A Life Cycle Assessment of reprocessing face masks during the Covid-19 pandemic

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Abstract

Introduction/background: The COVID-19 pandemic has led to threatening shortages in the healthcare of medical products such as face masks. Due to this major impact on our healthcare society, an initiative was conducted between March and July 2020 for reprocessing face masks from 19 different hospitals. This exceptional opportunity was used to study the cost impact and the effects of the CO_2 footprint of reprocessed face masks relative to new disposable face masks.

Aim: The aim of this study is to conduct a life cycle assessment (LCA) to assess and compare the environmental impact of disposed versus reprocessed face masks.

Methods: In total, 18,166 high-quality medical FFP2 face masks were reprocessed through steam sterilization between March and July 2020. CO_2 emissions equivalent (kg CO_2 eq) and other impact categories, such as water consumption during production, transport, sterilisation and end-of-life processes, were assessed. A Monte Carlo model was used to predict the sensitivity of different factors in the whole process on the kg CO_2 eq.

Results: The average kg CO_2 eq appears to be 42% lower for reprocessed face masks based on a rejection rate of 20% than new ones. The sensitivity analysis indicated that the loading capacity of the autoclave and rejection rate of face masks have a large influence on kg CO_2 eq. The estimated cost price of a reprocessed mask was €1,40 against €1.55.

Discussion: The life cycle assessment (LCA) demonstrates that reprocessed FFP2 face masks from a circular economy perspective have a lower environmental impact on kg CO_2 eq and water usage than new face masks. For policymakers, it is important to realize that the CO_2 footprint of medical products such as face masks may be reduced by means of circular economy strategies.

Conclusion: This study demonstrated a lower environmental impact and financial burden for reprocessed medical face masks than for new face masks without compromising qualifications. Therefore, this study may serve as an inspiration for investigating the reprocessing of other medical products that may become scarce. Finally, this study advocates that circular design engineering principles should be taken into account when designing medical devices. This may lead to more sustainable products that require less CO_2, have less water consumption and lower costs.

Introduction

According to the European Commission, the European recovery plan for the economy after COVID-19 aims to make the European economy more circular and more sustainable. The Green Deal on Sustainable Healthcare[1], as set out in The Netherlands, consists of a formal contract signed by hospitals, government organisations, industrials and universities and will be used in Europe's recovery strategy by stimulating a circular economy[2] by building a more resilient European Union. One of the goals seen from the Dutch

Green Deal on Sustainable Healthcare is to reduce waste. By 2030, the CO_2 emissions from healthcare should be reduced by 49% compared to the 1990 levels, and by 2050, realise a climate neutral situation.[1]

Hospital waste production in high-income countries varies between 1.7 and 8.4 kg per bed per day depending on hospital size and activities.[3] For hospitals in Europe ranging from 1.7 kg in the Netherlands to 3.6 kg in Germany, between 3.6-4.0 in Middle East countries such as Kuwait.[4] and in the US, these numbers are rising to 8.4 kg.[5] However, the impact of environmental change on public health has received little consideration. [6] In total, 5.9 million tons of medical waste is disposed of in the USA by hospitals annually, and healthcare produces 8% of the total CO_2 emissions in the US.[7] Subsequently, severe health risks associated with medical waste disposal by hospitals have been reported.[8]

The COVID-19 pandemic has led to severe shortages of medical products, particularly personal protective equipment (PPE).[9] These local shortages of PPE included face masks, aprons and isolation gowns. This period led to an emergency scenario in which reprocessing was devised as an alternative. This resulted in situations in which either no care could be given or in situations where health care professionals were not fully protected. The authorities decided to temporarily exempt these medical products from CE registration.[10] This means that manufacturers and suppliers were able to supply non-CE-marked medical equipment, such as face masks, at the explicit request of hospitals or other healthcare institutions when shortages as a result of the coronavirus occurred.

Upon request from several hospitals, a variety of methods for reprocessing were investigated for single-use face masks in the period starting on 17 March 2020.[11] The quality of reprocessed as well as new face masks was tested with a custom test setup that was built to measure the filter penetration of particles with different sizes and pressure drops over the face masks. With this system, the filter capacity and filter material pressure drop of all sterilized masks were evaluated between 17 March and 1 July 2020.[11,12] In total, 18,166 FFP2 face masks were steam sterilized at 121°C. In total, 88 different mask brands were evaluated, showing that the filter efficiency at the small particles ranged from that of the commonly used 3M 1862+ face mask without valves and that the 3M 1862 Aura with valves remained sufficient for reuse up to five times after multiple heat sterilization procedures.[12,13] This result was later confirmed in a technical bulletin by the manufacturer of the masks, 3M[14] and by the National Institute for Public Health and the Environment.[15] These studies demonstrated that a circular approach for certain face masks is feasible.

The coronavirus crisis period appeared to provide a potential motive to investigate the effects of reprocessing medical equipment. Since circular reprocessing involves steam sterilization, it is of equal importance to determine whether this approach is sustainable. This study was therefore conducted to demonstrate environmental sustainability by means of a life cycle assessment (LCA) and to investigate economic feasibility. For this, the CO_2 footprint (kg CO_2 eq) and costs of reprocessed face masks and new ones will be studied from a circular economy perspective.

Aim

The aim of this study is to conduct a life cycle assessment (LCA) to assess and compare the environmental impact of disposed versus reprocessed face masks.

Research questions

For this study, the following two research questions were formulated:

1. What is the environmental impact of reprocessed versus disposable FFP2 face masks?
2. What are the financial differences of reprocessed versus disposable face masks?

Methods

Sterilisation and PFE test data of the Aura 1862+ (3M, Saint Paul, Minnesota, USA) face mask indicate that this type of face mask shows good performance after multiple sterilisation cycles.[11,12,13] From the 18,166 reprocessed medical, single use FFP2 face masks sterilised after use in a medical autoclave at the sterilisation department of CSA Services, located in De Meern – Utrecht, the Netherlands, the majority (n=7,993) were Aura 1862+ (3M, Saint Paul, Minnesota, USA). Therefore, this particular type of face mask was chosen for the LCA.

The packaging materials were disposed of in the hospital where the face masks are used primarily. After first use, face masks were transported to the sterilisation department. All masks were manually checked before reprocessing by personnel wearing PPE. Of all Aura 1862+ facemasks that entered the CSA, approximately 10% were discarded. To remain conservative, the total rejection rate was set at 20%.

Face masks were placed in a sterilization bag that contained up to five masks. A total of 1,000 masks were placed into an autoclave (Getinge, GSS6713H-E, Sweden) per cycle. After sterilization, the masks were transported to the hospital. Masks were reprocessed a maximum of five times before final disposal.[11,12]

The assessment of environmental impact is performed following as closely as possible the internationally accepted life cycle assessment (LCA) method following the ISO 14040 and 14044 standards.[16,17] The LCA examines all the phases of the product's life cycle from raw material extraction to production, packaging, transport, use and reprocessing until final disposal.[18] The LCA was modelled using SimaPro 9.1.0.7 (PRé Sustainability, Amersfoort, The Netherlands). Life cycle impact analysis data were retrieved from the Ecoinvent database (Ecoinvent version 3.6, Zürich, Switzerland).[19]

In the LCA, the 'functional unit' defines the primary function that is fulfilled by the investigational products and indicates how much of this function is considered.[20] In this study, we pragmatically chose 'protection of 100 healthcare workers against airborne viruses using an FFP2 certified face mask'.

To make a valid comparison between the disposable and reprocessing face masks, the system boundaries should be equal in both scenarios. The system boundaries in this study consisted of the production, use and eventually disposal and waste treatment of the masks. For the reprocessed face masks, the lifecycle is extended due to the sterilisation process (figure 1). The production of machinery for the manufacturing of face masks and autoclaves was not included in this study.

Life cycle inventory analysis (LCIA)

The inventory data include all phases from production (including material production and part production), transport, sterilisation to end-of-life of the life cycle of the single use and reprocessed face masks. We disassembled one face mask to obtain the weight of each individual component on a precision scale (Fit Evolve, Bangosa Digital, Groningen, the Netherlands) with a calibrated inaccuracy of 1.5%. Component information and materials were obtained from the data fact sheet provided by the manufacturer. We conducted a separate validation experiment to establish the material composition in the filtering fabric (supplement file 1).

The production facility for the face masks is located in Shanghai, China.[21,22] Further distribution took place from Bracknell, UK, to Neuss, Germany, and the final destination was set in Rotterdam, the Netherlands.

The information gathered in the *life cycle impact assessment (LCI)* is stated in the ReCiPe midpoints by using SimaPro[23]. The kg CO_2 eq was chosen as the primary unit in the impact category.

Uncertainty analysis

The final LCA model contains several uncertainties based on assumptions and measurement inaccuracies.[24] To quantify the effect of the uncertainties on the primary endpoint, we performed a Monte Carlo analysis in which LCA system values were sampled from their probability function rather than assumed as a point estimate.[23] Thus, the probability function for all primary and secondary outcome measures was determined based on nominal value, a spread around that value and a probability distribution. An unpaired, two-sided T-test was conducted to identify differences between reprocessing and disposable scenarios. $P<0.05$ was considered to be statistically significant (supplemental file 2).

Sensitivity analysis

A sensitivity analysis was conducted to check the sensitivity of the outcome measures to variation in the input parameters. To determine which parameters are interesting to investigate, two aspects were considered: the variations of the assumption made for the parameter and the relative contribution of the parameters to the total impact. The following three parameter variations were chosen for the sensitivity analysis:

- Rejection percentage. The rejection rate was defined based on experiences from the participating sterilisation department and studies that show that sterilisation of the face masks up to 5 times is possible. Masks were used 5 times, and approximately 10% were discarded during the total life cycle.

Out of this experience and to remain conservative, the total rejection rate was set at 20%. Therefore, it is interesting to investigate whether variation in PFE testing outcomes or differences in user protocols influence the outcomes. This should indicate whether masks of higher or lower quality can also be suitable candidates for reprocessing.

- Autoclave capacity largely depends on the loading of the autoclave. To mimic different loads of the autoclave, it is interesting to know the influence of sterilising fewer masks per run on the model.
- As it is likely that many hospitals have a Central Sterilisation Services Department (CSSD), it is interesting to know the effect of having zero transportation. Moreover, in case hospitals are not willing to change the routing in their CSSD, it is interesting to observe how outcomes are influenced if transportation is set on the maximal realistic value of 200 km.

The parameters were varied with 250 and 500 face masks per sterilisation batch. A rate varying with 10% and 30% of the face masks being rejected due to quality reasons and variation in transport kilometres of 0 km – 200 km.

Cost price comparison

A cost analysis was performed to provide insight into costing from a procurement perspective. The cost analysis is based upon five face masks in a permeable laminate bag, Halyard type CLFP150X300WI-S20, and includes the expenses of energy, depreciation, water consumption, cost of personnel, and overhead and is compared to the prices for a new disposable 3M Aura face mask during the first and second Corona waves.

Results

Life cycle impact assessment (LCIA)

The results in Table 1 show that the results of the kg CO_2 eq (i.e. Global warming) is 44% lower for reprocessed face masks than for new face masks.

Table 1. Primary and secondary unit outcomes for processed versus new face masks.

Impact Category	Unit	Mean for new face masks	Mean for reprocessed face masks	Difference [%]
Global warming	**kg CO_2 eq**	**6,55E+00** **(SD 3,11E-01)**	**2,77E+00** **(SD 1,21E-01)**	**42**
Fine particulate matter formation	kg PM2.5 eq	1,11E-02 (SD 5,26E-04)	3,92E-03 (SD 1,65E-04)	35
Fossil resource scarcity	kg oil eq	2,55E+00 (SD 1,81E-01)	1,02E+00 (SD 6,18E-02)	40
Freshwater ecotoxicity	kg 1,4-DCB	5,61E-01 (SD 2,79E-01)	2,46E-01 (SD 1,18E-01)	44
Freshwater eutrophication	kg P eq	1,59E-03 (SD 1,05E-03)	7,94E-04 (SD 4,09E-04)	50
Human carcinogenic toxicity	kg 1,4-DCB	4,55E-01 (SD 2,65E-01)	1,64E-01 (SD 1,40E-01)	36
Human non-carcinogenic toxicity	kg 1,4-DCB	9,69E+00 (SD 9,65E+00)	4,18E+00 (SD 4,11E+00)	43
Ionizing radiation	kBq Co-60 eq	2,52E-01 (SD 3,62E-01)	1,31E-01 (SD 1,84E-01)	52
Land use	m2a crop eq	3,12E-01 (SD 5,06E-02)	2,18E-01 (SD 3,28E-02)	70
Marine ecotoxicity	kg 1,4-DCB	7,32E-01 (SD 3,83E-01)	3,19E-01 (SD 1,62E-01)	44
Marine eutrophication	kg N eq	3,31E-04 (SD 1,81E-05)	1,25E-04 (SD 8,33E-06)	38

Mineral resource scarcity	kg Cu eq	5,53E-02 (SD 5,18E-03)	1,70E-02 (SD 1,56E-03)	31
Ozone formation, Human health	kg NOx eq	2,10E-02 (SD 1,72E-03)	7,38E-03 (SD 5,19E-04)	35
Ozone formation, Terrestrial ecosystems	kg NOx eq	2,16E-02 (SD 1,73E-03)	7,59E-03 (SD 5,23E-04)	35
Stratospheric ozone depletion	kg CFC11 eq	3,15E-06 (SD 9,83E-07)	1,37E-06 (SD 3,78E-07)	44
Terrestrial acidification	kg SO2 eq	2,58E-02 (SD 1,13E-03)	8,94E-03 (SD 3,59E-04)	35
Terrestrial ecotoxicity	kg 1,4-DCB	2,34E+01 (SD 4,71E+00)	8,75E+00 (SD 1,84E+00)	37
Water consumption	m^3	5,98E-02 (SD 3,40E-02)	3,40E-02 (SD 5,50E-01)	57

The CO_2 or global warming impact of transport is 10% for a disposable mask compared to 4% for a reprocessed mask. Sterilisation is only applicable during reprocessing of a mask and equals 12% of the total CO_2 emissions of the reprocessed mask. The end-of-life phase, when a mask is discarded, equals 15% for a disposable mask and 0.04% for a reprocessed face mask.

Sensitivity Analysis

Figure 3 shows the sensitivity analysis outcomes based on absolute values in this study and alternative outcomes based on different autoclave loading capacities, rejection rates after inspection and transport differences.

The results show that even with relatively large variations in changing parameters, the reprocessed face masks continue to have a lower impact in all categories when compared to using new disposable masks (supplemental file 3).

Cost price comparison

The cost price of a reprocessed mask by means of steam sterilization in a permeable laminate bag is €1,40. The purchase price of a new, disposable face mask was €7 during the peak time of shortages in the hospital Haaglanden MC. The prices after the first coronavirus wave dropped to €186.06 per 120, with an average price of €1.55 per Aura 1862 face mask. Saving 560 Euro per 100 protected healthcare workers in the first wave and 15 Euro in the second Corona wave when using reprocessed masks.

Discussion And Interpretation

The main finding in this study, when looking back at the research questions, demonstrates that there is a significant environmental benefit if FFP2 face masks are reprocessed. Therefore, reprocessing may contribute to achieving a circular economy, as the life cycle assessment indicates an approximately 42% reduction in the CO2 footprint as defined in the LCA and measured in kg CO_2 eq.

Furthermore, there is a price benefit when reprocessing face masks compared to using new disposable masks. Although the prices after the first Corona wave dropped to €186.06 per 120, having an average price of €1.55 per Aura 1862 face mask for Haaglanden MC, this was still higher than the cost price of the reprocessed masks.

The reduction in CO_2 can be explained by the relatively high number, 2.83E-01 kg CO_2 eq, created during the assembly of the face mask during the production phase. With respect to the reprocessed phase of face masks (i.e. production 8.41E-02 and sterilization 3.68E-02 kg CO_2 eq), which is still more than double.

The Monte Carlo analysis, simulating the process 10,000 times in Simapro, confirms that reprocessing a face mask is the better solution of the various impact categories despite the variation of input data. The sensitivity analyses conducted in this study indicate that both loading fewer face masks into an autoclave and variation in the rejection rate have a significant impact on the end result. The relatively high impact of the sterilization process is in line with other studies that showed that the sterilization process is a critical process for the environmental footprint of sterile products.[25] Therefore, a hospital should take into consideration the optimal load of an autoclave since the volume has a significant effect on the cost price and environmental impact per product.

Hypothetically, 200 million disposable face masks are used per year in the Netherlands in all healthcare institutions during the Corona period. Taking a 20% rejection rate into contemplation would result in a total of 54.2 million new masks that are reprocessed 5 times after having it used for the first time. Hypothetically, a reduction of 7. E+07 kg CO_2 eq could be achieved (supplemental file 4).

Comparing this to the average CO_2 emissions of new cars in 2019 in the EU28, Iceland and Norway of 122.4 g CO_2/km[26], this represents 8,5 million km driven by these new cars in Europe (supplemental file 4). Moreover, the 145.8 million face masks of this hypothetical example would not need to be transported and disposed of as waste. Therefore, the overall emission reduction in this example is likely to be higher. Based on the weight of one face mask of 8.6 g, this means that a total of 1250,000 kg face masks do not need to be transported or handled, further reducing the environmental impact. These aspects further positively affect greenhouse gas emissions, have an impact on our climate and are mainly the result of energy use in the product life cycle.[27]

Face masks that were previously discarded demonstrate value and can facilitate the transition towards a circular economy for medical devices. These circular economic values may also encourage improved and circular product design. Repurposing products at the end of their life cycle to be reused or to become raw material for new medical devices should be included in the design of these products. The quality of the 3M 1862+ face mask used in this study remained of good quality with acceptable PFE after reprocessing up to 5 times. Other masks with similar FFP2 standards showed varying quality after sterilization. This should be taken into account when hospitals decide to reprocess different types or brands of face masks in times of shortage.

Other reprocessing candidates, such as instrument blue wrapping paper, drapes, anaesthetic and oxygen masks and oxygen tubing[28,] as well as disposable surgical instruments, could be subject to further study and may have a significant impact.[29,30] Translating this towards orthopaedic surgery, for instance, up to 6.2 kg of waste per case (patient) is generated, having an estimated recyclable waste of 1.70 kg per patient.[31] A reduction of 1.70 kg waste translates into a reduction of 0.37 kg CO_2 eq being saved per orthopaedic operating procedure. In the case of 100k orthopaedic cases per year, a reduction of 3.72E+04 kg CO_2 eq can be established. According to Gupta Strategists, the share of medical equipment and instruments in the total healthcare carbon footprint within a hospital equals 6%.[32]

Facing climate challenges and following the EU’s 2020 climate goals, it seems evident that our kg CO_2 eq needs to be reduced. For policymakers, it is important to realize that reducing the carbon footprint of medical devices such as face masks has significant and positive effects on climate change. The insights from this study could help to reach the goals of the Green Deal[33] by reducing CO_2 emissions by 49% in 2030.

Limitations

Although it is likely that CSSD employees always use a maximum autoclave loading, the LCA sensitivity analysis included variations in Holding capacity. However, it remains more interesting to know the impact on the LCA if different types and sizes of autoclaves are used that require different energy and water consumption. To better relate the model and study results to different CSSD setups (e.g., general practitioners, larger academic hospitals), a study expansion is needed that includes autoclave type in addition to holding capacity.

Life cycle costing (LCC) was not conducted in this study. An LCC would be recommended in further studies to analyse the cost of each phase. Furthermore, it may be helpful for designers when designing new (circular) products. The Monte Carlo analysis was conducted as an (uncertainty) analysis due to uncertainties in the data and only on the CO_2 component, whereas the water consumption was excluded from this analysis. Among other factors, the production of machinery for the manufacturing of face masks and autoclaves are not included in this study since these data were not readily available and therefore outside the system boundary.

Conclusion

The results of this study showed clear benefits of reprocessing face masks. The LCA demonstrated a significantly lower environmental impact for reprocessed medical face masks than for new, disposable face masks without compromising the qualifications (reliability). Furthermore, (circular) reprocessing results in lower costs. This study may serve as an inspiration for investigating the reprocessing of other medical devices due to the potential large environmental impact and cost reductions. Furthermore, this study advocates that circular design engineering principles should be taken into account when designing medical devices. This will lead to more sustainable products that require less CO_2, have less water consumption and lower costs. A circular economy for medical devices may therefore serve as potential to execute the goals of the Green Deal and the global sustainable development goals of the United Nations.

Declarations

Disclaimer

The Authors have nothing to declare.

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Figures

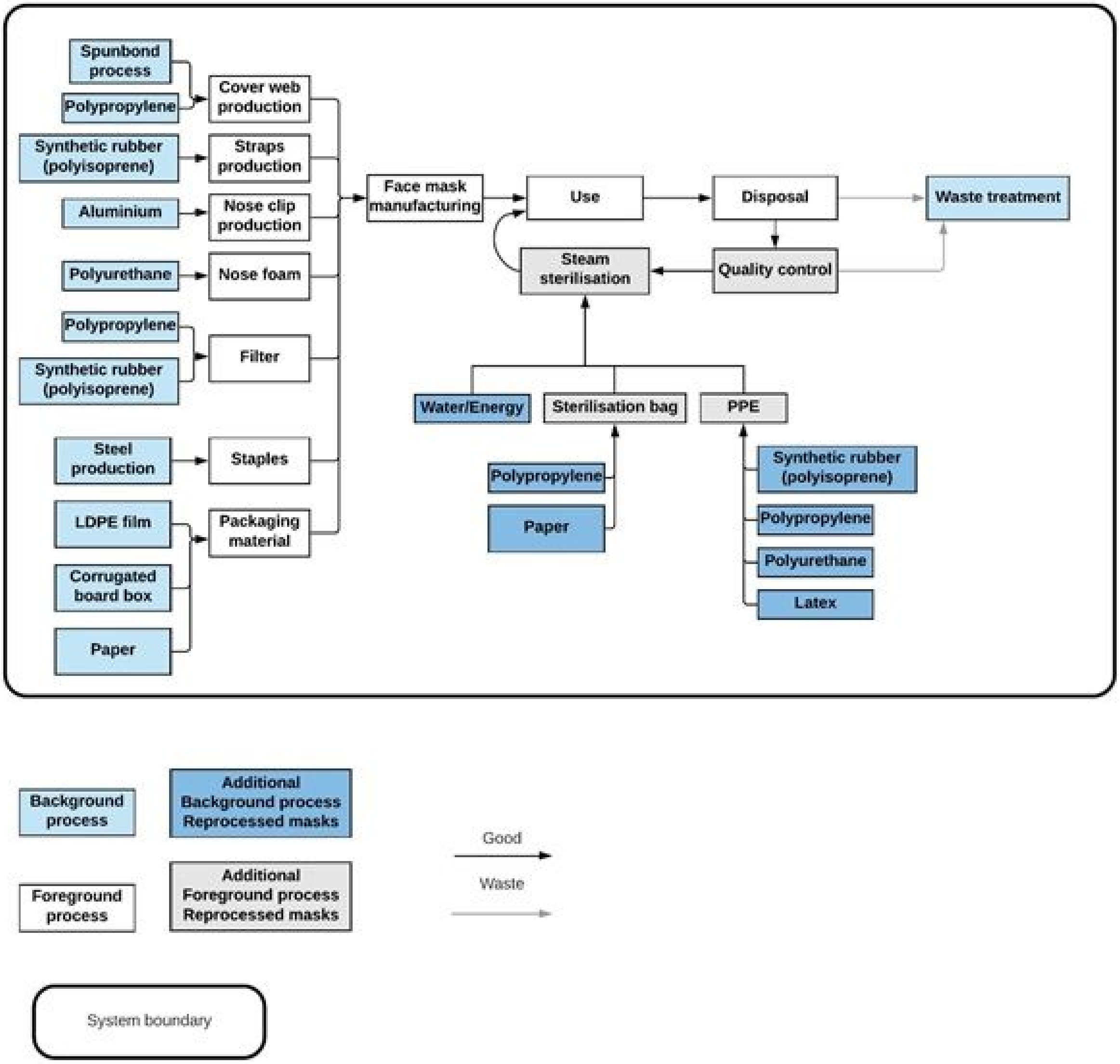

Figure 1

System boundary of new and reprocessed face masks

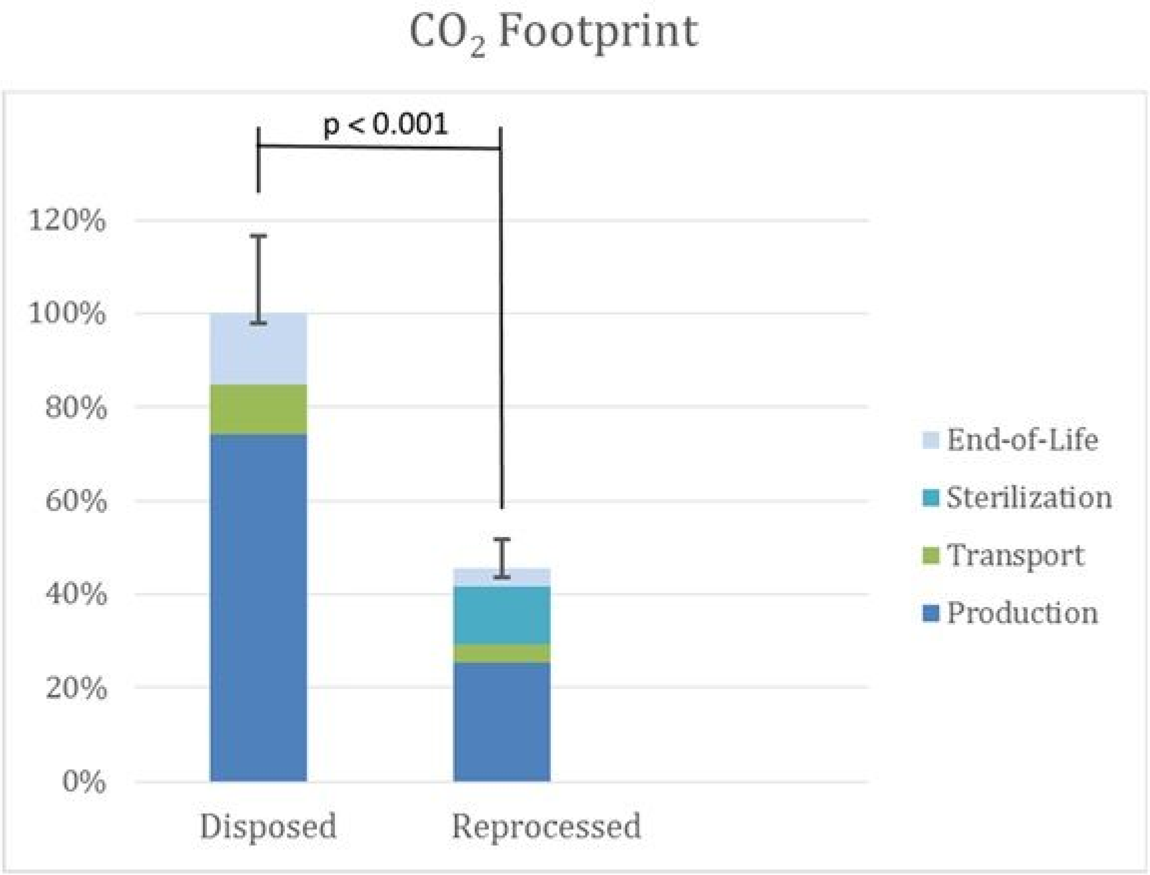

Figure 2

Relative impact of the reprocessed and disposable face masks

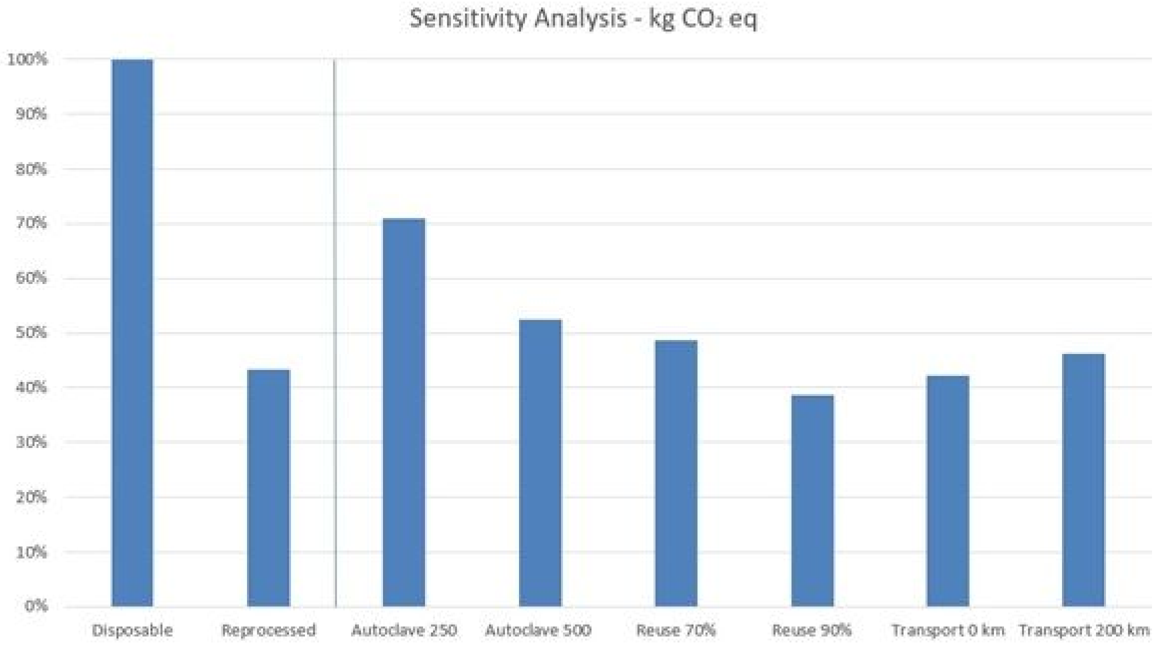

Figure 3

Sensitivity analysis. Left: outcomes based on absolute values in this study. Right panel, alternative outcomes based on different autoclave loading capacities, rejection rates after inspection and transport relative to disposable.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplementalfile1.pdf
- Supplementalfile2.pdf
- Supplementalfile3.pdf
- Supplementalfile4.pdf