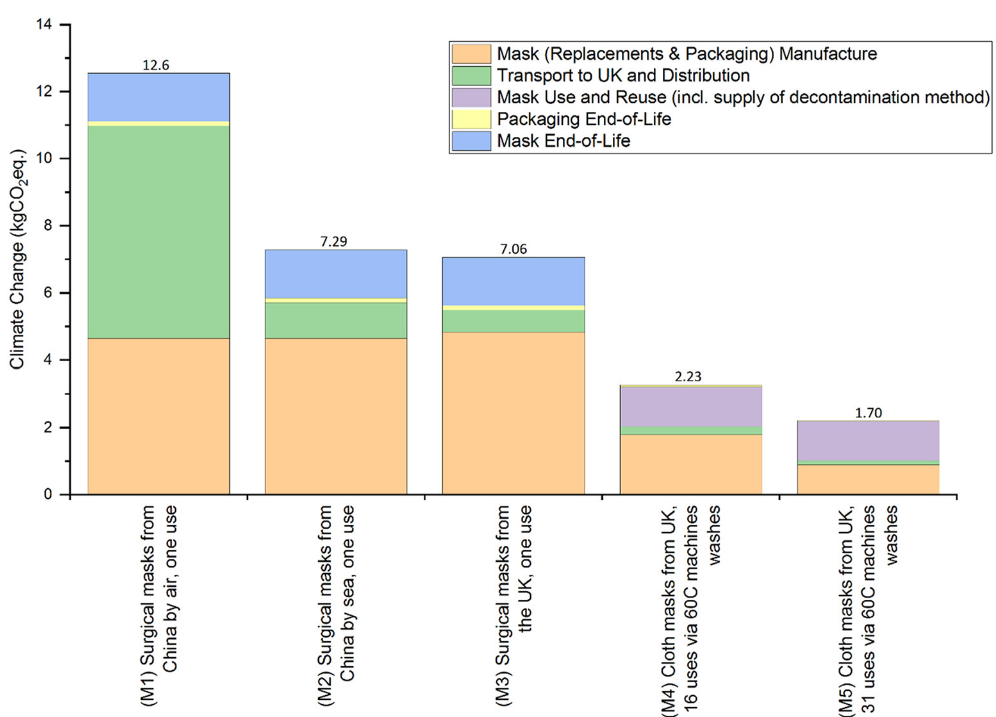


Fig. 2. Climate change results for Scenario M1 to M5, which envisage a healthcare worker using medical-grade face masks. [Colour required for print].

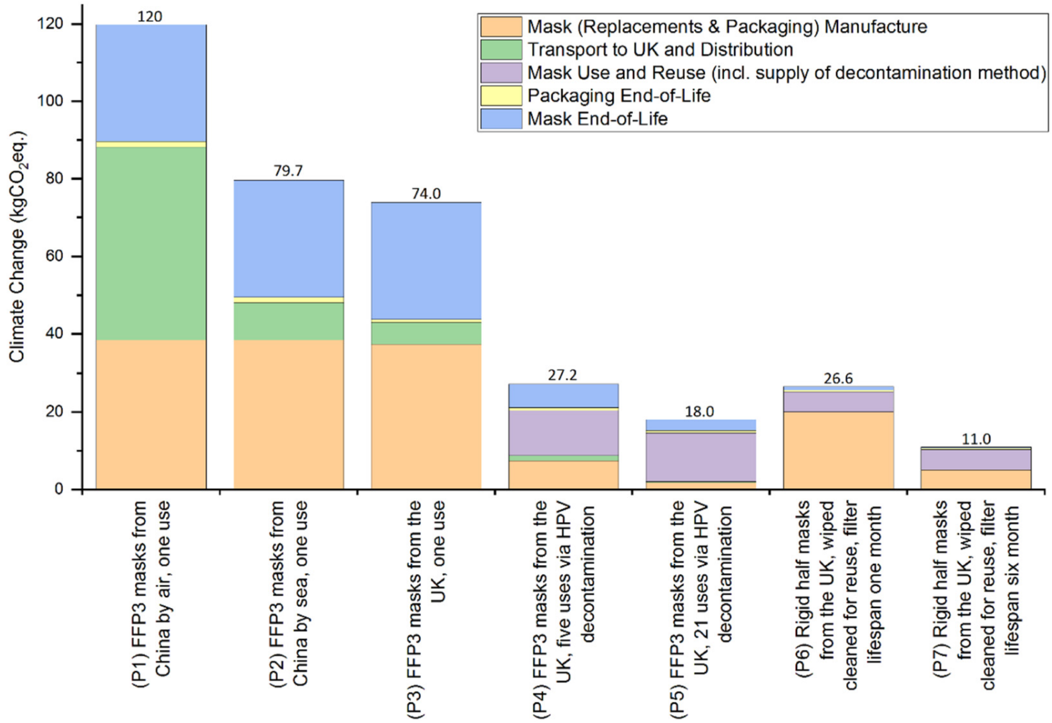


Fig. 3. Climate change results for Scenario P1 to P7, envisaging a healthcare worker using protective-device-grade face masks. [Colour required for print].

than the comparable alternative; however, their use in healthcare settings is yet to be tested, particularly regarding the frequency of filter replacement (see Section 2 and Section 3.1). If filters are required to be replaced more than what we assumed, total waste arising from rigid half masks will increase, perhaps overtaking that generated by the other scenarios.

4.2. Climate Change Impact

4.2.1. Masks Certified as Medical Devices

Fig. 2 reports climate change results for the medical-grade face mask scenarios (M1 to M5). The graph shows that reusable cloth masks (Scenarios M4 and M5) generate between three and seven times lower climate change impacts than single-use surgical masks (M1 to M3). The difference can be attributed to fewer masks required to protect a healthcare professional for a year (i.e. the functional unit; FU) corresponding to lower requirements of raw materials, of electricity for both materials and product manufacture, and of fuel for transportation. In addition, materials for reusable cloth masks are assumed to be sourced from Portugal, which is closer to the UK than Turkey and China; this further reduces the amount of fuel required for importing materials. All these activities, but especially electricity generation and transportation, release greenhouse gases (GHGs) from burning fossil fuels; hence, lower manufacturing needs generate less GHG emissions and lower impact on climate change. Our results concur with the findings of Allison et al. (2021), where reusable cotton masks were compared with surgical masks for public usage.

The same reasoning can be applied to the difference in the climate change results between the scenarios for reusable masks (M4 and M5). Scenario M5 assumes the highest number of reuses per mask and generates the lowest impact score (1.70 $kgCO_2eq.$). This is because higher reuses correspond to fewer masks being required per FU. As mentioned above, we note that the number of mask reuses is dependent on several factors like individuals' probability of losing the product and items of clothing containing beads and zips that may cause wear and tear of the mask during a machine wash cycle. Hence, environmental impact results for M4 and M5 can only be used as an approximate range for employing reusable masks cloth as the true number of masks required for healthcare professionals may differ.

For single-use surgical masks, Scenario M1 generated the highest climate change impact (12.6 $kgCO_2eq.$), which is about 1.7 to 1.8 times higher than M2 and M3. The impact differences between the surgical mask scenarios lie mainly with transport emissions, as shown in Fig. 2. Scenario M1 assumes that masks are imported from China by air freight, whilst in Scenario M2 they are ship freighted from China. Our results demonstrate that air freighting generates a higher carbon emission than ship freighting from the same country, although air transport occurs over a shorter distance. In Scenario M3, masks are assumed to be manufactured in the UK with materials imported by road from Turkey. The further road transport to supply raw materials for mask manufacturing in M3 as compared to local sourcing in China (M1 and M2) means that more carbon emissions are associated with the “Mask Manufacture” life cycle stage (Fig. 2). Nonetheless, the additional emissions generated in this life cycle stage in M3 offset those associated with importing the finished product from a farther country as less fossil fuel is consumed. Overall, our results illustrate that distance and mode of transport are major factors contributing to climate change impacts of medical-grade face masks.

4.2.2. Masks Certified as Protective Devices

Fig. 3 reports climate change results for protective-device-grade mask scenarios (Scenarios P1 to P7). The graph depicts a similar trend to that found for medical-grade masks (Section 4.2.1). Reusing FFP3 masks with vaporised hydrogen peroxide (VHP) decontamination (P4 and P5) and reusing rigid half masks with replaceable filters and straps (P6 and P7) generates between 3 and 11 times lower climate change impacts than single-using FFP3 masks (P1 to P3). Like for medical-grade masks, these results can be attributed to the lower quantity of materials (masks and mask components) required in Scenarios P4 to P7 as compared to P1 to P3, which implies lower fossil fuel consumption during transportation and “Mask Manufacture”. Also, similarly to single-use scenarios for medical-grade masks, the differences between climate change results generated by P1 to P3 lie with the mode of transport to supply masks to the UK. When the PET layer in FFP3 masks is replaced with cotton, the reuse scenarios are shown to have an even greater environmental benefit in the climate change impact category (see Supplementary Information Fig. S1). This highlights that the materials choices have significant effects on the overall environmental impacts of masks.

Fig. 3 also shows that reusing FFP3 masks (P4 and P5) and employing reusable rigid half masks (P6 and P7) yields similar climate change impacts. The difference lies with the highest contributing life cycle stage. The "Mask Use and Reuse" stage, particularly the decontamination of masks, is the most impactful stage for P4 and P5. For P6 and P7, the highest contributing stage is the "Mask (Replacement and Packaging) Manufacture" and particularly, the supply and manufacturing of filter replacements. It must be noted that although the VHP decontamination method for FFP3 masks was deemed most feasible through the Authors' interpretation of reviews and literature on mask decontamination, other methods (ECDC, 2020) have proven their potential. The climate change impacts of reusing FFP3 masks will vary according to the assumed decontamination method. Similarly, if filter reuse is less than the minimum lifespan assumed due to either health and safety or behavioural reasons, then the impact of employing rigid half masks may be greater than the range generated by P6 and P7.

4.3. Other Environmental Categories

4.3.1. Masks Certified as Medical Devices

Table 6 reports environmental impact results other than climate change for medical-grade face mask scenarios (M1 to M5). With a similar trend to climate change impact (Section 4.2.1), the table shows that reusable cloth masks (Scenario M4 and M5) yield the lowest impact scores in most environmental categories, which is due to fewer masks and less transportation required per FU; this is also why M5, where higher reuse of masks is assumed, generated lower impact scores than M4. The categories where Scenarios M4 and M5 do not represent the most advantageous options include water scarcity and ionising radiation. Reusable cloth masks generate the highest score in the category of water scarcity, and the second and third-lowest score in the category of ionising radiation, following Scenario M3. Hot-spot analysis revealed that both categories are highly affected by the cleaning of face masks in washing machines, which not only require significant quantities of water but also consume electricity. Notably, in the UK, about 20 % of the electricity is generated from nuclear power, compared to 4 % in China in 2016 (Sphera, 2020b). M1 generates the highest impact in the category of ionising radiation; this originates from the extraction of fossil fuel required to power aircraft, which is significantly higher than that required for road transport or ship freight.

Table 6
Environmental impact results for Scenario M1 to M5 for medical-grade face masks. Dark green indicates the lowest impact score; light green indicates the second-lowest impact score; light red indicates the second-highest impact score; dark red indicates the highest impact score. [Colour required for print].

	Surgical masks - One use			Reusable PET fabric masks (manufactured in the UK, material sourced from Portugal)	
Environmental Impact Categories	**(M1) Manufactured and air freighted from China**	**(M2) Manufactured and ship freighted from China**	**(M3) Manufactured in the UK (material source - Turkey)**	**(M4) 60C washed 15 times (16 uses)**	**(M5) 60C washed 30 times (31 uses)**
Acidification - terrestrial and freshwater [Mole of H+ eq.]	4.65E-02	2.77E-02	1.70E-02	4.89E-03	3.91E-03
Cancer human health effects [CTUh]	2.53E-09	2.16E-09	2.00E-09	7.78E-10	6.32E-10
Ecotoxicity freshwater [CTUe]	1.40E+02	1.01E+02	1.22E+02	3.03E+01	2.55E+01
Eutrophication freshwater [kg P eq.]	4.01E-04	3.59E-04	4.18E-04	1.20E-04	7.99E-05
Eutrophication marine [kg N eq.]	1.47E-02	6.18E-03	4.33E-03	2.01E-03	1.72E-03
Eutrophication terrestrial [Mole of N eq.]	1.60E-01	6.67E-02	4.53E-02	1.49E-02	1.21E-02
Ionising radiation - human health [kBq U235 eq.]	5.23E-01	1.97E-01	2.61E-01	2.40E-01	2.39E-01
Land use [Pt]	3.80E+01	2.88E+01	4.03E+01	1.58E+01	1.29E+01
Non-cancer human health effects [CTUh]	1.45E-07	7.75E-08	7.66E-08	2.24E-08	1.92E-08
Ozone depletion [kg CFC-11 eq.]	1.47E-06	2.65E-07	3.16E-07	2.67E-08	1.92E-08
Photochemical ozone formation - human health [kg NMVOC eq.]	4.38E-02	1.96E-02	1.42E-02	3.98E-03	3.03E-03
Resource use - energy carriers [MJ]	1.94E+02	1.21E+02	1.22E+02	3.65E+01	2.89E+01
Resource use - mineral and metals [kg Sb eq.]	6.09E-05	5.71E-05	6.63E-05	1.16E-05	8.29E-06
Respiratory inorganics [Disease incidences]	2.97E-07	2.55E-07	1.97E-07	4.73E-08	3.91E-08
Water scarcity [m^3 world equiv.]	1.16E+00	1.11E+00	9.92E-01	3.44E+00	3.12E+00

Among single-use surgical masks, Scenario M1 generated higher impacts than M2 in all environmental categories (Table 6). Hot-spot analysis showed that this is mainly due to greater emissions associated with air freighting compared to ship freighting. Furthermore, the results show that mask manufacturing in China (M1 and M2) yield higher impacts in most environmental categories than manufacturing in the UK with imports from Turkey (M3). This can be attributed to the higher transport emissions associated with importing masks from a country that's further from the UK and the higher emissions generated by electricity generation in China, which relies more heavily on fossil fuels compared to the UK (Sphera, 2020b).

The impact categories where M3 generated higher impacts than both M1 and M2 are freshwater eutrophication, land use, and minerals and metals resource use. The hot-spot analysis showed that M3 generated higher impacts in these categories, primarily because of raw materials transportation from Turkey to the UK via diesel-fuelled trucks. M3 additionally generated a higher ionising radiation impact as compared to M2 only, the main reason being the higher use of nuclear energy assumed in M3 (UK) compared to M2 (China).

4.3.2. Masks Certified as Respiratory Protective Devices

Table 7 reports environmental impact results other than climate change for protective-device-grade face mask scenarios (P1 to P7). Similar to what was found for medical-grade face masks, scenarios where masks are reused (P4 to P7) are environmentally preferable to scenarios where they are single-used (P1 to P3). The results concur with climate change results (Section 4.2.2) in that a higher number of reuses for FFP3 masks and a longer lifespan of filters for reusable rigid half masks (P5 and P7, respectively) generate the lowest environmental impacts (Table 7). In Table S10 in the Supplementary Information, we also show that when the FFP3 mask is made with a cotton layer instead of PET, the environmental impacts are consistently higher in most categories.

Our results indicate that the most environmentally preferable scenario is P7, where rigid half masks with six-monthly filter replacement are employed. On the other hand, if filter replacements are required monthly (P6) due to health and safety, and hygiene regulations, employing rigid half masks is less environmentally preferable than reusing masks via VHP decontamination (P4 and P5) in most categories. Further assessments were carried out to evaluate the environmental impacts of using rigid half masks with different filter change frequencies compared to FFP3 mask scenarios (see Supplementary Information – Table S11). The results presented in Table S11 show that when rigid half mask filter changes are less than once every 4 months, employing rigid half masks is environmentally preferable to reusing FFP3 masks up to 21 times via VHP decontamination (P5). When filter changes are more than once every 2 months, reusing FFP3 masks (from 5 reuses upwards) is more environmentally preferable to employing rigid half

Table 7
Environmental impact results for Scenario P1 to P7for protective-device-grade face masks. Dark green indicates the lowest impact score; light green indicates the second-lowest impact score; light red indicates the second-highest impact score; dark red indicates the highest impact score. [Colour required for print].

	FFP3 masks* - One use			FFP3 masks* (from the UK) - decontaminated via VHP		Rigid half masks** with replaceable P3 filters	
Environmental Impact Categories	**(P1) From China by air**	**(P2) From China by sea**	**(P3) From the UK (materials from Turkey)**	**(P4) 5 uses**	**(P5) 21 uses**	**(P6) Filters replaced monthly**	**(P7) Filters replaced six monthly**
Acidification - terrestrial and freshwater [Mole of H+ eq.]	3.99E-01	2.56E-01	1.60E-01	6.34E-02	4.41E-02	1.24E-01	4.05E-02
Cancer human health effects [CTUh]	2.85E-08	2.56E-08	2.34E-08	6.73E-09	3.47E-09	6.20E-09	2.51E-09
Ecotoxicity freshwater [CTUe]	1.20E+03	9.02E+02	8.24E+02	2.45E+02	1.31E+02	4.64E+02	1.49E+02
Eutrophication freshwater [kg P eq.]	8.02E-03	7.70E-03	7.33E-03	3.62E-03	2.87E-03	6.85E-03	2.11E-03
Eutrophication marine [kg N eq.]	1.19E-01	5.39E-02	3.71E-02	1.37E-02	9.01E-03	2.14E-02	7.41E-03
Eutrophication terrestrial [Mole of N eq.]	1.29E+00	5.81E-01	3.94E-01	1.45E-01	9.55E-02	2.07E-01	7.45E-02
Ionising radiation - human health [kBq U235 eq.]	4.70E+00	2.22E+00	2.67E+00	8.46E-01	4.84E-01	1.57E+00	5.40E-01
Land use [Pt]	6.98E+02	6.28E+02	7.60E+02	1.82E+02	7.09E+01	6.55E+01	2.43E+01
Non-cancer human health effects [CTUh]	1.65E-06	1.13E-06	1.08E-06	2.72E-07	1.15E-07	2.15E-07	9.26E-08
Ozone depletion [kg CFC-11 eq.]	1.21E-05	2.92E-06	2.17E-06	7.00E-07	3.83E-07	7.09E-07	2.65E-07
Photochemical ozone formation - human health [kg NMVOC eq.]	3.80E-01	1.95E-01	1.42E-01	5.73E-02	4.05E-02	6.40E-02	2.44E-02
Resource use - energy carriers [MJ]	1.75E+03	1.19E+03	1.15E+03	4.20E+02	2.77E+02	4.00E+02	1.87E+02
Resource use - mineral and metals [kg Sb eq.]	7.27E-04	6.97E-04	6.30E-04	2.02E-04	1.12E-04	1.50E-04	6.02E-05
Respiratory inorganics [Disease incidences]	2.75E-06	2.43E-06	1.69E-06	5.79E-07	3.57E-07	1.30E-06	3.90E-07
Water scarcity [m³ world equiv.]	2.53E+01	2.49E+01	2.43E+01	1.11E+01	8.50E+00	7.67E+00	2.83E+00

*FFP3 masks were assumed to be made of PP and PET materials; in Supplementary Information (Table S10), we show that FFP3 masks made of PP and Cotton materials have a much higher impact.

**The lifespan of the rigid half mask was assumed to be one year.

masks. In other words, the breakeven point between the two reuse options (for the case when FFP3 are reused five to 21 times) is when rigid half masks require bi- to four-monthly filter changes. In this case, the choice of either mask reuse option should consider other factors including waste arising, social preferences and costs. Notably, rigid half mask (P6 and P7) generates >50 % less waste than reusing FFP3 mask (P4 and P5), as shown in Table 5.

It must be reiterated that the number of reuses of either FFP3 masks and the life span of rigid half mask filters also depends on the health and safety recommendations (which are yet to be determined). Due to infection risk cautions, using rigid half masks may require more frequent filter changes (less than six-month); an alternative solution may be to develop ways to decontaminating filters between uses to maintain their usability in healthcare. In this study, filter decontamination was not studied due to limited information on how this would likely be carried out. However, any additional process required will no doubt carry additional environmental impacts. This may increase the overall impacts associated with using rigid half masks, possibly making reusing FFP3 masks via VHP decontamination the more environmentally preferable mask option. Nonetheless, further research on the likely requirements that will enable rigid half-mask use in healthcare is needed before further LCA studies can be conducted.

Scenario P1, where single-use FFP3 masks are air freighted from China to the UK, yielded the highest impacts in all environmental categories except land use; in this category, the highest impact is generated by Scenario P3, where FFP3 mask materials are sourced from Turkey for manufacturing in the UK. As discussed in Section 4.2.2, the high environmental impacts generated by Scenario P1 can be attributed to the combination of the mode of transport (air freight) assumed to import face masks and the higher contribution of coal to generate electricity in China. On the other hand, the high land use impact generated by P3 is due to additional road transport required to import masks from Turkey to the UK.

5. Conclusions

This article presented a comprehensive life cycle assessment (LCA) study comparing alternative medical-grade and protective-device-grade mask reuse options to the conventional single-use of surgical and FFP3 masks, respectively. The study focuses on the UK, but the results and conclusions are applicable to other healthcare settings. The functional unit corresponds to 1 year of mask-use by a healthcare professional committed to 240 shifts/year. The life cycle inventory is based on a mix of data collected by the Authors and literature data, complemented with data from Gabi and Ecoinvent databases.

This study demonstrates that reuse options for both medical- and protective-device-grade scenarios not only generate less waste but also lower environmental impacts in most categories than conventional single-use options. Notably, these benefits increase with increasing the number of reuses. This is because the wastes and environmental impacts associated with producing masks are far greater than those associated with their decontamination. Reusable alternatives generate 80–90 % less waste than single-use face masks, and from 3 and up to 11 times lower climate change impacts. When considering the full spectrum of environmental categories, reusable alternatives are favourable in the vast majority of categories with few exceptions. These include ionising radiations and water consumption for cloth masks, and land use and water consumption for FFP3 masks decontaminated with vapour hydrogen peroxide.

Our analysis also demonstrates that reusing rigid half masks with filter replacements is environmentally preferable to decontaminating up to 20 times the traditional FFP3 masks if filter changes are carried out four-monthly or less. If filter changes are required once a month or more, decontaminating FFP3 masks for reuse is preferable. We note that the number of reuses per mask and the length of time that filters can be employed depend on multiple factors, including health and safety, hygiene requirements, and user behaviours in the care of the masks (and their components). Hence, the environmental benefits of reuse options are to be considered as potential ranges. For single-use masks, our study showed that sourcing mask materials locally (Turkey as an alternative to China) and manufacturing masks in the UK (M3 and P3) is preferred over importing masks from China. This is because impacts associated with the transport of raw materials and masks held a high contribution to the overall environmental impacts.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2022.07.005.

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