Resources, Conservation & Recycling 170 (2021) 105580

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Life cycle assessment of single-use surgical and embedded filtration layer (EFL) reusable face mask

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A R T I C L E I N F O

Keywords:
Life cycle assessment
Reusable face mask
Waste generation
Carbon footprint
Environmental impact
Single-use face mask

A B S T R A C T

Background: The outbreak of the COVID-19 pandemic has led to an unprecedented amount of face mask consumption around the world. The increase in face mask consumption has brought focus to their environmental impact. To keep up with the increased demand for face masks, different variations of reusable face masks such as the embedded filtration layer (EFL) reusable face mask have emerged in the market. This study quantifies the environmental impact of the EFL reusable face mask and the single-use surgical face mask.
Methods: The life cycle assessment (LCA) study of the entire value chain from cradle-to-grave is applied to each face mask. Both face masks are evaluated over 1 functional unit (FU) of 31 12-h days for a single person. The ReCiPe method with the Hierachist perspective was applied. A total of nine impact categories as well as the generated waste of each face mask are evaluated.
Results: The results show that for 1 functional unit, the use of single-use surgical face mask and EFL reusable face mask will contribute 0.580 kg CO_2-eq and 0.338 kg CO_2-eq to climate change and generate 0.004 kg and 0.0004 kg of waste respectively.
Conclusion: Comparing both face masks, the EFL reusable face mask will have a lower emission of at least 30% in terms of the generated waste and the impact categories considered, except for water depletion, freshwater eutrophication, marine eutrophication, and human toxicity.

1. Introduction

Face masks have been worn to curb the spread of infectious diseases, with the first recorded use of face masks dating back to the late 19th century (MacIntyre, 2013). They are typically worn by health care professionals as well as infected individuals to reduce the risk of infectious droplet transfer. In an experiment conducted using a high-speed camera, it was shown that the transmission of droplets and aerosols ejected by coughing is significantly lower from subjects wearing a face mask as compared to those not wearing a face mask (A*STAR, 2020). A detailed description of how face masks work can be found in (Chua et al., 2020).

Since the start of the COVID-19 pandemic, there has been an increase in face mask consumption as the general population is encouraged to wear a face mask beyond their domestic space. The use of a face mask is considered by many as an important secondary non-pharmacological intervention strategy to reduce and prevent community transmission, with some countries (e.g. Singapore) going as far as issuing a mask mandate to curb community transmission.

While there is no denying in the importance of face mask usage during the pandemic, there are concerns on the amount of plastic waste that will be generated from single-use surgical face mask usage (Klemeš et al., 2020). It was estimated that UK would generate approximately 128,000 t of unrecyclable plastic waste if every single person in the UK wore a new single-use surgical face mask per day for an entire year (Allison et al., 2020). In addition, the consumption of face masks also

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This study provides a comparison of the environmental impact between single-use surgical face mask and EFL reusable face mask from local production. The study can be used to provide a more realistic estimation of the environmental impact of face mask usage. For policy makers, these results could be used when deciding on the choice of face mask for the wider population.This work also fills a gap in existing knowledge regarding the environmental impact of reusable face masks.

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https://doi.org/10.1016/j.resconrec.2021.105580
Received 16 September 2020; Received in revised form 16 March 2021; Accepted 18 March 2021
Available online 31 March 2021
0921-3449/

threatens to overload waste treatment facilities. At the peak of the pandemic, more than 20 cities across China were overloaded with medical waste, with Wuhan alone producing more than 240 t of medical waste in one month (Zuo, 2020). To make matters worse, there have been reports of face masks being found on seabeds and being washed up on beaches (Edmond, 2020; OceansAsia, 2020). Improper disposal of face masks into water bodies also threatens to worsen ocean pollution and marine life (Kassam, 2020).

Despite the potential environmental repercussions, the consumption of face masks is unlikely to recede in the new norm until a working vaccine for COVID-19 is formulated and distributed. Therefore, the general population can explore alternative face mask options that have a lower environmental impact to help alleviate the environmental burden of face mask usage. One such option would be the embedded filtration layer (EFL) reusable face mask (Forever Family, 2020b). This face mask was developed in Singapore at the start of the pandemic as an alternative face mask option for the general population to address the shortage of single-use surgical face masks. The EFL reusable face mask was shown to have a bacterial filtration efficiency of 95% after 30 washes through a series of tests conducted by the German testing company TÜV Süd in accordance with ASTM F2101 and EN14683 (Forever Family, 2020b; Lim, 2020). The certification of EN14683 meant that the EFL reusable face mask have a performance characteristic comparable with a single-use surgical face mask as defined by WHO definition for surgical face mask (World Health Organization, 2020). These EFL reusable face masks are widely used in Singapore with multiple nationwide distributions from the Singapore government (Ang, 2020a, 2020b).

Intuitively the use of a reusable device would be naturally thought of as the greener alternative to the single-use version of the device. However, this is not always true. Previous studies on reusable and disposable medical devices have shown that there is no definitive version of a device that will have a lower environmental impact. The evaluation of laryngoscopes (Sherman et al., 2018) and laryngeal mask airways (Eckelman et al., 2012) showed that reusable versions of the same device have a significantly lower environment impact compared to their disposable counterparts. Conversely, a study on the surgery instrument set for spinal fusion surgeries (Leiden et al., 2020) showed that the disposable surgery instrument set would lead to a lower environmental impact compared to its reusable counterparts. In the evaluation of the environmental impact of face mask usage, a University College London (UCL) study (Allison et al., 2020) showed that depending on the type of reusable face mask the result can go either way. This study compared the emissions of single-use face masks with reusable cloth face masks with and without single-use filters. Among the face masks considered, the reusable cloth face mask without filters was the most environmentally friendly option while the reusable cloth face mask with filters was the least environmentally friendly option. Therefore, it is important for different types of reusable face masks to be evaluated individually instead of applying a blanket assumption that all reusable face masks are environmentally superior over single-use surgical face masks.

With that in mind, this study will assess the emissions and waste generated from locally produced EFL reusable face masks and single-use surgical face masks. The study will help establish the environmental impact of the EFL reusable face masks which to the author's knowledge has yet to be published. This study will hence conduct life cycle assessments (LCA) of both face masks from cradle to grave in Singapore to report the environmental impact of the manufacturing, usage, and disposal of both face masks. Even though the results are being interpreted from the perspective of Singapore, the results are indicative of what can be done in other parts of the world.

2. Methodology

This paper assesses multiple midpoint environmental impacts as well as the waste generated from fabrication to disposal of used face masks in Singapore.

2.1. Description of face mask

2.1.1. Single-use surgical face mask

The 3-layer single-use surgical face mask is considered in this study. These single-use surgical face mask are recommended by the authorities and are widely used in Singapore (Health Sciences Authority, 2020). In fact, these face mask were distributed to each household at the start of the pandemic prior to the distribution of the EFL reusable face mask (Ang, 2020b). The construct of each face mask consists of an aluminum nose piece, polyurethane earloop, and a composite of melt-blown polypropylene (PP) sandwiched between a layer of spunbond PP with a grammage of 25 gsm and 20 gsm respectively.

The single-use surgical face mask is fabricated in a cleanroom class 1000 environment. The production line begins with material feeding followed by pleat-formation, nose piece insertion, layer bonding, and lastly earloop welding. Approximately 5% of the face mask is disposed at the production line for defects. The face mask is then packed manually into a paper box consisting of 50 face masks. 40 paper boxes are then packed into a cardboard box.

2.1.2. EFL reusable face mask

The EFL reusable face mask considered in this study has an embedded filter layer. The face mask consists of a polyurethane earloop and 3 distinct layers comprising a layer of polyester fabric with a hydrophobic coating, a layer of melt-blown PP and polyester fabric with hydrophobic coating composite, and a layer of polyester fabric.

The fabrication of the EFL reusable face mask comprises cutting, stacking, die cut, sewing, disinfection, and packing. Each face mask is packed individually in a paperboard packaging material lined with aplastic film, with a weight ratio of 5:1. 800 individually packed face masks would then be packaged into a cardboard box. The EFL reusable face mask has a lifetime of 30 washes, as recommended by the manufacturer (Forever Family, 2020a).

2.2. Goal and scope definition

The goal of the LCA study is to inform policymakers of the environmental impact of the use of single-use surgical and EFL reusable face masks. The reported result could be used to aid policymakers to factor in sustainability considerations when drafting contingency plans for a future pandemic. It can also help to guide public messaging.

In this LCA study, the entire value chain from material acquisition to the end of life (EoL) is considered as shown in Fig. 1. Adhering to the recommendation, single-use surgical face masks are considered to be contaminated once worn and should not be reused or recycled (Confederation of Paper Industries, 2020; Health Sciences Authority, 2020). Despite the availability of face mask recycling facilities such as those reported in (FRANCE 24, 2020), there are no known facilities in Singapore that process used face masks. Thus, recycling of face mask will not be considered in this study. A disposed face mask will be treated as municipal waste and thus will be incinerated in a waste-to-energy plant before ending up in the landfill (National Environment Agency, 2020).

For the EFL reusable face mask, the study assumes that the face mask is washed daily after considering an amalgamation of variables including recommendations from the manufacturer and health professional in context of the hot and humid climate of Singapore. With reference to the manufacturer's recommendation, this assessment considers that the EFL reusable face mask is washed daily by hand with room temperature water (Forever Family, 2020c). From Ariel's guide on hand washing and the UCL study, approximately 6.24 g of liquid detergent and approximately 6 l of water is required in each manual washing session (Allison et al., 2020; Ariel, 2020). Using a similar manual washing scenario as the UCL study, it was assumed that the EFL reusable face mask of an entire household will be washed together (Allison et al., 2020). Thus, the average washing consumables required for each EFL reusable face mask will be calculated by normalizing the

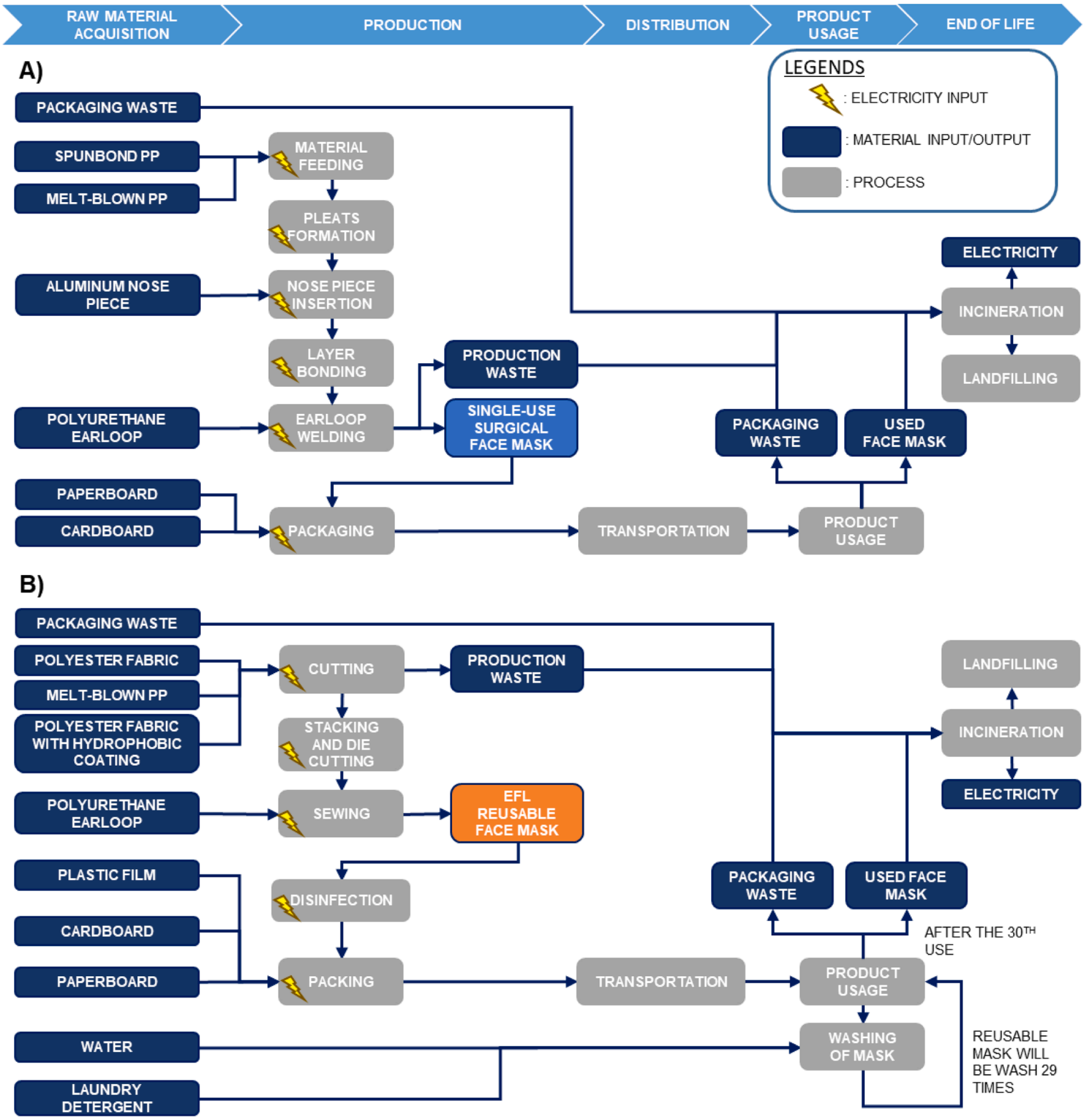

Fig. 1. Process map of a) Single-use surgical face mask b) EFL Reusable face mask.

consumables required per manual washing session by the average size of the household. With a reported average household size of 3.16 in Singapore, the washing consumables required for each EFL reusable face mask is approximately 1.975 g of liquid detergent and 1.899 l of water per wash (Singapore Department of Statistics, 2020).

The functional unit (FU) for this study would be the consumption of face mask by a person in a month (31 days). The duration of face mask usage per day was assumed to be less than 12 h. For the single-use surgical face mask, 1 FU would be equivalent to the usage of 31 face masks. Whereas for the EFL reusable face mask, 1 FU comprises of 1 face mask and washing consumables sufficient for 30 washes. EoL of the waste generated in the raw material acquisition stage will not be included in this study.

2.3. Inventory analysis

The Ecoinvent 3.6 database was used to determine the emission factors (EF) and waste generated for the LCA study. Published data for water and electricity emission in Singapore was used with supplementary data of a comparable system from the Ecoinvent database. Table 1 summarizes the references for each emission source used in the study.

The life cycle inventory data for the fabrication of each face mask is provided by researchers from the Singapore Institute of Manufacturing Technology (SIMTech). The consumables and electricity consumption from the fabrication of the single-use and reusable face masks as well as the assumptions made regarding the life cycle impact assessment of raw materials are summarized in appendix A.

2.4. Impact assessment

The goal of the study is to understand the long-term environmental impact, impact on water bodies, and resource use from face mask consumption. The selected impact categories reflect the environmental issues that were observed from face mask usage discussed in the introduction. Categories relating to resource use are selected based on materials required in face mask fabrication and usage. Nine relevant midpoint impact categories were considered: climate change (CC), fossil fuel depletion (FD), metal depletion (MD), water depletion (WD), freshwater ecotoxicity (FET), freshwater eutrophication (FE), marine ecotoxicity (MET), marine eutrophication (ME), and human toxicity

Table 1
Source for emissions factors.

Emission Source	Emission Factor Reference
Production of polyester fabric	fiber: ecoinvent (symeonidis, 2018) weaving: (symeonidis, 2019)
Production of melt-blown PP	PP Granulate: Ecoinvent, (Froehlich, 2016) Electricity, Japan: Ecoinvent (Treyer, 2012)
Production of spunbond PP	PP Granulate: Ecoinvent (Froehlich, 2016) Spun Bond: Ecoinvent (Datta, 2018)
Production of aluminum nose piece	Ecoinvent (Steiner, 2007)
Production of earloop	Spandex foam: Ecoinvent (Hischier, 2007b) Electricity, China: (Ecoinvent, 2015)
Production of paperboard packaging	Ecoinvent (Hischier, 2007c)
Production of cardboard packaging	Ecoinvent (Brunner, 2015)
Production of plastic film packaging	Ecoinvent (Hischier, 2007a)
Production of grid electricity (Singapore)	Grid Emission Factor (Energy Market Authority of Singapore, 2019) Supplementary data from Ecoinvent (Treyer, 2007)
Production of water (Singapore)	Emissions for tap water: (Hsien et al., 2019) Supplementary data from Ecoinvent (Dussault, 2013)
Production of laundry detergent	Ecoinvent: (FitzGerald, 2007)
Transport of inputs by land	Ecoinvent: (Simons, 2010)
Transport of inputs by sea	Ecoinvent: (Notten, 2018)
Incineration of polyester	Ecoinvent: (Doka, 2013f)
Incineration of polypropylene	Ecoinvent: (Doka, 2013c)
Incineration of spandex/ polyurethane	Ecoinvent: (Doka, 2013d)
Incineration of aluminum	Ecoinvent: (Doka, 2013a)
Incineration of paperboard and cardboard	Ecoinvent: (Doka, 2013b)
Incineration of plastic film	Ecoinvent: (Doka, 2013e)

(HT). The ReCiPe method with the Hierachist perspective was used as it consists of the relevant impact categories relevant to the study (Goedkoop et al., 2009). Besides the nine impact categories listed, waste generated (W1) will also be computed.

3. Results and discussion

3.1. Emission impact analysis

Table 2 summarizes the emission factor for each impact category, the waste generated as well as the breakeven point of both face masks. The breakeven point was calculated by finding the number of days it takes for the cumulative emission of single-use surgical face masks to surpass the emission of an EFL reusable face mask over 1 FU. Comparing each emission factor over 1 FU, the EFL reusable face mask has a lower value for most of the impact categories except for WD, FE, ME, and HT. When discussing the breakeven point, the use of the EFL reusable face mask will not break even for the same 4 categories over 1 FU. EFL reusable face mask will never break even when compared with the FE of a single-use surgical face mask. For WD, ME, and HT, an EFL reusable face mask will only break even if the same EFL reusable face mask is used for more than 595, 221, and 86 days respectively exceeding the recommended lifetime of the EFL reusable face mask.

Based on the emission factor generated from the LCA study, the EFL reusable face mask is clearly the more environmentally friendly option compared to the single-use surgical face mask with an emission reduction of at least 30% for CC, FD, MD, FET, MET, and W1. This reduction is especially significant when scaled by the face mask consumption of Singapore's population.

Fig. 2 provides a breakdown of emissions for each impact category at each LCA stage for both face masks. Among the impact categories considered, except for WD and FE, the impact contribution associated with raw material acquisition has the lion's share of the cumulative emission compared to the contribution of other LCA stages, for both face masks. In the breakdown for WD, raw material acquisition remains as the main contributor to the overall emission factor of the single-use surgical face mask. A deviation in this trend was observed for the EFL reusable face mask where the contribution from its usage and raw material acquisition is comparable as shown in Fig. 2d. The high contribution observed in the usage category is expected, as water is discharged from the washing process as shown in the EFL reusable face mask process map.

When discussing the breakdown of FE, the incineration of either face mask will produce a negative emission value that offsets the cumulative emissions from the other LCA stages. For the single-use surgical face mask, the offsets from the incineration happens to be much higher than the combine emissions from the other stages that it resulted in a net positive effect on the environmental. The emission value of FE is calculated by consolidating the amount of phosphate, phosphorus, and phosphoric acid that is emitted (Bourgault, 2020). The negative emission value for FE in the EoL could be attributed to the absence of these substances in most of the material that was incinerated as indicated in the Ecoinvent database, as well as the presence of substances that aid in their removal (ecoinvent, 2020).

Fig. 3 describes the contribution of the waste generated from the production to the usage stage of the LCA as well as the waste generated at EoL. The waste generated at EoL was not added into the cumulative waste generated as the incineration process reduces the weight and volume of the waste generated from production to usage, instead of producing additional waste (Bridgwater, 1980). Therefore, the waste generated at EoL is segregated from the waste generated by other life cycle stages by a red line. The generated waste at EoL can be thought of as the updated value for the cumulative waste after the incineration process. Unlike the emission factor described in Fig. 2, the main contributor to W1, as shown in Fig. 3, is from the usage of the face mask. The quantity of waste generated in the usage category correlates with the quantity of material used in the construct and packaging of the face mask.

The information shown in Figs. 2 and 3 provide a clear breakdown of

Table 2
Emission factor of single-use surgical and EFL reusable face mask over 1 with the number of days for a reusable face mask to breakeven with the single-use face mask.

Impact Category	Abbr	Units	Single-use surgical face mask	EFL reusable face mask	Breakeven
Climate change	CC	kg CO_2-eq	0.580	0.338	17 days
Fossil fuel depletion	FD	kg oil-eq	0.308	0.083	8 days
Metal depletion	MD	kg Fe-eq	0.045	0.019	13 days
Water depletion	WD	m^3 Water eq	0.006	0.116	595 days
Freshwater ecotoxicity	FET	kg 1,4-DCB-eq	0.033	0.022	20 days
Freshwater eutrophication	FE	kg P-eq	−0.00012	0.00013	^{2} N.A
Marine ecotoxicity	MET	kg 1,4-DB-eq	0.029	0.014	15 days
Marine eutrophication	ME	kg N-eq	0.0001	0.0009	221 days
Human toxicity	HT	kg 1,4-DCB-eq	0.034	0.098	86 days
^{1}Waste Generated	W1	kg	0.004	0.0004	3 days

Notes: 1: Waste generated excludes the waste generated from raw material production. 2: Compared with negative value EFL reusable face mask will never breakeven.

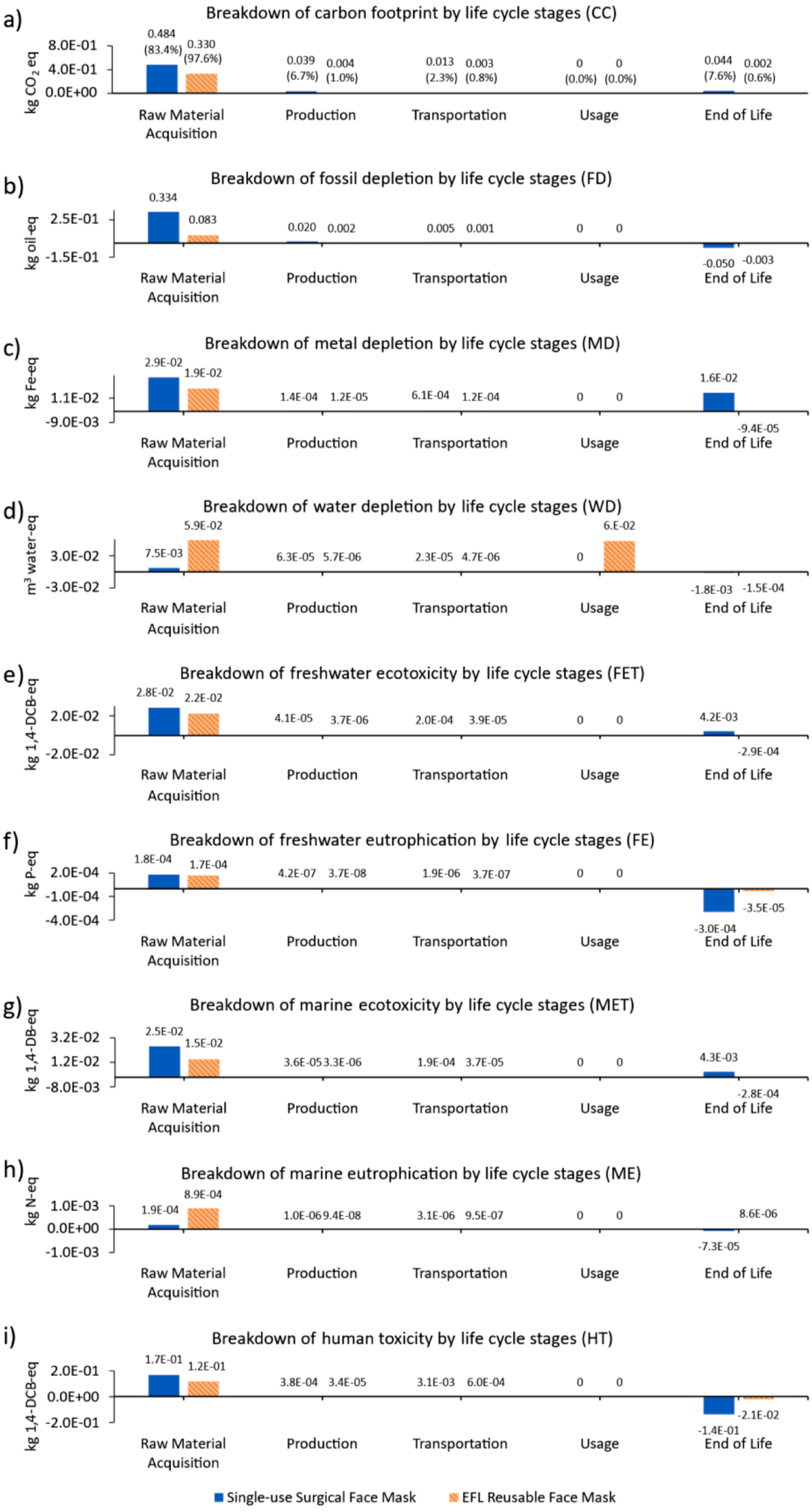

Fig. 2. Graph of base case emission breakdown by LCA stage for a) CC b) FD c) MD d) WD e) FET f) MET g) FE h) ME i) HT.

the emissions contribution at each stage of the face mask life cycle. However, it would be difficult to provide any meaningful suggestion regarding improving the environmental impact of each face mask based on this information alone, especially regarding which elements of the face mask whose improvement will have the greatest overall impact. This motivates a more detailed analysis to determine environmental hotspots in the life cycle of each face mask. The breakdown for CC and W1 could be particularly useful in the context of Singapore, which has a standing commitment to the Paris agreement and is rapidly running out of landfill space on its offshore landfill on Semakau island (Low, 2019). The next section describes the sensitivity analysis on CC and W1.

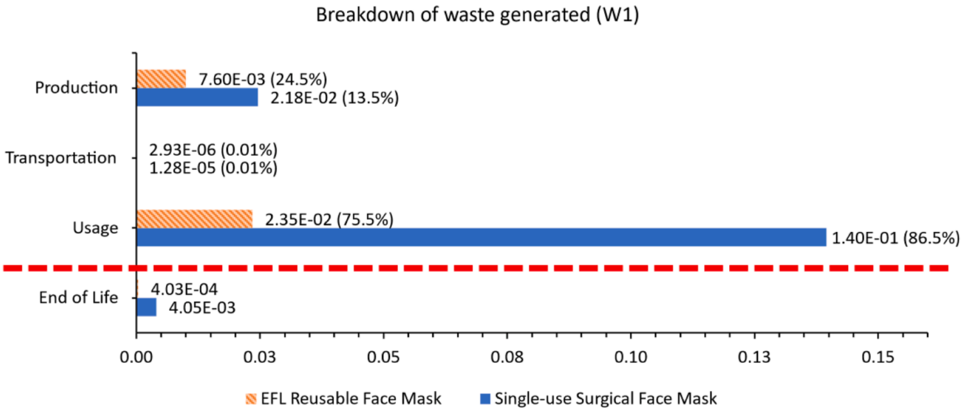

Fig. 3. Waste generated from raw material extraction to the end of life. Waste generated at EoL was not added into the cumulative waste generated. Therefore, the waste generated at EoL is segregated from the other categories by a red line, indicating the updated value for the waste generated after the incineration process. Disposal of waste generated from the raw material acquisition is not considered for this study and is therefore not included in the figure.

3.2. Sensitivity analysis

The Pareto principle states that 80% of the effect is caused by 20% of the population. Therefore, elements from the top contributing LCA stage for CC and W1 will be investigated. There are seven and eight identified elements in the raw material acquisition stage for the single-use surgical and EFL reusable face mask respectively, and six elements for the usage stage for each face mask. Following the Pareto principle, the top two elements from CC and W1 of each face mask with the highest contribution as shown in Fig. 4 will be investigated.

Fig. 4a shows the breakdown of the contributing elements in the raw material acquisition stage for CC. For a single-use surgical face mask, the top two elements were observed to come from the production of material relating to the construction of the face mask such as spunbond PP and spandex earloop. For the EFL reusable face mask, the main contributor to CC was observed to come from the production of detergent and polyester. Fig. 4b provides a detailed breakdown of the contribution of each element to W1 in the usage stage, this figure can also be interpreted as the mass composition of each material used in the fabrication and packaging of each face mask. The main contributor to W1 for single-use surgical face masks came from the quantity of spunbond PP and paperboard used. For the EFL reusable face mask, the main contributor to W1 came from the quantity of polyester and paperboard used.

In addition to the four elements identified for each face mask, elements with comparable contributions as the identified elements will also

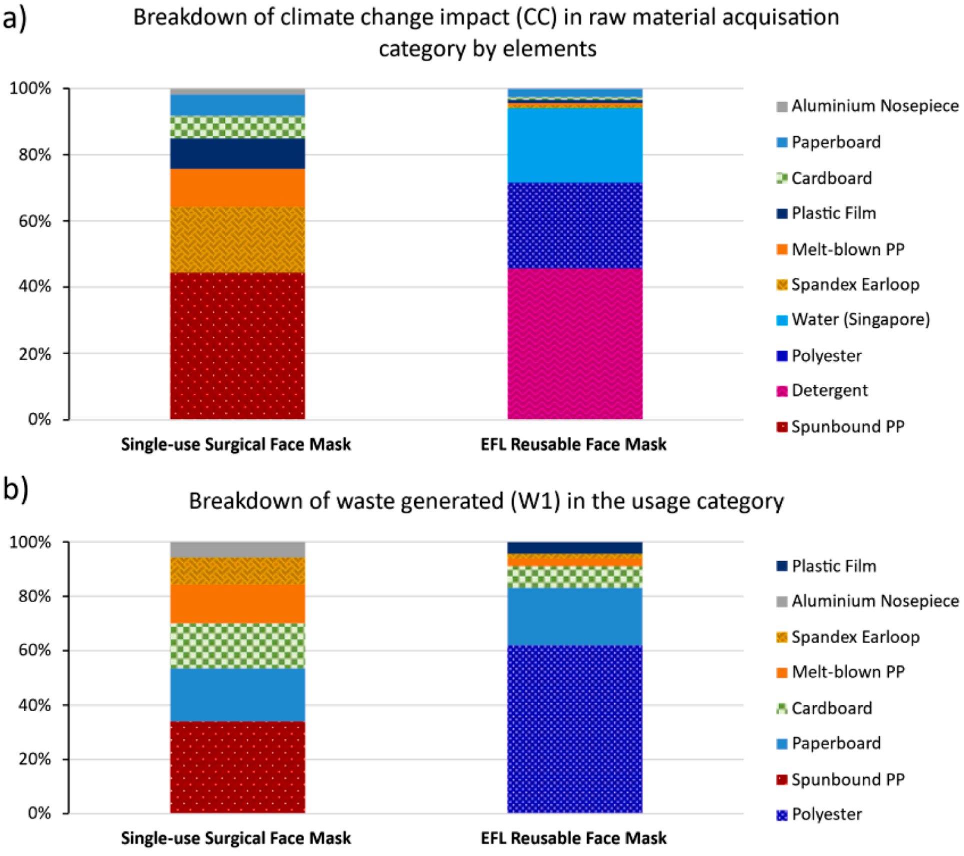

Fig. 4. Breakdown of the elemental contribution of a) Raw material acquisition category b) Waste generated in the usage category.

be included in the sensitivity analysis. Therefore, the quantity of cardboard and melt-blown PP used for a single-use surgical face mask and contribution from water production for an EFL reusable face mask will also be investigated.

A sensitivity study on the input emission factor was conducted for elements shortlisted from the raw material acquisition stage of CC. A sensitivity analysis on the input quantity of materials was also conducted for the elements shortlisted from the usage stage of W1. Variation in the emission factor value of the material can be thought of as changes made to the process for the acquisition of the raw material. The variation in the input quantity of the material can be interpreted as a percentage reduction in the quantity of material used in the manufactured face mask.

Fig. 5 compiles the tornado diagram for CC and W1 where the input value of each element is altered by ±10% from the base value. Results from elements associated with the change in emission factor were omitted from the tornado diagram of W1 as they do not alter the waste generated from production to EoL.

From Fig. 5a, it was observed that the CC emission of the single-use surgical face mask is most sensitive to the material used in the construction of the face mask whereas the CC emission of the EFL reusable face mask is most sensitive to the material used in the washing process. The sensitivity study shows that the CC impact of a single-use surgical face mask is most sensitive to the quantity of spunbond PP used and the EF of spunbond production. The EFL reusable face mask is most sensitive to the EF of detergent production while changes in the quantity of polyester used, EF of polyester production, and water production have a comparable effect on the overall CC impact. This result shows that for the EFL reusable face mask, emissions associated with the materials required for the washing process has a larger influence on the face mask CC impact compared to materials involved in its construct. Consolidating the sensitivity study for CC impact for both face masks, it can be said that for materials involved in the face mask construction, reducing the quantity of material used in a face mask would have a larger impact in reducing the CC, rather than reducing the emission from material acquisition.

In the tornado diagram for W1, the single-use surgical face mask is most sensitive to the quantity of spunbond PP used while the EFL reusable face mask is most sensitive to the quantity of polyester used. The results reflected in Fig. 5b for both face masks are expected as spunbond PP and polyester represent the main components in the production of the single-use surgical face mask and the EFL reusable face mask respectively. The sensitivity analysis of CC and W1 show that when confined within the design parameters of the face mask, efforts directed towards reducing the emission factor of material acquisition and quantity of the spunbond PP and polyester used would lead to a significant improvement in environmental impact of each respective face mask. This insight helps highlight potential areas of improvement such as material selection, design optimization, or manufacturing improvements that would lead to the largest influence on emission impact of the current face masks.

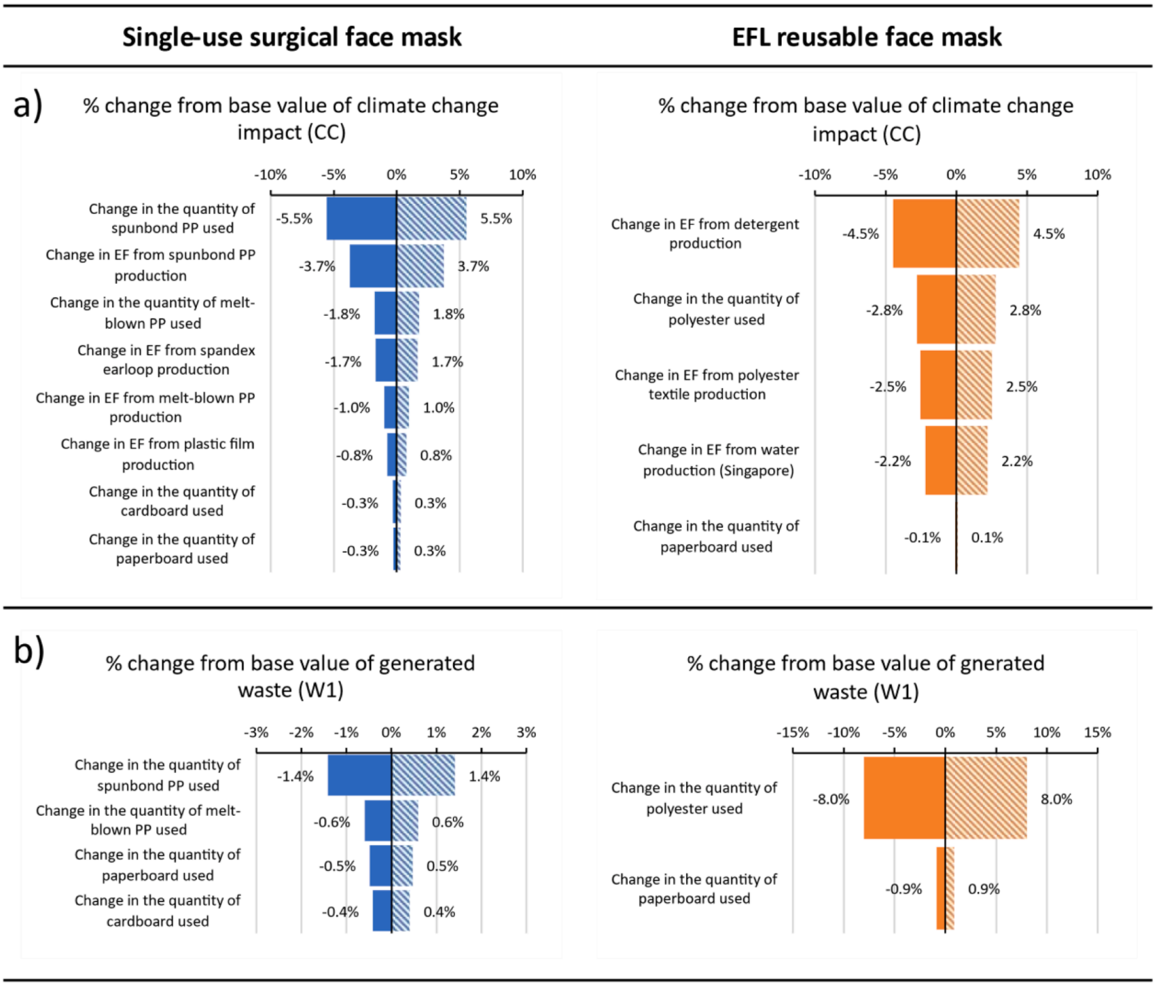

Fig. 5. Compilation of tornado diagram percentage change from base value for a) climate change (CC) impact and b) waste generated (W1) for both face mask when the shortlisted input variables is altered by ±10%.

3.3. Monte-Carlo analysis

This section evaluates the reliability of the emission values summarized in Table 2 by applying Monte-Carlo simulations from the Brightway2 framework (Steubing et al., 2020). The analysis of W1 will be omitted due to the absence of uncertainty data. It should also be noted that for emission values that are supplemented by localized values, such as the CC values from the production of grid electricity (Singapore) and the CC, FD, HT, and WD values from the production of water (Singapore), a deterministic value will be applied for their respective contributions in the Monte Carlo simulation.

The distribution of the Monte Carlo analysis for the single-use surgical face mask and EFL reusable face mask is shown in Figs. 6 and 7 respectively. In addition, key values from the Monte Carlo simulations such as the minimum, lower quartile, median, upper quartile, and maximum values can be found in Appendix B2. From the distribution of the Monte Carlo analysis, it was observed that the calculated emissions (from Table 2) fall below the lower quartile of the analysis. One possible explanation for the observation could be attributed to the lognormal uncertainty distribution provided by the Ecoinvent database.

The Monte Carlo distribution was then evaluated through the application of the *t*-test. The *t*-test is used to determine if the mean of reusable and single-use surgical face mask Monte Carlo distributions is significantly different by comparing the calculated p-value with a predefined significance level. In the evaluation of both face mask Monte Carlo distribution for each impact category, the p-value for two-tail test is computed and compared against a predefined significance level of 0.05. A p-value below 0.05 would suggest the rejection of the null hypothesis which states that the mean of both distributions is equal. In the context of this paper, the rejection of the null hypothesis would bolster the credibility of the observation made for each impact category as it rejects the notion that the mean of the distributions is similar despite proximity in their values. The p-values for the two-tailed form of the *t*-test for all the nine impact categories produces values that are below the predefined significance level of 0.05. Compilation of the *t*-test results can be found in Appendix B3. For the calculated variance, it was observed that the variance for the HT of single-use surgical face mask is higher than its mean value. Thus, there exist a scenario where the HT of the single-use surgical face mask is higher than the HT of EFL reusable face mask. Comparing the mean for both face mask, EFL reusable face masks will have a lower emission for CC, FD, MD, FET, and MET while the single-use surgical face mask has a lower emission for WD, FE, HT, and ME compared to the opposing mask. This observation is similar to those made in Section 3.1.

3.4. Scenario analysis

This section explores the changes in the emission factor that arise from alternative scenarios that deviate from the base case. The scenarios considered describe different face mask usage habits and waste treatment processes. To facilitate subsequent discussion, the label used for each scenario will be tagged with either D (disposable) or R (reusable) to describe the scenario of single-use surgical and EFL reusable face masks respectively.

Scenario 1 describes the use of face mask by users with a heightened hygiene protocol. In this scenario each face mask will not be worn for more than 6 h (Toomey et al., 2020). Under this setting, the quantity of single-use surgical face masks used per functional unit will be doubled under the assumption of 12-h of face mask consumption per day (Scenario 1D). For the EFL reusable face mask the number of face mask used will be increase to two per day (Scenario 1R). 2 different sub-scenario will be investigated, in the first scenario the amount of washing consumables used per functional unit will be the same as the base case under the assumption that the face mask will be washed together (Scenario 1Ra). In the second sub-scenario, the amount of washing consumables used per functional unit will also be doubled assuming the face mask are washed separately (Scenario 1Rb).

Scenario 2 describes the use of face masks by users that spend most of their time in the domestic space. Thus, the time spent wearing a face mask per day is limited. These users are inclined to employ a face mask hygiene protocol that is less stringent compared to the recommended protocol employed in the base case. In this scenario, each single-use surgical face mask is used for 2 days (Scenario 2D) and each EFL reusable face mask will be washed once every 2 days (Scenario 2R). This meant that for the same quantity of face mask and consumables used in the base case, the period of usage will be doubled to 62 days. To ensure a fair comparison between the scenarios, the calculated values for each impact category in scenario 2 is normalized and scaled to 31 days (1 FU).

Scenario 3 describes the omission of the incineration process in the EoL of the face mask. In this scenario, waste generated from face mask consumption will be sent directly to the landfill. Scenario 4 describes the use of washing machine instead of handwashing in the cleaning of the EFL reusable face mask. Since the washing of face mask is unique to the EFL reusable face mask, this scenario is omitted for the single-use surgical face mask.

Table 3 is a compilation of CC and W1 values of the described

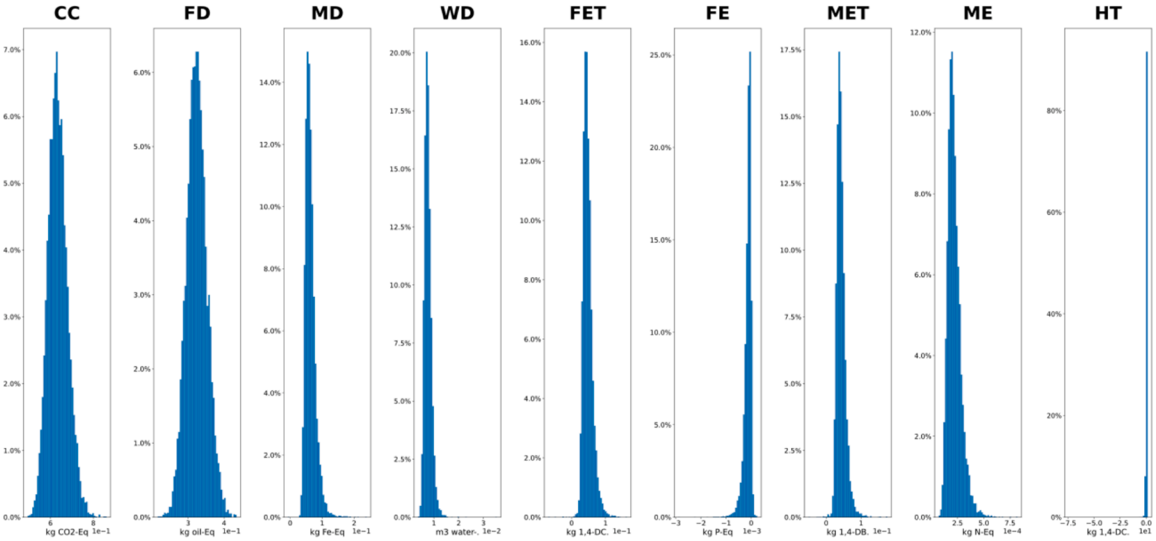

Fig. 6. Distribution of single-use surgical face mask Monte-Carlo analysis (10,000 iterations).

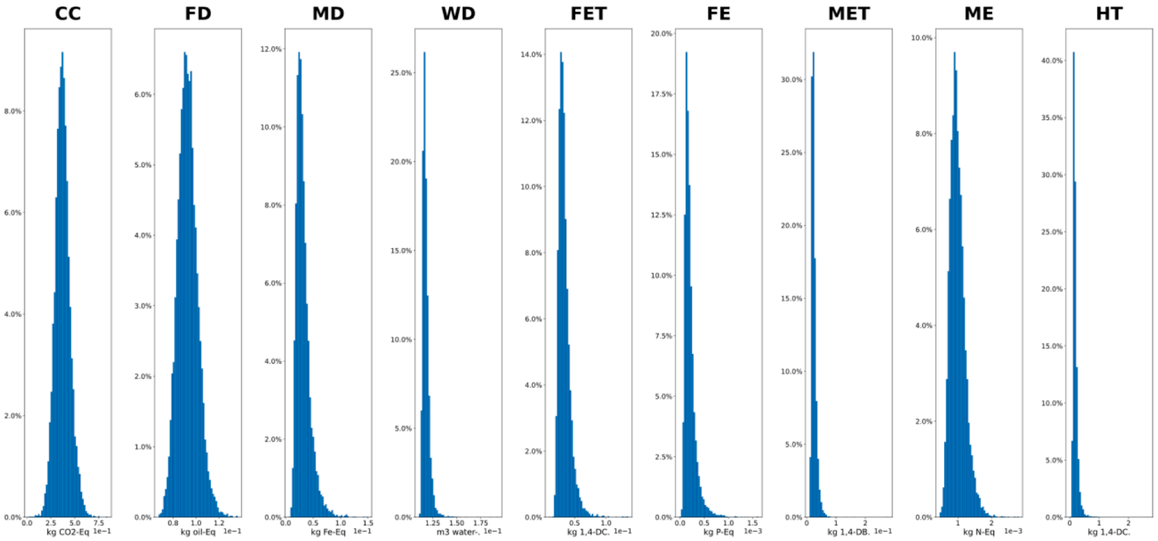

Fig. 7. Distribution of EFL reusable face mask Monte-Carlo analysis (10,000 iterations).

Table 3
Compilation of climate change (CC) impact and waste generated (W1) values of the base case and described scenarios. Δ_D% describe difference in the value of the scenario examined with respect to the single-use surgical face mask base case scenario. Δ_R% describe difference in the value of the scenario examined with respect to the EFL reusable face mask base case scenario.

	Climate change, kg CO_2-eq			Waste Generated, kg		
Single-use surgical face mask scenario						
	EF Value	Δ_D%	Δ_R%	Value	Δ_D%	Δ_R%
Base case scenario	0.580	0%	+72%	0.004	0%	+905%
Scenario 1D (Heightened hygiene protocol)	1.159	+100%	+243%	0.008	+100%	+1911%
Scenario 2D (Reduced hygiene protocol)	0.290	−50%	−14%	0.002	−50%	+403%
Scenario 3D (Direct landfilling of waste)	0.536	−8%	+59%	0.161	+3885%	+39,971%
EFL reusable face mask scenario						
	EF Value	Δ_D%	Δ_R%	Value	Δ_D%	Δ_R%
Base case scenario	0.338	−41%	0%	0.0004	−90%	0%
Scenario 1Ra (Heightened hygiene protocol, wash together)	0.451	−22%	+33%	0.0008	−80%	+100%
Scenario 1Rb (Heightened hygiene protocol, wash separately)	0.676	+17%	+100%	0.0008	−80%	+100%
Scenario 2R (Reduced hygiene protocol)	0.169	−71%	−50%	0.0002	−95%	−50%
Scenario 3R (Direct landfilling of waste)	0.336	−42%	−1%	0.0311	+668%	+7618%
Scenario 4R (Washing Machine)	0.115	−80%	−66%	0.0004	−90%	0%

scenarios for both face masks and their respective deviation from the base case, expressed in percentage change. Compared with the base case scenario for the single-use surgical face mask, scenario 1D and 2D will see a difference of +100% and −50% from the base value respectively for both CC and W1. This result is expected as Scenario 1D and 2D depict half and double the quantity of single-use surgical face mask used respectively, which translate to a proportional change to the material input and their corresponding output emissions.

For the EFL reusable face mask, there is a difference of +100% for both CC and W1 from the base value for scenario 1Rb. This change is expected as the scenario is essentially describing the doubling of all inputs from the base case. For scenario 1Ra, there is a difference of +33% and +100% for the CC and W1 from the base value. The change in CC from the base value for scenario 1Ra is lower than the change observed in scenario 1Rb since only the quantity of face mask is doubled while the quantity of washing consumables required remains the same as the base case for scenario 1Ra. In scenario 2R, there is a change of −50% in the value for CC and W1 compared with the base case. The observation for scenario 2R reflects the scenario setting where the duration of usage is doubled to 62 days. Thus, over the defined 1 functional unit of 31 days the cumulative emission is halved.

Similar to the base case, the EFL reusable face mask will have a lower CC and W1 value in scenario 1 and 2 compared to the same scenario for single-use surgical face mask. From the analysis of the deviation in cumulative emission for different base case, scenario 2D has a lower CC of 14% compared to the CC value of the EFL reusable face mask base case. For the EFL reusable face mask, the CC value of scenario 1 Ra and scenario 1Rb will have a difference of −22% and +17% compared to the base case of the single-use surgical face mask.

In scenario 3R and 3D, there is a difference of +3885% and +7618% in W1 and a change of −8% and −1% in the CC value from their respective base case values. As described previously, the incineration of waste material reduces the weight and volume of the waste, thus its omission will result in a significant increase in W1 as shown in scenario 3R and 3D (Bridgwater, 1980). Beyond comparing against their respective base case value, scenario 3 quantifies the amount of waste that will be generated per face mask for countries that rely on direct landfilling. In these countries, the use of EFL reusable face mask would be more beneficial to the local environment compared to the use of single-use surgical face mask, as less waste will be discharged into the environment.

The application of scenario 4R results in a decrease of 66% in CC value compared with the EFL reusable face mask case. The decrease in CC value can be attributed to the decrease in washing consumables used. Washing consumables required in this scenario are scaled to the weight of the face mask from the total amount of detergent and water required for a full load of the washing machine. This produces a quantity of washing consumables that is much lower than the quantity of the washing consumables described in the base case.

In addition to CC and W1, the scenario analysis of other impact categories can be found in appendix D. Within the same scenario setting, the value of both face masks for the other impact categories exhibits a largely similar trend as those reported in Table 2. Deviation from the trend of Table 2 was observed for the FE and HT of scenario 3. The omission of the incineration process from the cumulative emission value allows the EFL reusable face mask to have a lower value than the single-use surgical face mask for FE and HT. This is also observed in Fig. 2, whereby the EFL reusable face mask is shown to have a lower emission value compared to the single-use surgical face mask for both impact categories in every LCA stage except for the EoL stage. When evaluating scenario 4R and the single-use surgical face mask base case, scenario 4R has a lower cumulative emission value for 9 impact categories. This deviates from Table 2, which shows that the use of the EFL reusable face mask is advantageous over single-use surgical face mask in 6 impact categories. The additional impact categories that scenario 4R outperforms the single-use surgical face mask are HT, ME, and WD. These impact categories registered a lower cumulative emission value due to the reduction in washing consumables required as describe by scenario 4R.

4. Conclusion

Living in a pandemic, the use of face mask by the wider population not only plays an essential role in curbing infected individuals from spreading the virus, but also reduces the chance of healthy individuals from getting infected. While there is no denying of the importance of face mask usage, we need to be aware of the environmental impact from the increase in face mask consumption. In this study, we developed and compared the LCAs of single-use surgical face mask and EFL reusable face mask manufactured and used in Singapore.

The results from the LCA of both face masks show that the use of the EFL reusable face mask will generate less waste and have a lower impact of at least 30% among the impact categories considered compared to the use of single-use surgical face mask except for FE, ME, WD, and HT. An analysis of the contribution at each life cycle stage concludes that emission occurs predominantly at the raw material acquisition stage of the LCA for most of the impact categories of both face masks with the exception being the WD for EFL reusable face mask and FE of a single-use surgical face mask. In addition, if incineration is included in the LCA EoL stage the use of a single-use surgical face mask will lead to a net positive FE. In the analysis of W1, the usage stage in the LCA was identified as the main contributor to cumulative waste.

To address the presence of uncertainty, Monte Carlo analysis was performed on the calculated values. The analysis of the Monte Carlo distribution through the application of *t*-test verify that the mean of both distributions is not equal. The mean from the Monte Carlo distribution shared the same conclusion as those made with the calculated values. The EFL reusable facemask will have a lower emission for CC, FD, MD, FET, and MET while the single-use surgical face mask has a lower emission for WD, FE, HT, and ME compared to the opposing face mask.

In the sensitivity analysis, the input emission factor and the quantity of material used of selected elements were varied by ±10% from the base value to determine the emission hotspots for each face mask. The analysis done on the input emission factor for raw material acquisition identify areas where improvement in the raw material acquisition process would have the largest impact on the cumulative emission of the face mask. Simultaneously, the analysis of the input quantity of materials identifies material inputs that have the greatest impact on the face mask cumulative emission. Using the Pareto principle as a jump-off point a total of eight and five elements were identified for the sensitivity analysis of the single-use surgical and EFL reusable face mask respectively. Among the element investigated for the single-use surgical face mask, modulating the quantity of spunbond PP required in the fabrication of the face mask was found to have the largest impact on its CC and W1. The EFL reusable face mask is most sensitive to the EF from detergent production for CC and quantity of polyester used for W1. The analysis also shows that emission factors associated with the washing process have a more significant impact on the CC of the EFL reusable face mask compared to the other elements. From the observation made in the sensitivity analysis, it can be concluded that changes made to the EF of material acquisition and quantity of the main material used would have a significant impact on the environmental impact of both face mask. For the EFL reusable face mask, reducing the EF associated with the production of detergent and water will also lead to significant improvements in its CC value. Hence, reducing detergent usage or the use of more sustainable detergent in washing reusable masks can be incorporated into public messaging.

For the scenario analysis, three different scenarios were considered for both face masks. Scenarios 1 and 2 discuss the face mask usage habits of an individual with a heightened and reduce hygiene protocol respectively. Scenario 3 describes a scenario where the country employs direct landfilling in its waste management system. Across all three scenarios, the EFL reusable face mask continues to be a greener option with comparatively lower CC and W1 value over single-use surgical face mask. The analysis shows that in scenario 1D and 2D, the quantity of single-use surgical face masks used is directly proportional to the change reflected in CC and W1. This meant that in scenario 1D and 2D there will be an observed change of +100% and −50% respectively for both CC and W1 from their base. For the EFL reusable face mask, the CC and W1 value of scenario 1Ra will be increase by +33% and +100% respectively from the base value. The emission of scenario 1Rb for CC and W1 will be changed by +100% from the base value. For scenario 2R, both CC and W1 will be changed by −50% from their base value. In scenario 3, the absence of the incineration process in the EoL of the LCA result in a significant increase in W1 of +3885% and +7618% for single-use surgical and EFL reusable face masks respectively. The analysis in scenario 1 and 2 provide an alternative set of results for policymakers to consider when the face mask usage habits deviate from the recommendation. Scenario 3 provides the alternative CC and W1 value that can be expected from countries that omit incineration in its waste treatment. Besides the 3 scenarios, a fourth scenario exploring the use of washing machines in place of hand washing was applied to the EFL reusable face mask. From the analysis, scenario 4R will have a lower CC of 66% compared to the EFL reusable face mask base case. The decrease in CC value is attributed to the decrease in washing consumables required in scenario 4R.

In summary, the study quantifies the environmental impact of locally manufactured single-use surgical and EFL reusable face mask over 1 functional unit. From the LCA study of both face masks, the EFL reusable face mask was found to have a lower emission for most of the impact categories considered. Therefore, to mitigate the environmental impact of mass face mask consumption by the wider population, EFL reusable face mask should be recommended. This recommendation will not only alleviate the environmental impact of face mask usage but also increase the availability of personal protective equipment. The EFL reusable face mask contains less polypropylene per face mask compared to the single-use surgical face mask and this difference becomes larger over the entire lifetime of the EFL reusable face mask. The reduction in polypropylene usage per face mask frees polypropylene as a resource for the fabrication of more personal protective equipment. This would address the shortage in personal protective equipment for healthcare workers at the start of the COVID-19 pandemic, caused by public demand for personal protective equipment such as face masks for personal usage.

Beyond recommending a face mask with lower environment impact, this study identifies emission hotspots in each face mask which would greatly reduce the emission impact of face mask consumption. This can be used as a guide in directing research efforts or ecodesign improvements for future face mask designs. It should be noted while this study does not discuss about the durability and functionality of the material involve, these attributes should not be undermined to reduce the environmental impact of the face mask. The LCA results can also be modified to represent emissions from different countries by modifying the transportation stage of the LCA and selecting scenario 3 for the EoL stage of the LCA depending on the country's waste management system.

COVID-19 will eventually subside; however, this is not a one-off occurrence, a new pandemic will eventually emerge. Even though environmental impacts associated with face masks are unavoidable, there are options available that can keep the impact to a minimum. The results presented in this study can serve as a guide to policymakers to consider the environmental impact in their decisions and help guide public messaging involving the choice of face mask and its usage.

CRediT authorship contribution statement

Amos Wei Lun Lee: Software, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Edward Ren Kai Neo:** Software, Methodology, Writing – review & editing. **Zi-Yu Khoo:** Methodology, Writing – review & editing. **Zhiquan Yeo:** Supervision, Writing – review & editing. **Yee Shee Tan:** Supervision, Writing – review & editing. **Shuyun Chng:** Resources, Investigation. **Wenjin Yan:** Resources, Investigation. **Boon Keng Lok:** Resources, Investigation. **Jonathan Sze Choong Low:** Supervision, Methodology, Writing – review & editing.

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.

Acknowledgments

We would like to thank colleagues from SIMTech as well as Ramatex for providing us with the life cycle inventory data for the fabrication of the single-use surgical face mask and EFL reusable face mask.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2021.105580.

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