Life Cycle Assessment of Single-Use and Reprocessed Face Masks Using UV-C Radiation

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Abstract: The COVID-19 pandemic pushed for the exponential increase in the global production and consumption of face masks, which now has become a pollution problem. Various studies have shown the benefits of reprocessing face masks, but so far, no studies on Life Cycle Assessment (LCA) of UV-C disinfection of face masks have been found. To address this research gap, this work conducted "cradle-to-gate" LCA on scenarios namely, (imported) single-use face masks, (imported) N95 face masks with UV-C disinfection, (imported) FPP2 face masks with UV-C disinfection, and (locally sourced) cotton masks with UV-C disinfection. The imported face masks were assumed to be from China, and the locally sourced cotton masks as well as the final users are located in the Philippines. Results have shown that using locally sourced reusable cotton masks with UV-C disinfection has the highest overall impact while using imported reprocessed N95 masks with UV-C disinfection has the least impact across all impact categories. The impact of the UV-C disinfection step is almost negligible in all three cases of reprocessed masks due to the total capacity of the equipment throughout its lifespan. Nevertheless, the face mask raw material has a big influence on the results, such as in the case of cotton masks. Sensitivity analysis shows that for the best-case scenario of using reprocessed N95 masks, increasing the rejection rate up 30% and decreasing the capacity of the UV-C equipment up to 1 million face masks has little effect on the performance of the N95 UV-C reprocessed face mask as compared to the disposable surgical masks. Hence, the results imply the robustness of UV-C as a disinfection method for face masks. For future work, it is recommended to check other UV-C equipment configurations and other locally sourced face mask materials and to include end-of-life scenarios in the system boundaries.

Key Words: SARS-CoV-2; personal protective equipment (PPE), face masks; life cycle assessment (LCA); reusable

1. INTRODUCTION

The COVID-19 pandemic pushed for the exponential increase in the global production and consumption of face masks, which has resulted in 1.56 billion face masks ending up in the oceans in 2020, thereby threatening marine life and ecosystems (De-la-torre et al., 2021). To address the environmental and cost issues of disposable face masks, governments around the world have been promoting the manufacture and use of reusable face masks (Rodríguez et al., 2021). These reusable face masks require a disinfection step such as washing with soap and water, steam sterilization, or microwave disinfection before reuse (Liang et al., 2021), and thus, also require additional inputs in their life cycle. Hence, comparative Life Cycle Assessment or LCA studies have been performed between disposable and reusable face masks.

A study by Schmutz and colleagues in 2020 compared the performance of washable cotton masks versus surgical masks using a simplified LCA approach. The results show that the washable cotton masks performed slightly better than disposable masks in terms of carbon footprint and energy (still depending on the usage) but underperformed in terms of water footprint (Schmutz et al., 2020). A study by Allison et al. (2020) compared five scenarios using single-use face masks, manual washing of reusable face masks, reusable N95 masks with disposable filters, machine washing of reusable face masks, and machine washing of reusable face masks with disposable filters and have concluded that machine washing of reusable face masks without filters has the least overall impact. A hospital study compared Aura 3M masks disinfected via steam sterilization (reused five times) versus disposable face masks and showed that the reused masks had a lower footprint at 2.77 kg CO_2 eq footprint versus the 6.55 kg CO_2 eq footprint for the disposable masks (van Straten et al., 2021). Another study compared five different masks, two out of which were reusable and disinfected by alcohol and washing, concluded that the reusable counterparts were the most sustainable option, “with a drastic reduction in environmental impact across all categories” (Rodríguez et al., 2021). A newer disinfection technique is using Ultraviolet or UV-C radiation. According to the literature, UV-C radiation is effective in airborne pathogens using a wavelength of 222 nm and surfaces take only 10 seconds for decontamination (Kitagawa et al., 2021). UV-C light possesses strong disinfecting properties and can be successfully used in disinfecting non-critical handheld electronic devices used in clinical healthcare facilities with a complete reduction in bacterial contamination up to 87% (Cremers-Pijpers, 2021). A recent study conducted disinfection tests on N95 masks using an open-source UV-C device called LUCIA, which was built using cost-effective materials (Bentancor et al., 2021). Results showed that the device is capable of reducing the viral load (using an RNA virus with the same characteristics as COVID-19) by 4 times in magnitude (Bentancor et al., 2021).

So far, no studies have been found comparing the carbon footprints of disposable face masks versus reusable face masks disinfected using UV-C through LCA. A Scopus database search using the keywords “LCA” and “face masks” and “UV-C” yielded zero results as of January 30, 2022. To address this research gap, this study assessed and compared the environmental impacts in terms of carbon footprint, human toxicity, freshwater ecotoxicity, and marine ecotoxicity through life cycle assessment of the disposable face mask versus the reprocessed facemask using UV-C radiation.

2. METHODOLOGY

2.1 Scope

Four scenarios namely, imported single-use face masks, imported N95 face masks with UV-C disinfection, imported FPP2 face masks with UV-C disinfection, and locally sourced cotton mask with UV-C disinfection were investigated in this work. The Bacterial Filtration Efficacy or BFE is the measure of the performance in filtering bacteria with a size of 1 micron (Allison et al., 2021), which can also be a good indicator of the mask’s efficiency against viruses. The surgical mask, N95, and FPP2 masks all have a BFE value above 95%, while the cotton mask only has a BFE value between 58-83.2% (Allison et al., 2021; Rodriguez et al., 2021).

For its impact assessment, a “cradle-to-gate” approach was considered, which is from raw material acquisition, production, distribution, and product usage (single-use or reuse). The functional unit used in this work is 100 uses of face masks. It is assumed that the manufacturer of the surgical, N95, and FPP2 masks is located in Suzhou, China, while the manufacturer of the cotton masks is locally sourced from Benguet, Philippines. Benguet province is one of the remaining provinces still manufacturing cotton in the Philippines. The final user in all scenarios is located at the De La Salle University, Manila, Philippines. It was also assumed that the UV-C disinfection equipment is stationed at De La Salle University. The system boundaries are found in Fig. 1 based on the study of Allison et al. (2021).

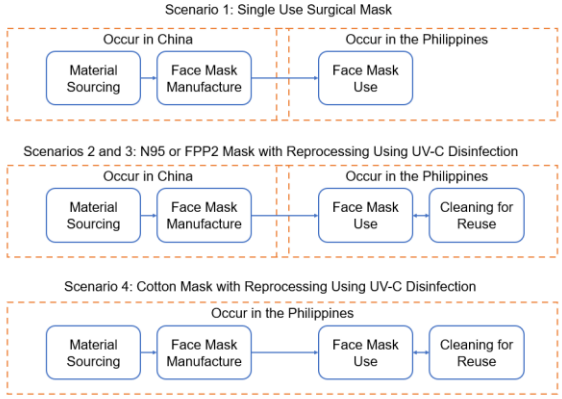

Fig. 1. System boundaries. End-of-life scenarios and packaging are excluded from the scope

It was assumed that the effective use for each N95 face mask given its filtration capacity and fit and seal quality will be 5 consecutive uses (Bergman et al., 2012). Given that the disinfection failure/rejection rate for UV-C is approximately at 13% (Cremers-Pijpers, 2021) and each mask could be used up to 5 consecutive times, the raw material acquisition and production impact for the N95 masks would only be accounted for 23 new masks to achieve the functional unit of 100 uses. Since FPP2 and N95 are equivalent masks (Allison et al., 2021), the same assumptions in the number of new masks were assumed for the FPP2 scenario. For easier comparison, the same assumptions for the reuse of the cotton face masks were used. On the other hand, the single-use face masks, per definition, will be assessed for 100 new masks as they will be disposed of after 1-time use. It is important to note that the packaging of the masks is excluded from the assessment.

2.2 Life cycle inventory (LCI)

The inventory data of four different face masks were acquired from published literature (Allison et al., 2021; Rodriguez et al., 2021). Using the Ecoinvent educational license database, the items and the provider selected were as much as possible exactly the same as the reference. In cases wherein there are no same items found in the Ecoinvent database, equivalent items are substituted using engineering judgment. The transport distances were obtained using Google maps using the locations mentioned in Section 2.1.

The inventory data of the UV-C equipment were taken from an LCA study using UV for wastewater disinfection (Lee et al., 2012) since no studies have been found using UV for face mask disinfection. The electricity requirement in running the equipment was obtained from the study of Bentancor et al. (2021) using three UV-C lamps with a 30 W rating. The lifespan of the UV equipment was allocated according to the functional unit. The number of face masks that can be disinfected by 1 unit of UV equipment was calculated using the following information:

- The disinfection time per batch of face masks is 30 seconds, which results in a 99.7% reduction in viral load (Kitagawa, 2021).
- Four face masks can be accommodated per disinfection batch (Bentancor et al., 2021).
- The lifespan of one UV lamp is approximately 9,000 hours (CureUV, 2013).

Based on the information, the calculated number of face masks that can be disinfected by UV equipment throughout its lifespan is up to 4,300,000 face masks.

2.3 Life cycle impact assessment (LCIA)

The following impact categories were selected in this work referring to a calculation of the impact for 100 years.

- Climate change (GWP 100a) in kg CO_2-eq
- Human toxicity (HTP 100a) in kg 1,4-DCB-eq
- Freshwater aquatic ecotoxicity (FAETP 100a) in kg 1,4-DCB-eq
- Marine aquatic ecotoxicity (MAETP 100a) in kg 1,4-DCB-Eq

The impact assessment method CML 2001 was implemented using the software openLCA version 1.10.3, using the Ecoinvent educational license database. Further investigation was made on the climate change (GWP 100a) impact category by analyzing the contribution of each process step (manufacture, transport, and disinfection) in the total impact.

2.4 Sensitivity analysis

Focusing on the climate change (GWP 100a) impact category, sensitivity analysis was conducted on the best-performing face mask to check the changes in the output based on changes in the input. The following variations were investigated:

1) Rejection percentage. The baseline scenario assumes a rejection rate of 13% so that the face masks are reused for 5 consecutive times and 23 new face masks are needed to fulfill the functional unit of 100 use. Higher rejection rates of 20% and 30% were compared with the baseline study.
2) UV-C equipment capacity. The baseline scenario assumes that 4.3 million face masks can be disinfected in the lifetime of the UV-C equipment. However, this does not take into consideration the possible maintenance and breakdown of the equipment. Hence, for the sensitivity analysis, scenarios wherein the capacity of the UV-C equipment were reduced to 3 million and 1 million face masks.

3. RESULTS AND DISCUSSION

Fig. 2 shows the impact analysis of the different scenarios. Based on the results, using locally sourced reusable cotton masks with UV-C disinfection has the highest impact while using imported reusable N95 masks with UV-C disinfection has the least impact across all impact categories. Imported reusable FPP2 masks with UV-C disinfection follow next as the option with the least impact, and imported disposable surgical masks rank third. Looking at the climate change (GWP 100a) impact category, the worst scenario has 29.4 times more carbon footprint than the best scenario. Comparing the disposable surgical mask with the best scenario, the disposable surgical masks scenario has 7.3 times more carbon footprint than the reusable N95 face mask scenario.

The better performance of reprocessed versus single-use face masks in Scenarios 2 and 3 of this study (using imported reprocessed N95 and FPP2 masks) agree with the results of other studies such as reprocessing of face masks using steam distillation (van Straten et al., 2021) and using manual and machine washing (Allison et al., 2021; Rodriguez et al., 2021). However, the poor performance of reprocessed cotton masks in Scenario 4 is in contrast with the results of the study by Schmutz et al., (2020), wherein washable cotton masks performed better over disposable surgical masks. In the present study, the reprocessed cotton masks performed worse than the disposable surgical masks despite being locally sourced.

Fig. 3 shows the contribution of each step (manufacture, transport, and UV-C disinfection) in the climate change (GWP 100a) impact category. Based on the analysis, the bulk of the impact comes from the manufacturing step, and only a small portion is allocated to transportation. The UV-C disinfection step is almost negligible in all three cases of reprocessed masks. It is expected that a difference in the contribution of transportation will be evident in the locally sourced cotton mask, given the large distance between the user and source in imported masks. However, in this case, the manufacturing step contributed significantly to all three scenarios as compared to the transportation and disinfection steps. Since transportation is highly dependent on the distance assumed, the effect of transportation in the present study cannot be compared with published studies.

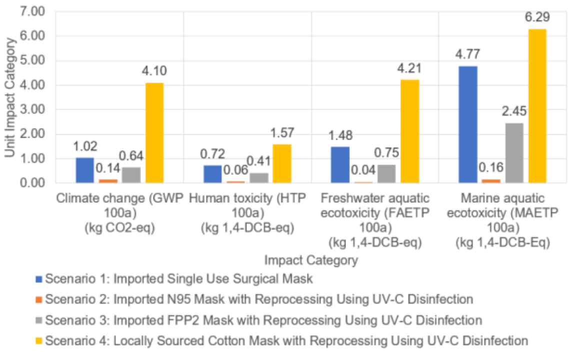

Fig. 2. Results of the impact analysis

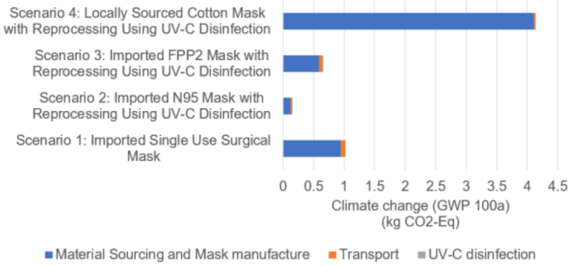

Fig. 3. Contribution of each step (manufacture, transport, and UV-C disinfection) in the climate change (GWP 100a) impact category

Another important observation is the insignificant contribution of the UV-C disinfection step. UV-C disinfection only contributes 0.09% in the total carbon footprint of the N95 scenario and 0.01% in the FPP2 scenario. Its contribution in the cotton mask scenario is negligible. Thus, the contribution of this step is not visible in Fig. 3.

Further investigating the best-performing scenario, the top contributors in Scenario 2 (reprocessed N95 face masks) are from the polypropylene (PP) production, synthetic rubber production, sea transport, electricity, and polyethylene (PE) production. These contributors are from the manufacturing and transportation steps. Face masks are usually made of polypropylene, although some are also made of polyethylene (PE) or polyester (PET) (Allison et al., 2021). In this case, the main material is the highest contributor to the impact.

On the other hand, for the worst-performing scenario (Scenario 4, cotton masks), the highest contributor is textile cotton production. The other top contributors (electricity, rubber, transport, and sheet rolling) lag behind the top contributor, which is cotton production. The significant contribution of cotton in the impact assessment may explain the results in Fig. 2. Despite being locally sourced and undergoing reprocessing, the high impact of the cotton raw material has affected the overall performance of the cotton mask.

The results of this study imply that although UV-C may seem desirable as a disinfection method due to its low impact, ultimately, the type of face mask affects the overall performance of the face mask, such as in the case of reusable cotton face masks. In addition, although locally sourced masks may seem more desirable due to shorter transportation distances, the materials used in the face mask still have a great influence on the final results.

The results of the sensitivity analysis are shown in Fig. 4. Based on the graph, changing the face mask rejection rate from 13 to 20 and even 30% has little effect on the carbon footprint of the reusable N95 face masks using UV-C as a disinfection method as compared to using disposable surgical masks. In addition, reducing the capacity of the UV-C disinfection equipment from 4.3 million to 3 or 1 million face masks also has little effect on the carbon footprint relative to using disposable face masks. The results show the robustness of the UV-C disinfection method. The results are in agreement with that of another study where steam distillation is used (van Straten et al., 2021). The sensitivity analysis has shown that decreasing the load in the autoclave from 1000 to 250 face masks and increasing the rejection rate from 20 to 30% affected the carbon footprint of the method, however, the reusable face mask scenario still performed better than the disposable masks scenario (van Straten et al., 2021).

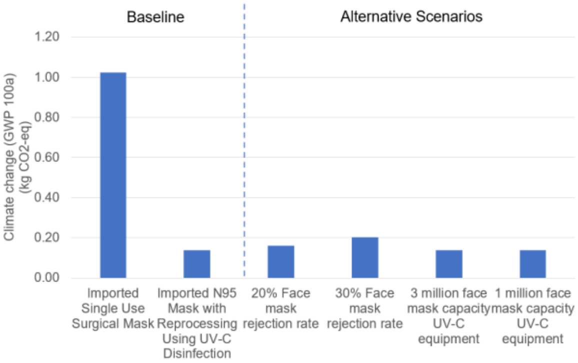

Fig. 4. Sensitivity analysis. The baseline scenario for the imported N95 mask is using a 13% rejection rate and UV-C equipment capacity of 4.3 million face masks

4. CONCLUSIONS

In this work, cradle-to-gate life cycle assessments were conducted for four scenarios of face mask usage: namely, (1) single-use of imported face masks, (2) reuse of imported N95 face masks via UV-C disinfection, (3) reuse of imported FPP2 face masks via UV-C disinfection, and (4) reuse of locally sourced cotton masks with UV-C disinfection. Results show that using locally sourced reusable cotton masks with UV-C disinfection has the highest impact while reusing imported reusable N95 masks via UV-C disinfection has the least impact across all impact categories. Despite the importation of the facemasks, the impact of transportation is only small compared to the impact of the manufacturing process. The resulting impact of the UV-C disinfection step is almost negligible in all three scenarios of reprocessed masks making UV-C a desirable disinfection method. However, the significant difference in the results for Scenarios 2-4 implies that it is the type of face mask that ultimately affects the overall impact, such as in the case of reusable cotton face masks. Although the reusable cotton face masks were locally sourced making it a desirable option due to its shorter transportation distance, the manufacturing of its materials still has a great influence on the final results. Sensitivity analysis shows that for the best-case scenario of using N95 masks, increasing the rejection rate up to 30% and decreasing the capacity of the UV-C equipment to as low as 1 million face masks, still has little effect on the overall impact of N95 UV-C reprocessed face masks compared to the single-use surgical masks. This suggests that UV-C is a robust disinfection method for face masks.

For future work, it is recommended to check other UV-C equipment configuration and operations and to consider alternatives for locally sourced face mask materials (e.g., bamboo fiber, recycled cotton). It could also be worthwhile to consider end-of-life scenarios for a cradle-to-grave approach. Conducting a multi-criteria decision analysis (MCDA) like the Analytical Hierarchy Process (AHP) based on the environmental impact, social acceptability (including the convenience of use), efficacy, cost, etc., will also further guide decision-makers in adopting UV-C as a disinfection method.

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