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Exergy intensity and environmental consequences of the medical face masks curtailing the COVID-19 pandemic: Malign bodyguard?

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A R T I C L E  I N F O

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A B S T R A C T

On January 30, 2020, the World Health Organization identified SARS-CoV-2 as a public health emergency of global concern. Accordingly, the demand for personal protective equipment (PPE), including medical face masks, has sharply risen compared with 2019. The new situation has led to a sharp increase in energy demand and the environmental impacts associated with these product systems. Hence, the pandemic’s effects on the environmental consequences of various PPE types, such as medical face masks, should be assessed. In light of that, the current study aimed to identify the environmental hot-spots of medical face mask production and consumption by using life cycle assessment (LCA) and tried to provide solutions to mitigate the adverse impacts. Based on the results obtained, in 2020, medical face masks production using fossil-based plastics causes the loss of 2.03 × 10 4 eq CO2 to 4.99 × 10 4 eq CO2 additional damage to the environment in 2020 as compared to 2019. The replacement of fossil-based plastics with bio-based plastics, at rates ranging from 10 to 100%, could mitigate the product’s total yearly environmental damage by 4–43%, respectively. Our study calls attention to the environmental sustainability of PPE used to prevent virus transmission in the current and future pandemics.

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1. Introduction

A contagious viral disease caused by a novel coronavirus (CoV), which was later called “SARS-CoV-2”, emerged in Wuhan, China, in late December 2019 and not only quickly spread in China but also worldwide (Gautret et al., 2020). The rapid spread of the disease throughout the world drove the Emergency Committee of the World Health Organization (WHO) to officially declare the “SARS-CoV-2” pandemic as a Public Health Emergency of International Concern on January 30, 2020 (Zheng et al., 2020). From December 30 through May 13, over 160,074,267 COVID-19 cases and 3,325,260 deaths had been reported worldwide (World Health Organization, 2021).

Vaccines are not yet available to all people worldwide to fight this contagious and deadly virus; thus, the prevention and control of SARS-CoV-2 transmission are crucial (Zheng et al., 2020). Probably, the main transmission route for this virus to enter is through large droplets landing in the nose – where there is a high density of angiotensin-converting enzyme 2 (ACE2) cell receptors (Sungnak et al., 2020). Therefore, blocking virus transmission by creating a cheap and affordable physical barrier is currently regarded as the most basic and effective method to prevent and control this pandemic. Medical face masks as a type of personal protective equipment can effectively serve this purpose (Liu and Zhang, 2020). Accordingly, wearing masks (often ‘N95’, which are intended to remove 95% of airborne particles) has been advocated as a means by which to slow the spread of the virus in the broader community or to protect healthcare professionals from infection. Overall, the decrease caused by mitigating interventions, including public face mask application, can reach up to 50% (Fig. 1).

In light of the fact mentioned above, on March 4, 2020, the WHO recommended using the standard medical face masks to all health care providers, even personnel who are not directly in close contact with sick people (Repici et al., 2020). By August 2020, more than 100 countries had mandated the public wearing of masks (Felter and Bussemaker, 2020). Consequently, global production of medical face masks has increased dramatically: China alone has increased manufacture 30-fold, from 15 million/d in 2019 to 450 million/d in 2020 (Thomala, 2020). The manufacturer 3M is reported to be making 35 masks/s in October 2020 (Garside, 2020), and US mask production is expected to exceed 1 billion units in 2021 (Lopez, 2020).

Although the use of a medical face mask in this period is vital, a significant volume of these masks that are disposable and are usually produced from plastic will pose severe challenges to humanity in the present and future. For example, discarded masks may be swallowed by people, even personnel who are not directly in close contact with sick people (Repici et al., 2020). By August 2020, more than 100 countries had mandated the public wearing of masks (Felter and Bussemaker, 2020). Consequently, global production of medical face masks has increased dramatically: China alone has increased manufacture 30-fold, from 15 million/d in 2019 to 450 million/d in 2020 (Thomala, 2020). The manufacturer 3M is reported to be making 35 masks/s in October 2020 (Garside, 2020), and US mask production is expected to exceed 1 billion units in 2021 (Lopez, 2020).

2. Materials and methods

As mentioned earlier, the recent pandemic has led to significant challenges to medical face mask production and consumption from an environmental point of view. At the same time, challenges have also arisen in the supply and demand of this commodity worldwide. To investigate the environmental impacts associated with the production and consumption of medical face masks, it is necessary to understand the magnitude by which the pandemic has affected its volume production and use.

China is generally the largest producer (50%) and exporter (70%) of masks in the world (Kulkarni, 2021). Based on the available data, the annual production of masks in China in 2018 and 2019 was reported to equal 4.5 and 5 billion pieces, respectively, i.e., about 15 million/day. However, the latest estimates indicate that this figure would reach 450 million/day throughout 2020, i.e., 3.4 million/day N95 mask and 446.6 million/day surgical mask due to the pandemic circumstances (Thomala, 2020). Nevertheless, given the currently faced uncertainties concerning the proper management of the viral pandemic, including lack of...
This study investigated the environmental effects of mask production if bio-based plastics are used instead of fossil-based plastics. Data related to bio-polyester was extracted from the Ecoinvent database.
v3.2, while data for bio-polypropylene production was obtained from Moretti et al. (2020) and Joosten (1998) (Table 4).

Table 2
Raw data for surgical mask production (on average, the mass of each mask is 5 g).

| Item                     | Type of mask | Unit |
|--------------------------|--------------|------|
|                          | Fossil-based plastics | 10% bio-based plastics | 50% bio-based plastics | 100% bio-based plastics |
| Materials/fuels          | Polypropylene, granulate (GLO) market for | Alloc Def, U | 4.33 | 3.89 | 2.16 | 0 | g |
|                          | Polyester resin, unsaturated (GLO) market for | Alloc Def, U | 3.12 | 2.81 | 1.81 | 0 | g |
|                          | Aluminium, cast alloy (GLO) market for | Alloc Def, U | 3.62 | 3.62 | 3.62 | 3.62 | g |
|                          | Bio-based polypropylene | | 0 | 4.33 | 2.16 | 4.33 | g |
|                          | Polyester-complexed starch biopolymer (GLO) market for | Alloc Def, U | 0 | 3.12 | 1.81 | 3.12 | g |
| Electricity/heat         | Electricity, medium voltage (CN) market group for | Alloc Def, U | 4.50 | 4.50 | 4.50 | 4.50 | Wh |
| Waste flow               | Plastic waste | | 4.64 | 4.17 | 2.34 | 0 | g |
|                          | Aluminium waste | | 3.62 | 3.62 | 3.62 | 3.62 | g |

Jiang and Lu (2020) is the reference on which polypropylene is based. Inge (2018) is the reference on which polyester is based. Bhatia et al. (2020) is the reference on which polypropylene is based. Moretti et al. (2020) is the reference on which bio-based polypropylene instead of polyester is based. Nieder-Heitmann et al. (2019) is the reference on which polyester-complexed starch biopolymer instead of polyester is based.

Data for bio-based polypropylene production was obtained from Moretti et al. (2020) and Joosten (1998) (Table 4).

Table 3
Raw data for N95 mask production (on average, the mass of each mask is 10 g).

| Item                     | Type of mask | Unit |
|--------------------------|--------------|------|
|                          | Fossil-based plastic | 10% bio-based plastic | 50% bio-based plastic | 100% bio-based plastic |
| Materials/fuels          | Polypropylene, granulate (GLO) market for | Alloc Def, U | 8.53 | 7.67 | 4.26 | 0 | g |
|                          | Polyester resin, unsaturated (GLO) market for | Alloc Def, U | 8.38 | 7.54 | 4.19 | 0 | g |
|                          | Aluminium, cast alloy (GLO) market for | Alloc Def, U | 6.36 | 6.36 | 6.36 | 6.36 | g |
|                          | Bio-based polypropylene | | 0 | 8.53 | 4.26 | 8.53 | g |
|                          | Polyester-complexed starch biopolymer (GLO) market for | Alloc Def, U | 0 | 8.38 | 4.19 | 8.38 | g |
| Electricity/heat         | Electricity, medium voltage (CN) market group for | Alloc Def, U | 1.15 | 1.15 | 1.15 | 1.15 | Wh |
| Waste flow               | Plastic waste | | 9.36 | 8.43 | 4.68 | 0 | g |
|                          | Aluminium waste | | 6.36 | 6.36 | 6.36 | 6.36 | g |

Jiang and Lu (2020) is the reference on which polypropylene is based. Inge (2018) is the reference on which polyester is based. Bhatia et al. (2020) is the reference on which aluminium is based. Vahidi et al. (2016) is the reference on which electricity, medium voltage is based. Moretti et al. (2020) is the reference on which bio-based polypropylene instead of polyester is based. Nieder-Heitmann et al. (2019) is the reference on which polyester-complexed starch biopolymer instead of polyester is based.

3. Results and discussion
3.1. Environmental impacts of medical face mask production

Table 5 shows the mid-point impact categories associated with annual medical face mask production in China in 2020. Fig. 2 also indicates the contributions of different inputs on different IMPAC 2002+ based mid-point impact categories in the medical face mask production.

As depicted in Fig. 2, the most significant contributor to carcinogens (92%), respiratory organics (60%), terrestrial acidification/nutriﬁcation (43%), aquatic acidification (39%), aquatic eutrophication (33%), global warming (50%), and non-renewable energy (76%) mid-point impact categories was the polypropylene used as the primary material in the production of masks. Also, the share of input energy (i.e., the electricity used for processing materials, e.g., for converting polypropylene to spunbond and for mask production) in ionizing respiratory inorganics (36%) mid-point impact category was higher than those of other inputs. Aluminum used as mask nose clip had the highest share in ionizing radiation (42%), ozone layer depletion (65%), aquatic ecotoxicity (46%), terrestrial ecotoxicity (54%), and mineral extraction (95%) mid-point impact categories. Finally, the polyester used in mask production was mainly responsible for non-carcinogens (54%) and land
Table 4
Raw data for 1 kg of bio-based polypropylene production.

| Item                                                                 | Amount          | Unit           |
|----------------------------------------------------------------------|-----------------|----------------|
| A: Steam cracking process per 1 kg of bio-based propylene made from bio-based naphtha (Moretti et al., 2020). |                 |                |
| Liquefied petroleum gas (RoW) | 6.30 × 10^{-1}  | kg             |
| Steam, in chemical industry (RoW) | 2.90            | kg             |
| Bio-based naphtha           | 2.67            | kg             |
| Output from system          |                 |                |
| Steam, in chemical industry (RoW) | 5.10            | kg             |
| Emissions to air            |                 |                |
| Nitrogen oxides             | 1.30 × 10^{-3}  | kg             |
| Carbon dioxide, fossil      | 1.30            | kg             |
| Carbon monoxide, fossil     | 1.75 × 10^{-4}  | kg             |
| Methane, fossil             | 1.90 × 10^{-5}  | kg             |
| Dinitrogen monoxide         | 8.50 × 10^{-5}  | kg             |
| Particulates, < 2.5 μm      | 5.70 × 10^{-5}  | kg             |
| Particulates, > 2.5 μm, and <10 μm       | 1.90 × 10^{-5}  | kg             |
| VOC, volatile organic compounds | 2.50 × 10^{-5}  | kg             |
| Sulfur oxides               | 1.60 × 10^{-6}  | kg             |
| B: Polymerization process per 1 kg of bio-based polypropylene made from bio-based propylene (Joosten, 1998). |                 |                |
| Steam, in chemical industry (RoW) | 4.87 × 10^{-1}  | kg             |
| bio-based propylene         | 1.02            | kg             |
| Electricity/heat            |                 |                |
| Electricity, medium voltage (CN) | 2.14            | MJ             |

Materials/fuels

| Item                                                                 | Amount          | Unit           |
|----------------------------------------------------------------------|-----------------|----------------|
| Liquefied petroleum gas (RoW) | 6.30 × 10^{-1}  | kg             |
| Steam, in chemical industry (RoW) | 2.90            | kg             |
| Bio-based naphtha           | 2.67            | kg             |
| Output from system          |                 |                |
| Steam, in chemical industry (RoW) | 5.10            | kg             |
| Emissions to air            |                 |                |
| Nitrogen oxides             | 1.30 × 10^{-3}  | kg             |
| Carbon dioxide, fossil      | 1.30            | kg             |
| Carbon monoxide, fossil     | 1.75 × 10^{-4}  | kg             |
| Methane, fossil             | 1.90 × 10^{-5}  | kg             |
| Dinitrogen monoxide         | 8.50 × 10^{-5}  | kg             |
| Particulates, < 2.5 μm      | 5.70 × 10^{-5}  | kg             |
| Particulates, > 2.5 μm, and <10 μm       | 1.90 × 10^{-5}  | kg             |
| VOC, volatile organic compounds | 2.50 × 10^{-5}  | kg             |
| Sulfur oxides               | 1.60 × 10^{-6}  | kg             |

change; and 1.88 × 10^6 MJ damage to resources.

The most damaging single lifecycle element is the use of polypropylene in mask manufacture. Specifically, in medical face mask production, about 47%, 50%, and 76% of the damage to human health, climate change, and resources are ascribed to polypropylene (Fig. 3).

Based on the results of different damage categories for medical face mask production, it is still challenging to determine which category carries the most significant damage. Therefore, the environmental impacts were weighed to obtain single-scored environmental damage based on the IMPACT 2002+ (Aghbashlo et al., 2019a). Based on the weighted results, the total environmental impact of medical face mask production is estimated at 8.85 × 10^5 Pt/yr in 2020 (Table 7) (approximately 2.95 × 10^5 Pt/yr in 2019), of which 42% is related to the resources damage category. It should be noted that 60% of the total environmental impact is associated with the polypropylene used in mask production (Fig. 3).

Due to the critical role of the used polypropylene in the environmental impacts, production and consumption of environmentally friendly masks instead of the conventional masks made of plastic materials should be considered and applied in the near future. Bio-based plastics manufactured from natural materials such as vegetable oil, sugarcane, and other biomass feedstocks are similar to fossil-based plastics in terms of properties and chemical structure (Spierling et al., 2018). They are introduced as a new generation of plastics that can be used as a replacement for fossil-based counterparts.
promising martial to contribute to environmental sustainability goals.

Tables 8 and 9 show the mid-point impact categories and end-point damage categories of medical face mask production when 10% (short-term strategy), 50% (medium-term strategy), and 100% (long-term strategy) of plastics could be harnessed. However, incineration may lead to in

It should be mentioned that primary energy consumption, also considered more favorable than landfilling because the energy content of plastics can be harnessed. However, incineration may lead to increasing the possibility of transferring pathogens (Peng et al., 2020). Under such circumstances, contaminated wastes are either buried or burned. Generally, policies promoting incineration of plastic wastes are generally a promising method to solve the concerns related to energy use, emissions of harmful gases such as gases contributing to climate change, and other environmental pollution (Finnveden et al., 2005). Under such circumstances, contaminated wastes are either buried or burned. Generally, policies promoting incineration of plastic wastes are generally a promising method to solve the concerns related to energy use, emissions of harmful gases such as gases contributing to climate change, and other environmental pollution (Finnveden et al., 2005).

3.2. Environmental impacts of medical face mask post-consumption

It is important to note that recycling plastic-based materials is generally a promising method to solve the concerns related to energy use, emissions of harmful gases such as gases contributing to climate change, and other environmental pollution (Finnveden et al., 2005). However, it is not practical to recycle contaminated wastes associated with viral infections according to health protocols. This is ascribed to the fact that recycling medical face masks has been reported to significantly increase the possibility of transferring pathogens (Peng et al., 2020). Under such circumstances, contaminated wastes are either buried or burned. Generally, policies promoting incineration of plastic wastes are generally a promising method to solve the concerns related to energy use, emissions of harmful gases such as gases contributing to climate change, and other environmental pollution (Finnveden et al., 2005).

Table 6

Results of four end-point damage categories achieved for annual medical face mask production in China in 2020 (based on IMPACT, 2002+).

| Damage category          | Unit       | Surgical mask | N95 mask | Total   |
|--------------------------|------------|---------------|----------|---------|
| Human health             | DALY       | 1.99 × 10^7   | 3.26 × 10^1 | 2.03 × 10^3 |
| Ecosystem quality        | PDF/m^2·yr | 1.61 × 10^8   | 2.60 × 10^8 | 1.63 × 10^10 |
| Climate change           | kg CO₂eq   | 2.10 × 10^3   | 3.46 × 10^3 | 2.13 × 10^6 |
| Resources                | MJ primary | 5.56 × 10^10  | 8.76 × 10^9  | 5.65 × 10^10 |

446,600,000 pieces of surgical mask and 3,400,000 pieces of N95 mask are produced per day (Thomala, 2020). The contributions of the various inputs of one piece of surgical mask and one piece of N95 mask production to end-point damage categories are presented in Table A1 and A2, respectively, presented in the Appendix.

As shown in Table 11, the annual production of medical face masks resulted in 5.88 × 10^10 TJ demand for exergy in 2020 (approximately 1.96 × 10^10 TJ/yr in 2019). The findings obtained herein show that 90% of the demand for exergy is met by the “non-renewable, fossil” category. It is evident from the data depicted in Fig. 5 that polypropylene application in medical face mask production has the largest share in this category. Hence, it could be concluded that replacing fossil-based polypropylene with bio-based polypropylene can significantly reduce the exergy requirement of medical face mask production.

More specifically, if 10, 50, and 100% of polypropylene and polyester used in medical face masks had been replaced with bio-based polypropylene and bio-based polyester, the total CExD index could have been reduced by 6.03, 29.97, and 61.90%, respectively (Fig. 6).
7 MJ of energy in 2020, albeit releasing 1.43 × 10^8 kg CO2eq. Such energy content is equal to the energy content of 5.90 × 10^10 tons of diesel fuel, 5.86 × 10^10 tons of gasoline fuel, or 5.01 × 10^10 tons of natural gas. However, the incinerators available in different countries may not be capable of coping with the large volume of used masks and other hospital wastes (Kumar, 2020). As a result, most medical face masks are likely to go to the landfill or be merely abandoned in the environment (Arzagah, 2020). Assuming that all medical face masks produced in China in 2020 are abandoned in the environment, that would lead to 4.99 × 10^5 Pt damage to the environment (according to the EDIP, 2003) energy content is equal to the energy content of 5.90 × 10^10 tons of gasoline fuel, or 5.01 × 10^10 tons of natural gas. However, the incinerators available in different countries may not be capable of coping with the large volume of used masks and other hospital wastes (Kumar, 2020). As a result, most medical face masks are likely to go to the landfill or be merely abandoned in the environment (Arzagah, 2020). Assuming that all medical face masks produced in China in 2020 are abandoned in the environment, that would lead to 4.99 × 10^5 Pt damage to the environment (according to the EDIP, 2003).

Also, in the current situation, the facilities available in different countries are incapable of coping with the large volume of used masks and other hospital wastes. Hence, non-degradable medical face masks will eventually either be buried or abandoned in the environment. Accordingly, in addition to the environmental damage caused by the cradle-to-gate production of medical face masks, they could also lead to environmental problems post-consumption.

The polypropylene and polyester used in the medical face masks have calorific values of 44 (Hizrat et al., 2019) and 41.8 (Wasilewski and Stydyla, 2013) MJ/kg, and, if incinerated, would generate 2.68 × 10^10 MJ of energy in 2020, albeit releasing 1.43 × 10^8 kg CO2eq. Such energy content is equal to the energy content of 5.90 × 10^10 tons of diesel fuel, 5.86 × 10^10 tons of gasoline fuel, or 5.01 × 10^10 tons of natural gas. However, the incinerators available in different countries may not be capable of coping with the large volume of used masks and other hospital wastes (Kumar, 2020). As a result, most medical face masks are likely to go to the landfill or be merely abandoned in the environment (Arzagah, 2020). Assuming that all medical face masks produced in China in 2020 are abandoned in the environment, that would lead to 4.99 × 10^5 Pt damage to the environment (according to the EDIP, 2003).

![Fig. 3. Contributions of key inputs of medical face masks to various environmental areas and the total weighted impacts.](image)

### Table 7
Results of four weighted end-point damage categories achieved for annual medical face mask production in China in 2020 (based on IMPACT, 2002+).

| Damage category       | Unit     | Surgical mask | N95 mask | Total  |
|-----------------------|----------|---------------|----------|--------|
| Total                 | Pt       | 8.70 × 10^5  | 1.41 × 10^4 | 8.85 × 10^5 |
| Human health          | Pt       | 2.91 × 10^5  | 4.60 × 10^4 | 2.85 × 10^5  |
| Ecosystem quality     | Pt       | 1.17 × 10^6  | 1.89 × 10^5 | 1.19 × 10^6  |
| Climate change        | Pt       | 2.12 × 10^5  | 3.52 × 10^4 | 2.15 × 10^5  |
| Resources             | Pt       | 3.67 × 10^5  | 5.76 × 10^4 | 3.72 × 10^5  |

*a The contributions of the various inputs of one piece of surgical mask and one piece of N95 mask production to end-point damage categories are tabulated in Table A3 and A4, respectively, presented in the Appendix.*

### Table 8
Results of mid-point impact categories achieved for annual production of medical face mask containing 10%, 50%, and 100% bio-based plastics in China in 2020 (based on IMPACT, 2002+).

| Impact category       | Unit     | 10% bio-based plastics | 50% bio-based plastics | 100% bio-based plastics |
|-----------------------|----------|------------------------|------------------------|-------------------------|
| Carcinogens           | kg C6H5Cl eq | 1.95 × 10^8             | 2.00 × 10^8             | 2.01 × 10^8             |
| Non-carcinogens       | kg C6H5Cl eq | 3.02 × 10^7             | 1.97 × 10^7             | 2.01 × 10^7             |
| Respiratory inorganics| kg PM2.5 eq  | 1.90 × 10^6             | 1.97 × 10^6             | 2.01 × 10^6             |
| Ionizing radiation    | Bq C-14 eq  | 2.79 × 10^9             | 5.04 × 10^9             | 7.63 × 10^9             |
| Ozone layer depletion | kg CFC-11 eq | 9.92 × 10^1             | 1.14 × 10^2             | 1.25 × 10^2             |
| Respiratory organs    | kg C4H10 eq  | 1.94 × 10^6             | 1.21 × 10^6             | 1.50 × 10^6             |
| Aquatic ecotoxicity   | kg TEG eq  | 4.23 × 10^10            | 3.84 × 10^10            | 3.02 × 10^10            |
| Terrestrial ecotoxicity| kg TEG eq | 1.17 × 10^10            | 1.19 × 10^10            | 1.11 × 10^10            |
| Terrestrial acid/nutri| kg SO2 eq  | 3.19 × 10^7             | 3.03 × 10^7             | 2.75 × 10^7             |
| Land occupation       | m^2eq. arable | 3.07 × 10^7             | 3.61 × 10^7             | 3.49 × 10^7             |
| Aquatic acidification | kg SO2 eq  | 9.66 × 10^6             | 9.38 × 10^6             | 8.81 × 10^6             |
| Aquatic eutrophication| kg P2O5 eq  | 2.41 × 10^5             | 2.25 × 10^5             | 1.90 × 10^5             |
| Global warming        | kg CO2 eq  | 2.07 × 10^9             | 1.85 × 10^9             | 1.53 × 10^9             |
| Non-renewable energy  | MJ        | 5.27 × 10^10            | 3.85 × 10^10            | 1.97 × 10^10            |
| Mineral extraction    | MJ        | 7.40 × 10^7             | 7.31 × 10^7             | 7.13 × 10^7             |

*a Negative sign means save environmental effects due to the steam production in the process of converting waste cooking oil into bio-based polypropylene.*
Table 9
Results of four end-point damage categories achieved for annual production of medical face masks containing 10%, 50%, and 100% bio-based plastics in China in 2020 (based on IMPACT, 2002+).

| Damage category | Unit | 10% bio-based plastics | 50% bio-based plastics | 100% bio-based plastics |
|-----------------|------|------------------------|------------------------|------------------------|
| Human health    | DALY | 1.97 x 10^3            | 1.75 x 10^3            | 1.44 x 10^3            |
| Ecosystem       | m^3/a | 1.63 x 10^3            | 1.68 x 10^3            | 1.58 x 10^3            |
| Quality         | kg CO_2eq | 2.07 x 10^3 | 1.85 x 10^3 | 1.53 x 10^3 |
| Resources       | MJ primary | 5.27 x 10^10  | 3.87 x 10^10  | 1.98 x 10^10  |

*The contributions of the various inputs of one piece of surgical mask and one piece of N95 mask production to end-point damage categories are tabulated in Table A5-A10, presented in the Appendix.

Table 10
Results of four weighted end-point damage categories achieved for annual production of medical face mask containing 10%, 50%, and 100% bio-based plastics in China in 2020 (based on IMPACT, 2002+).

| Damage category | Unit | 10% bio-based plastics | 50% bio-based plastics | 100% bio-based plastics |
|-----------------|------|------------------------|------------------------|------------------------|
| Total (single score) | Pt | 8.47 x 10^5          | 7.01 x 10^5          | 5.01 x 10^5          |
| Human health    | Pt   | 2.77 x 10^5          | 2.48 x 10^5          | 2.03 x 10^5          |
| Ecosystem       | Pt   | 1.19 x 10^4          | 1.23 x 10^4          | 1.16 x 10^4          |
| Climate change  | Pt   | 2.09 x 10^5          | 1.87 x 10^5          | 1.55 x 10^5          |
| Resources       | Pt   | 3.46 x 10^5          | 2.54 x 10^5          | 1.30 x 10^5          |

* The contributions of the various inputs of one piece of surgical mask and one piece of N95 mask production to end-point damage categories are tabulated in Table A11-A16, presented in the Appendix.

method). This damage could be reduced to 4.49 x 10^5, 2.52 x 10^5, and 0 Pt, if 10%, 50%, and 100% of the plastics used in medical face mask production were to be replaced with bio-based plastics.

It should be highlighted that in addition to the lower environmental impacts of bio-based plastics when used in medical face mask production, they are also biodegradable. During the biodegradation of bio-based plastics, they are broken down into simpler components, and through elemental cycles, including the nitrogen and carbon cycles, they are redistributed. Bio-based plastics could be converted into biomass, water, carbon dioxide, and heat under aerobic conditions, while under anaerobic conditions, they could be converted into biomass, methane, hydrocarbons, carbon dioxide, heat, etc. (Karamanlioglu et al., 2017).

Consequently, the application of bio-based medical face masks prevents plastic contamination and the loss of valuable resources such as oil. It also provides downstream opportunities for valorizing the consumed products, i.e., through biodegradation of bio-based plastics under anaerobic digestion for methane generation (Batori et al., 2018). In addition to methane and electricity, anaerobic biodegradation of bio-based plastic wastes could also result in the generation of anaerobic sludge, which could serve as a quality value-added soil fertilizer. This, in turn, could lead to a reduction in the application of chemical fertilizers and contribute to climate change mitigation. Hence, from the zero-discharge, circular economy, climate change mitigation, and energy perspective, bio-based plastics seem highly preferred materials for medical face mask production.

Table 11
Results of impact categories on CExD achieved for annual production of medical face mask in China in 2020.

| Impact category | Unit | Surgical mask | N95 mask | Total |
|----------------|------|---------------|----------|-------|
| Total          | TJ   | 5.79 x 10^3   | 9.14 x 10^3 | 5.88 x 10^4 |
| Non-renewable, fossil | TJ | 5.21 x 10^3   | 8.21 x 10^3 | 5.30 x 10^4 |
| Non-renewable, nuclear | TJ | 3.26 x 10^3   | 5.03 x 10^3 | 3.32 x 10^4 |
| Renewable, kinetic | TJ | 7.25 x 10^3   | 1.39      | 7.36 x 10^3 |
| Renewable, solar   | TJ | 8.47 x 10^3   | 1.26 x 10^3 | 8.58 x 10^3 |
| Renewable, potential | TJ | 9.37 x 10^3   | 1.58 x 10^3 | 9.54 x 10^3 |
| Non-renewable, primary | TJ | 1.44 x 10^4   | 2.74 x 10^3 | 1.47 x 10^4 |
| Renewable, biomass   | TJ | 6.69 x 10^3   | 1.10 x 10^3 | 6.81 x 10^3 |
| Renewable, water      | TJ | 7.25 x 10^3   | 1.15 x 10^3 | 7.36 x 10^3 |
| Non-renewable, metals | TJ | 1.78 x 10^3   | 2.51      | 1.81 x 10^3 |
| Non-renewable, minerals | TJ | 1.55 x 10^3   | 2.48 x 10^3 | 1.58 x 10^4 |

* The contributions of the various inputs of one piece of surgical mask and one piece of N95 mask production to CExD impact categories are tabulated in Table A17-A18, presented in the Appendix.

Fig. 4. Environmental benefits of using bio-based plastics in place of fossil-based plastics in the production of medical face masks.
4. Practical implications

The findings of the present study shed light on the potential advantages of using renewable and sustainable bio-based plastics to produce disposable and non-recyclable medical face masks. The development of bio-based medical face masks will be a promising way to overcome environmental challenges faced due to the global measures being taken to confine the current COVID-19 pandemic and similar incidences in the future. However, a significant volume of bio-based medical face masks is not yet available; thus, their commercial production proportional to the anticipated needs should be planned. In light of that and based on the results of this investigation, policymakers are encouraged to focus on expanding the bio-based plastic production industries so that the input materials needed by the face mask production industries could be supplied without disturbances.

Moreover, being aware of the irreparable consequences of fossil-based medical face masks production/post-consumption, efforts should be put into persuading manufacturers and consumers to produce and use bio-based medical face masks, even at a slightly higher price, respectively. Finally, in the short term and until the full commercialization of bio-based medical face masks will be realized, policymakers are encouraged to find the best methods to dispose of used masks and inform consumers of such practices.

Fig. 5. Contributions of key inputs of medical face masks to various impact categories of CExD.
5. Limitations and challenges

The use of bio-based plastics as the primary material in medical face mask production faces various limitations, restricting the commercial application of this commodity at this time. The main reason for the current limitations on bio-based plastics compared to fossil-based plastics is that the conventional plastics industries are very mature, while the bio-based plastics industries are still in their infancy (Peelman et al., 2015). In addition, the cost of bio-based plastics is currently higher than that of fossil-based plastics (Kalita et al., 2020). Under conditions similar to the current pandemic, all people with different income levels are obligated to use medical face masks, but the high cost of bio-based medical face masks renders their usage by low- and even middle-income individuals. Disposal of bio-based plastics waste to landfills that are not equipped with a gas recovery system might contribute to greenhouse gas emissions (Muthusamy and Pramasivam, 2019). Finally, crop cultivation for bio-based plastics could create competition over arable lands and water resources, leading to increased food/feed commodities prices. Moreover, diverting these resources towards bio-based plastics production could potentially endanger food security. However, these problems can be solved by valorizing wastes such as food wastes into bio-based plastics (Tsang et al., 2019).

6. Conclusions

6.1. Concluding remarks

In response to approximately 160,074,267 SARS-CoV-2 cases and more than 3,325,260 deaths recorded until May 13, 2021 (World Health Organization, 2021), the world has faced a severe crisis. Because of the high transmission and the possibility of further contamination, many public sectors have been forced to shut down around the world as a measure to contain the COVID-19 pandemic. This, in turn, has decreased the global energy consumption rate and the consequent energy-related environmental impacts. These seemingly-favorable impacts are believed to be temporary and are projected to be overshadowed by the expected surge in fossil-based energy consumption upon the normalization of the global conditions. During the pandemic period, the need for safety equipment such as medical face masks has significantly increased and is likely to be around for quite some time, even in the post-pandemic era. The increases in the use of plastic-made PPE are associated with subsequent unfavorable effects on the environment and human health, currently overlooked to a large extent, given the much larger magnitude of the pandemic crisis itself.

In light of the above, the present study examined the environmental impacts of the production and consumption of medical face masks to identify environmental hotspots. Moreover, solutions were provided to reduce these impacts under current circumstances and in preparation for possible similar crises in the future. The results of this study showed that compared with 2019, the SARS-CoV-2 outbreak and the subsequent increase in the production and consumption of medical face masks in 2020 increased the damages to human health, the quality of the environment, climate change, and resources categories due to higher consumption of polypropylene. Our findings are also indicative of the fact that if not appropriately treated, waste medical face masks can lead to $4.99 \times 10^5$ Pt/yr damage to the environment in 2020. The main reason behind these substantial increments in environmental impacts caused by the production of medical face masks and their post-consumption is the higher consumption of polypropylene. Finally, this study shows that a transition from fossil-based plastics to bio-based plastics, even at a low replacement rate of 10%, for medical face mask production is essential to mitigate the discussed environmental problems not only under the current circumstances but also in preparation for similar crises in the future.

6.2. Prospects

Further development of bio-based plastics seems essential for creating a more sustainable community. However, at present, the share of bio-based plastics in the global market is very low (1% of all plastics) (Zimmermann et al., 2020). As a result, attempts should be made to increase bio-based plastics production in the future.

It should be highlighted that future production plans should be well aligned with the very principles of sustainable development and be scrutinized using advanced sustainability assessment tools such as exergy (Aghbashlo et al., 2018a, 2018b, 2018b), exergoeconomic...
The contributions of the various inputs of one piece of N95 mask production to end-point damage categories (based on IMPACT, 2002).

| Damage category  | Unit          | Total       | Polypropylene | Polyester | Aluminium | Electricity |
|------------------|---------------|-------------|---------------|-----------|-----------|-------------|
| Human health     | DALY          | 3.29 × 10⁻⁸ | 1.43 × 10⁻⁸   | 4.07 × 10⁻⁸ | 5.01 × 10⁻⁹ | 9.50 × 10⁻⁹ |
| Climate change   | kg CO₂ eq     | 5.79 × 10⁻⁴ | 7.15 × 10⁻⁴   | 8.79 × 10⁻⁴ | 4.50 × 10⁻⁴ |             |
| Resources        | MJ primary    | 6.44 × 10⁻¹ | 7.73 × 10⁻²   | 4.66 × 10⁻² | 1.16 × 10⁻¹ |             |

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Declaration of competing interest

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

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CRediT authorship contribution statement

Meisam Tabatabaei: Conceptualization, Writing – review & editing, Supervision, Project administration. Homa Hosseinzadeh-Bandbafha: Investigation, Writing – original draft. Yi Yang: Data curation, Writing – review & editing. Mortaza Aghbashlo: Methodology, Writing – review & editing, Supervision, Project administration. Su Shiung Lam: Validation, Resources. Hugh Montgomery: Writing – review & editing, Supervision. Wanxi Peng: Funding acquisition, Resources.

Appendix

Table A1
The contributions of the various inputs of one piece of surgical mask production to end-point damage categories (based on IMPACT, 2002-+).

| Damage category  | Unit         | Total       | Polypropylene | Polyester | Aluminium | Electricity |
|------------------|--------------|-------------|---------------|-----------|-----------|-------------|
| Human health     | DALY         | 1.53 × 10⁻⁹ | 7.25 × 10⁻⁹   | 1.52 × 10⁻⁹ | 2.85 × 10⁻⁹ | 3.72 × 10⁻⁹ |
| Climate change   | kg CO₂ eq    | 8.08 × 10⁻² | 1.46 × 10⁻³   | 1.99 × 10⁻³ | 4.61 × 10⁻² |             |
| Resources        | MJ primary   | 4.28 × 10⁻¹ | 3.27 × 10⁻¹   | 2.88 × 10⁻² | 2.65 × 10⁻² | 4.56 × 10⁻² |

Table A2
The contributions of the various inputs of one piece of N95 mask production to end-point damage categories (based on IMPACT, 2002-+).

| Damage category  | Unit         | Total       | Polypropylene | Polyester | Aluminium | Electricity |
|------------------|--------------|-------------|---------------|-----------|-----------|-------------|
| Human health     | DALY         | 3.29 × 10⁻⁸ | 1.43 × 10⁻⁸   | 4.07 × 10⁻⁸ | 5.01 × 10⁻⁹ | 9.50 × 10⁻⁹ |
| Climate change   | kg CO₂ eq    | 5.79 × 10⁻⁴ | 7.15 × 10⁻⁴   | 8.79 × 10⁻⁴ | 4.50 × 10⁻⁴ |             |
| Resources        | MJ primary   | 6.44 × 10⁻¹ | 7.73 × 10⁻²   | 4.66 × 10⁻² | 1.16 × 10⁻¹ |             |

Table A3
The contributions of the various inputs of one piece of surgical mask production to weighted end-point damage categories (based on IMPACT, 2002-+).

| Damage category  | Unit  | Total       | Polypropylene | Polyester | Aluminium | Electricity |
|------------------|-------|-------------|---------------|-----------|-----------|-------------|
| Total            | μPt   | 6.70        | 4.01          | 5.70 × 10⁻¹ | 8.14 × 10⁻¹ | 1.30        |
| Human health     | μPt   | 2.16        | 1.02          | 2.14 × 10⁻¹ | 4.02 × 10⁻¹ | 5.24 × 10⁻¹ |
| Ecosystem quality| μPt   | 9.02 × 10⁻² | 2.14 × 10⁻²   | 1.94 × 10⁻² | 3.65 × 10⁻² | 1.29 × 10⁻² |
| Climate change   | μPt   | 1.63        | 8.17 × 10⁻¹   | 1.48 × 10⁻¹ | 2.01 × 10⁻¹ | 4.66 × 10⁻¹ |
| Resources        | μPt   | 2.81        | 2.15          | 1.89 × 10⁻¹ | 1.75 × 10⁻¹ | 3.00 × 10⁻¹ |
Table A4
The contributions of the various inputs of one piece of N95 production containing 50% bio-based plastics to end-point damage categories (based on IMPACT, 2002-+).

| Damage category | Unit | Total | Polypropylene | Polyester | Aluminium | Bio-based polypropylene | Bio-based polyester | Electricity |
|-----------------|------|-------|--------------|-----------|-----------|------------------------|-------------------|-------------|
| Total           | µPt  | 1.42 × 10^3 | 7.91         | 1.53      | 1.43      | 3.33                   |                   |             |
| Human health    | µPt  | 4.63       | 2.01         | 5.74 × 10^{-1} | 7.06 × 10^{-1} | 1.34                   |                   |             |
| Ecosystem quality | µPt | 1.91 × 10^{-1} | 4.23 × 10^{-2} | 5.22 × 10^{-2} | 6.41 × 10^{-2} | 3.29 × 10^{-2} |                   |             |
| Climate change  | µPt  | 3.55       | 1.61         | 3.96 × 10^{-1} | 3.53 × 10^{-1} | 1.19                   |                   |             |
| Resources       | µPt  | 5.82       | 4.24         | 5.08 × 10^{-1} | 3.07 × 10^{-1} | 7.66 × 10^{-1} |                   |             |

Table A5
The contributions of the various inputs of one piece of surgical mask production containing 10% bio-based plastics to end-point damage categories (based on IMPACT, 2002-+).

| Damage category | Unit | Total | Polypropylene | Polyester | Aluminium | Bio-based polypropylene | Bio-based polyester | Electricity |
|-----------------|------|-------|--------------|-----------|-----------|------------------------|-------------------|-------------|
| Human health    | DALY | 1.49 × 10^{-8} | 6.52 × 10^{-9} | 1.36 × 10^{-9} | 2.85 × 10^{-9} | 3.64 × 10^{-10} | 6.88 × 10^{-11} | 3.72 × 10^{-7} |
| Ecosystem quality | PDF* m^3 yr | 1.23 × 10^{-3} | 2.64 × 10^{-4} | 2.39 × 10^{-4} | 5.00 × 10^{-4} | 4.83 × 10^{-4} | 4.71 × 10^{-5} | 1.76 × 10^{-4} |
| Climate change  | kg CO_2eq | 1.57 × 10^{-2} | 7.28 × 10^{-3} | 1.32 × 10^{-3} | 1.99 × 10^{-3} | 4.43 × 10^{-4} | 5.69 × 10^{-5} | 4.61 × 10^{-5} |
| Resources       | MJ primary | 4.00 × 10^{-1} | 2.94 × 10^{-1} | 2.59 × 10^{-2} | 2.65 × 10^{-2} | 6.21 × 10^{-3} | 1.57 × 10^{-3} | 4.56 × 10^{-3} |

Table A6
The contributions of the various inputs of one piece of N95 mask production containing 50% bio-based plastics to end-point damage categories (based on IMPACT, 2002-+).

| Damage category | Unit | Total | Polypropylene | Polyester | Aluminium | Bio-based polypropylene | Bio-based polyester | Electricity |
|-----------------|------|-------|--------------|-----------|-----------|------------------------|-------------------|-------------|
| Human health    | DALY | 3.19 × 10^{-8} | 1.29 × 10^{-8} | 3.67 × 10^{-7} | 5.01 × 10^{-9} | 7.18 × 10^{-10} | 1.85 × 10^{-10} | 9.50 × 10^{-7} |
| Ecosystem quality | PDF* m^3 yr | 2.63 × 10^{-3} | 5.21 × 10^{-4} | 6.43 × 10^{-4} | 8.79 × 10^{-4} | 9.52 × 10^{-4} | 1.27 × 10^{-4} | 4.50 × 10^{-4} |
| Climate change  | kg CO_2eq | 3.42 × 10^{-2} | 1.43 × 10^{-2} | 3.53 × 10^{-3} | 3.49 × 10^{-3} | 8.73 × 10^{-4} | 1.53 × 10^{-4} | 1.18 × 10^{-4} |
| Resources       | MJ primary | 8.29 × 10^{-1} | 5.80 × 10^{-1} | 6.95 × 10^{-2} | 4.66 × 10^{-2} | 1.22 × 10^{-2} | 4.21 × 10^{-3} | 1.16 × 10^{-3} |

Table A7
The contributions of the various inputs of one piece of surgical mask production containing 50% bio-based plastics to end-point damage categories (based on IMPACT, 2002-+).

| Damage category | Unit | Total | Polypropylene | Polyester | Aluminium | Bio-based polypropylene | Bio-based polyester | Electricity |
|-----------------|------|-------|--------------|-----------|-----------|------------------------|-------------------|-------------|
| Human health    | DALY | 1.33 × 10^{-8} | 3.62 × 10^{-8} | 8.80 × 10^{-10} | 2.85 × 10^{-9} | 1.82 × 10^{-9} | 3.99 × 10^{-9} | 3.72 × 10^{-6} |
| Ecosystem quality | PDF* m^3 yr | 1.27 × 10^{-3} | 1.47 × 10^{-4} | 1.54 × 10^{-4} | 5.00 × 10^{-4} | 2.41 × 10^{-4} | 2.73 × 10^{-4} | 1.76 × 10^{-4} |
| Climate change  | kg CO_2eq | 1.40 × 10^{-2} | 4.04 × 10^{-3} | 8.48 × 10^{-4} | 1.99 × 10^{-3} | 2.22 × 10^{-3} | 3.30 × 10^{-4} | 4.61 × 10^{-3} |
| Resources       | MJ primary | 2.92 × 10^{-1} | 1.63 × 10^{-1} | 1.67 × 10^{-2} | 2.65 × 10^{-2} | 3.10 × 10^{-2} | 9.09 × 10^{-3} | 4.56 × 10^{-2} |

Table A8
The contributions of the various inputs of one piece of N95 mask production containing 50% bio-based plastics to end-point damage categories (based on IMPACT, 2002-+).

| Damage category | Unit | Total | Polypropylene | Polyester | Aluminium | Bio-based polypropylene | Bio-based polyester | Electricity |
|-----------------|------|-------|--------------|-----------|-----------|------------------------|-------------------|-------------|
| Human health    | DALY | 2.82 × 10^{-8} | 7.14 × 10^{-9} | 2.04 × 10^{-7} | 5.01 × 10^{-9} | 3.59 × 10^{-9} | 9.24 × 10^{-10} | 9.50 × 10^{-7} |
| Ecosystem quality | PDF* m^3 yr | 2.66 × 10^{-3} | 2.90 × 10^{-4} | 3.57 × 10^{-4} | 8.79 × 10^{-4} | 4.76 × 10^{-3} | 6.33 × 10^{-4} | 4.50 × 10^{-4} |
| Climate change  | kg CO_2eq | 3.03 × 10^{-2} | 7.97 × 10^{-3} | 1.96 × 10^{-2} | 3.49 × 10^{-3} | 4.37 × 10^{-2} | 7.64 × 10^{-4} | 1.18 × 10^{-2} |
| Resources       | MJ primary | 6.06 × 10^{-1} | 3.22 × 10^{-1} | 3.86 × 10^{-2} | 4.66 × 10^{-2} | 6.12 × 10^{-2} | 2.10 × 10^{-2} | 1.16 × 10^{-7} |

Table A9
The contributions of the various inputs of one piece of surgical mask production containing 100% bio-based plastics to end-point damage categories (based on IMPACT, 2002-+).

| Damage category | Unit | Total | Aluminium | Bio-based polypropylene | Bio-based polyester | Electricity |
|-----------------|------|-------|----------|------------------------|-------------------|-------------|
| Human health    | DALY | 1.09 × 10^{-8} | 2.85 × 10^{-9} | 3.64 × 10^{-9} | 6.88 × 10^{-10} | 3.72 × 10^{-7} |
| Ecosystem quality | PDF* m^3 yr | 1.20 × 10^{-3} | 5.00 × 10^{-4} | 4.83 × 10^{-5} | 4.71 × 10^{-4} | 1.76 × 10^{-4} |
| Climate change  | kg CO_2eq | 1.16 × 10^{-2} | 1.99 × 10^{-3} | 4.43 × 10^{-3} | 5.69 × 10^{-4} | 4.61 × 10^{-3} |
| Resources       | MJ primary | 1.50 × 10^{-1} | 2.65 × 10^{-2} | 6.21 × 10^{-2} | 1.57 × 10^{-2} | 4.56 × 10^{-2} |
Table A10
The contributions of the various inputs of one piece of N95 mask production containing 100% bio-based plastics to end-point damage categories (based on IMPACT, 2002).

| Damage category     | Unit Total | Aluminium | Bio-based polypropylene | Bio-based polyester | Electricity |
|---------------------|------------|-----------|--------------------------|---------------------|-------------|
| Human health        | m² yr      | 2.35 × 10⁻⁸ | 5.01 × 10⁻⁹ | 7.18 × 10⁻⁹ | 1.85 × 10⁻⁶ | 9.50 × 10⁻⁷ |
| Ecosystem quality   | kg CO₂eq   | 2.55 × 10⁻² | 3.49 × 10⁻³ | 8.73 × 10⁻³ | 1.53 × 10⁻² | 1.18 × 10⁻² |
| Resources           | MJ primary | 3.27 × 10⁻¹ | 4.66 × 10⁻² | 1.22 × 10⁻¹ | 4.21 × 10⁻² | 1.16 × 10⁻² |

Table A11
The contributions of the various inputs of one piece of surgical mask production containing 10% bio-based plastics to weighted end-point damage categories (based on IMPACT, 2002).

| Damage category     | Unit Total | Polypropylene | Polyester | Aluminium | Bio-based polypropylene | Bio-based polyester | Electricity |
|---------------------|------------|---------------|-----------|-----------|--------------------------|---------------------|-------------|
| Total               | μPt        | 6.41          | 5.13 × 10⁻¹ | 1.37 × 10⁻¹ | 2.92 × 10⁻² | 3.00 × 10⁻² |
| Human health        | μPt        | 2.10          | 1.92 × 10⁻¹ | 4.02 × 10⁻¹ | 5.14 × 10⁻² | 9.70 × 10⁻³ | 5.24 × 10⁻³ |
| Ecosystem quality   | μPt        | 8.99 × 10⁻²  | 1.93 × 10⁻² | 3.65 × 10⁻² | 3.53 × 10⁻⁴ | 3.44 × 10⁻³ | 1.29 × 10⁻³ |
| Climate change      | μPt        | 1.58          | 1.33 × 10⁻¹ | 2.01 × 10⁻¹ | 4.48 × 10⁻² | 5.74 × 10⁻³ | 4.66 × 10⁻³ |
| Resources           | μPt        | 2.63          | 1.70 × 10⁻¹ | 1.75 × 10⁻¹ | 4.08 × 10⁻² | 1.03 × 10⁻² | 3.00 × 10⁻³ |

Table A12
The contributions of the various inputs of one piece of surgical mask production containing 10% bio-based plastics to weighted end-point damage categories (based on IMPACT, 2002).

| Damage category     | Unit Total | Polypropylene | Polyester | Aluminium | Bio-based polypropylene | Bio-based polyester | Electricity |
|---------------------|------------|---------------|-----------|-----------|--------------------------|---------------------|-------------|
| Total               | μPt        | 1.36 × 10¹    | 1.38      | 1.43      | 2.71 × 10⁻¹ | 7.84 × 10⁻² | 3.33        |
| Human health        | μPt        | 4.50          | 5.17 × 10⁻¹ | 7.06 × 10⁻¹ | 1.01 × 10⁻¹ | 2.61 × 10⁻² | 1.34        |
| Ecosystem quality   | μPt        | 3.92 × 10⁻¹   | 4.69 × 10⁻² | 6.41 × 10⁻² | 6.95 × 10⁻⁴ | 9.24 × 10⁻³ | 3.29 × 10⁻³ |
| Climate change      | μPt        | 3.45          | 3.57 × 10⁻¹ | 3.53 × 10⁻¹ | 8.82 × 10⁻² | 1.54 × 10⁻² | 1.19        |
| Resources           | μPt        | 5.45          | 4.58 × 10⁻¹ | 3.07 × 10⁻¹ | 8.05 × 10⁻² | 2.77 × 10⁻² | 7.66 × 10⁻² |

Table A13
The contributions of the various inputs of one piece of surgical mask production containing 50% bio-based plastics to weighted end-point damage categories (based on IMPACT, 2002).

| Damage category     | Unit Total | Polypropylene | Polyester | Aluminium | Bio-based polypropylene | Bio-based polyester | Electricity |
|---------------------|------------|---------------|-----------|-----------|--------------------------|---------------------|-------------|
| Total               | μPt        | 5.31          | 3.31 × 10⁻¹ | 8.14 × 10⁻¹ | 6.87 × 10⁻¹ | 1.69 × 10⁻¹ | 1.30        |
| Human health        | μPt        | 1.87          | 1.24 × 10⁻¹ | 4.02 × 10⁻¹ | 2.57 × 10⁻¹ | 5.63 × 10⁻² | 5.24 × 10⁻² |
| Ecosystem quality   | μPt        | 9.31 × 10⁻²   | 1.13 × 10⁻² | 3.65 × 10⁻² | 1.76 × 10⁻³ | 2.00 × 10⁻² | 1.29 × 10⁻² |
| Climate change      | μPt        | 1.42          | 8.56 × 10⁻² | 2.01 × 10⁻¹ | 2.24 × 10⁻¹ | 3.33 × 10⁻² | 4.66 × 10⁻² |
| Resources           | μPt        | 1.92          | 1.10 × 10⁻¹ | 1.75 × 10⁻¹ | 2.04 × 10⁻¹ | 5.98 × 10⁻² | 3.00 × 10⁻² |

Table A14
The contributions of the various inputs of one piece of N95 mask production containing 50% bio-based plastics to weighted end-point damage categories (based on IMPACT, 2002).

| Damage category     | Unit Total | Polypropylene | Polyester | Aluminium | Bio-based polypropylene | Bio-based polyester | Electricity |
|---------------------|------------|---------------|-----------|-----------|--------------------------|---------------------|-------------|
| Total               | μPt        | 1.12 × 10¹    | 3.95      | 7.66 × 10⁻¹ | 1.43         | 1.35         | 3.92 × 10⁻¹ | 3.33        |
| Human health        | μPt        | 3.98          | 2.87 × 10⁻¹ | 7.06 × 10⁻¹ | 5.06 × 10⁻¹ | 1.30 × 10⁻¹ | 1.34        |
| Ecosystem quality   | μPt        | 1.94 × 10⁻¹   | 2.61 × 10⁻² | 6.41 × 10⁻² | 3.47 × 10⁻³ | 4.62 × 10⁻² | 3.29 × 10⁻² |
| Climate change      | μPt        | 3.06          | 1.98 × 10⁻¹ | 3.53 × 10⁻¹ | 4.41 × 10⁻¹ | 7.71 × 10⁻² | 1.19        |
| Resources           | μPt        | 3.99          | 2.54 × 10⁻¹ | 3.07 × 10⁻¹ | 4.03 × 10⁻¹ | 1.38 × 10⁻¹ | 7.66 × 10⁻¹ |
Table A15
The contributions of the various inputs of one piece of surgical mask production containing 100% bio-based plastics to weighted end-point damage categories (based on IMPACT, 2002+).

| Damage category | Unit | Total | Bio-based polypropylene | Bio-based polyester | Electricity |
|-----------------|------|-------|-------------------------|---------------------|-------------|
| Total           | µPt  | 3.78  | 8.14 × 10⁻¹              | 1.37                | 2.92 × 10⁻¹ | 1.30        |
| Human health    | µPt  | 1.54  | 4.02 × 10⁻¹              | 5.14 × 10⁻¹         | 9.70 × 10⁻² | 5.24 × 10⁻¹ |
| Ecosystem quality | µPt | 8.73 × 10⁻² | 3.65 × 10⁻² | 3.53 × 10⁻³ | 3.44 × 10⁻² | 1.29 × 10⁻² |
| Climate change  | µPt  | 1.17  | 2.01 × 10⁻¹              | 4.48 × 10⁻¹         | 5.74 × 10⁻² | 4.66 × 10⁻² |
| Resources       | µPt  | 9.86 × 10⁻¹ | 1.75 × 10⁻¹ | 4.08 × 10⁻¹ | 1.03 × 10⁻¹ | 3.00 × 10⁻¹ |

Table A16
The contributions of the various inputs of one piece of N95 production containing 100% bio-based plastics to weighted end-point damage categories (based on IMPACT, 2002+).

| Damage category | Unit | Total | Bio-based polypropylene | Bio-based polyester | Electricity |
|-----------------|------|-------|-------------------------|---------------------|-------------|
| Total           | µPt  | 8.25  | 1.43                    | 2.71                | 7.84 × 10⁻¹ | 3.33        |
| Human health    | µPt  | 3.32  | 7.06 × 10⁻¹             | 1.01                | 2.61 × 10⁻¹ | 1.34        |
| Ecosystem quality | µPt | 1.96 × 10⁻¹ | 6.41 × 10⁻² | 6.95 × 10⁻³ | 9.24 × 10⁻² | 3.29 × 10⁻² |
| Climate change  | µPt  | 2.58  | 3.53 × 10⁻¹             | 8.82 × 10⁻¹         | 1.54 × 10⁻¹ | 1.19        |
| Resources       | µPt  | 2.15  | 3.07 × 10⁻¹             | 8.05 × 10⁻¹         | 2.77 × 10⁻¹ | 7.66 × 10⁻¹ |

Table A17
The contributions of the various inputs of one piece of surgical mask production to impact categories (based on CEED).

| Impact category | Unit | Total | Polypropylene | Polyester | Aluminium | Electricity |
|-----------------|------|-------|---------------|-----------|-----------|-------------|
| Total           | kJ   | 4.46 × 10⁵ | 3.30 × 10⁵ | 3.22 × 10⁵ | 3.29 × 10⁵ | 5.09 × 10⁵ |
| Non-renewable, fossil | kJ | 4.01 × 10⁵ | 3.06 × 10⁵ | 2.67 × 10⁵ | 2.27 × 10⁵ | 4.54 × 10⁵ |
| Non-renewable, nuclear | kJ | 2.51 × 10⁴ | 1.84 × 10⁴ | 1.89     | 3.49     | 1.36       |
| Renewable, kinetic | kJ | 5.57 × 10⁻⁴ | 4.64 × 10⁻⁴ | 8.57 × 10⁻⁵ | 4.11 × 10⁻⁵ | 4.25 × 10⁻⁵ |
| Renewable, solar | kJ | 6.51 × 10⁻⁴ | 6.01 × 10⁻⁴ | 1.24 × 10⁻⁴ | 4.61 × 10⁻⁴ | 6.42 × 10⁻⁴ |
| Renewable, potential | kJ | 7.21   | 1.30   | 4.20 × 10⁻¹ | 2.19     | 3.30       |
| Non-renewable, primary | kJ | 1.11 × 10⁻⁴ | 2.13 × 10⁻⁴ | 8.92 × 10⁻² | 2.15 × 10⁻² | 1.25 × 10⁻² |
| Renewable, biomass | kJ | 5.15   | 8.54 × 10⁻¹ | 1.98 | 2.26     | 6.74 × 10⁻² |
| Renewable, water | kJ | 5.57   | 3.33   | 9.30 × 10⁻¹ | 9.35 × 10⁻¹ | 3.66 × 10⁻¹ |
| Non-renewable, metals | kJ | 1.37   | 6.39 × 10⁻³ | 1.22 × 10⁻¹ | 1.22     | 2.36 × 10⁻² |
| Non-renewable, minerals | kJ | 1.19 × 10⁻⁴ | 7.19 × 10⁻⁴ | 4.23 × 10⁻² | 6.97 × 10⁻² | 2.35 × 10⁻² |

Table A18
The contributions of the various inputs of one piece of N95 production to impact categories (based on CEED).

| Impact category | Unit | Total | Polypropylene | Polyester | Aluminium | Electricity |
|-----------------|------|-------|---------------|-----------|-----------|-------------|
| Total           | kJ   | 9.25 × 10² | 6.50 × 10² | 8.65 × 10⁴ | 5.79 × 10⁴ | 1.30 × 10² |
| Non-renewable, fossil | kJ | 8.31 × 10² | 6.03 × 10² | 7.16 × 10⁴ | 3.99 × 10⁵ | 1.16 × 10⁵ |
| Non-renewable, nuclear | kJ | 5.08 × 10² | 3.62 × 10² | 5.08 | 6.13     | 3.46       |
| Renewable, kinetic | kJ | 1.40   | 9.15 × 10⁻¹ | 2.30 × 10⁻¹ | 7.23 × 10⁻² | 1.09       |
| Renewable, solar | kJ | 1.28 × 10⁻³ | 1.19 × 10⁻⁴ | 3.32 × 10⁻⁴ | 8.11 × 10⁻⁴ | 1.64 × 10⁻⁵ |
| Renewable, potential | kJ | 1.60 × 10⁻³ | 2.56 | 1.13     | 3.85     | 8.43       |
| Non-renewable, primary | kJ | 2.77 × 10⁻³ | 4.20 × 10⁻⁴ | 2.40 × 10⁻¹ | 3.77 × 10⁻² | 3.18 × 10⁻⁵ |
| Renewable, biomass | kJ | 1.11 × 10⁻³ | 1.68 | 5.31     | 3.96     | 1.72 × 10⁻² |
| Renewable, water | kJ | 1.16 × 10⁻³ | 6.57 | 2.50     | 1.64     | 9.36 × 10⁻³ |
| Non-renewable, metals | kJ | 2.54   | 1.26 × 10⁻² | 3.29 × 10⁻¹ | 2.14     | 6.10 × 10⁻² |
| Non-renewable, minerals | kJ | 2.51 × 10⁻¹ | 1.42 × 10⁻² | 1.14 × 10⁻¹ | 1.22 × 10⁻¹ | 6.01 × 10⁻⁴ |

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