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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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ABSTRACT

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 2.03×10^3 disability-adjusted life years (DALYs); 1.63×10^8 PDF*m^2*yr damage to ecosystem quality; the climate-damaging release of 2.13×10^9 kg CO_{2eq}; and 5.65×10^{10} MJ damage to resources. Besides, annual medical face mask production results in 5.88×10^4 TJ demand for exergy. On the other hand, if used makes are not appropriately handled, they can lead to 4.99×10^5 Pt/yr additional damage to the environment in 2020 as determined by the EDIP 2003. 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 animals and subsequently stuck in their digestive system, leading to death (Hellewell et al., 2020). Most importantly, medical face masks are generally made from skinny polypropylene layers, which do not break down easily. Nevertheless, through their gradual degradation into micro-plastic over time and the subsequent introduction of these tiny particles into the environment, the risk of food chain contamination intensifies (Lin, 2016). On the other hand, increasing demands for masks will also lead to elevated demands for plastic, whose production would result in unfavorable effects on the environment and human health (Harding et al., 2007). Consequently, the adverse effects of continued lack of attention to such impacts could far exceed those of the virus over the long term.

Therefore, environmental assessment of the medical face masks’ life cycle masks from production to the end of utilization is currently one of the most critical environmental requirements. More specifically, this assessment helps determine the extent of environmental damage caused by the increased production and consumption of medical face masks during the pandemic and beyond. Also, assessing the environmental impacts of bio-based medical face masks is essential to be aware of their role in reducing environmental impacts and increasing the sustainability of medical face mask use in similar cases in the future. Life cycle assessment (LCA) could be considered a promising approach to achieving these critical purposes (Rajaeifar et al., 2017). There have been no reports about investigating and comparing the environmental impacts of production and consumption of fossil-based plastic and bio-based plastic medical face masks by LCA to the best of our knowledge. The most important investigations concerning the environmental impact assessment of medical face masks production/consumption are summarized in Table 1 to further elaborate the novelty of the current study. Besides, to provide a more in-depth picture of resource elimination (as one of the critical indicators in LCA studies), the life cycle exergy demand of medical face mask production is quantified by employing cumulative exergy demand (CExD) (Bösch et al., 2007).

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

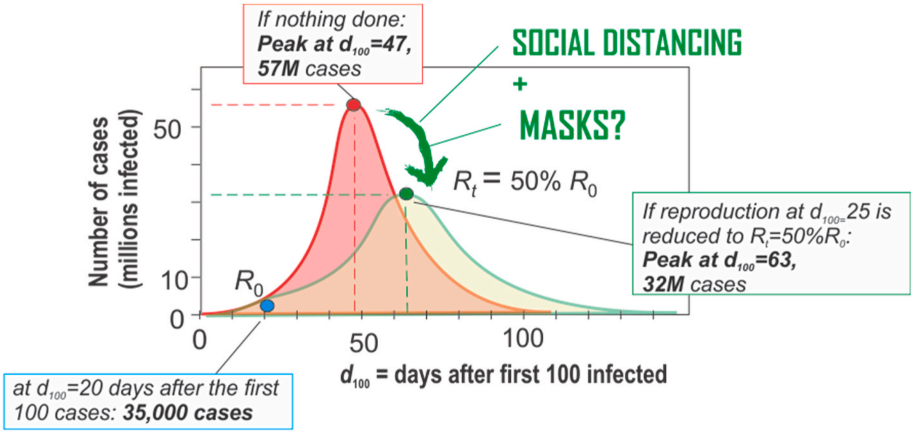

Fig. 1. Reducing the initial rate of infection by 50% when mitigating interventions are implemented on the 25th day. The red curve represents the number of infected cases without intervention. The green curve reflects the flattened curve after the mitigating intervention. Day 0 (March 3, 2020) – the time when the 100 infected cases were confirmed (d100 = 0) (Huang, 2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
A summary of literature done on the environmental impact assessment of medical face masks production/consumption.

Purpose of study	Approach and method used	Boundaries of the system under study	Remarkable results	Reference
Assessment of emissions, environmental impacts, and waste generated from surgical face masks and embedded filtration layer of reusable face masks	LCA/ReCiPe method	From material extraction used in the production of mask, packaging mask and treatment after consumption by incineration	✓Among the element investigated in surgical face mask production, polypropylene used had the most considerable impact on climate change and waste generated impact categories. ✓Reusable face masks had a lower impact of >30% for climate change than surgical face masks.	Lee et al. (2021)
Environmental assessment of 5 types of widely used face masks, including a 3D printed mask with changeable filters, surgical mask, FFP2 mask with valve, FFP2 mask without the valve, and washable mask	LCA/ReCiPe method	From material extraction to end-of-life	✓Lower consumption of polypropylene and polyester improved the environmental impacts of face masks. ✓Reusable masks and masks with interchangeable filters potentially improved the environmental burdens in all the considered impact/damage categories.	Rodríguez et al. (2021a)
Providing an overview of invested energy sources and carbon footprints of medical face masks	Energy and carbon footprints	Production and consumption of medical face masks	✓Polypropylene was the main contributor to carbon dioxide emission caused by mask production. ✓Reusable personal protection equipment had lower energy consumption/environmental footprints.	Klemeš et al. (2020)
Evaluating the relative human health and environmental impacts caused by the production and consumption of personal protective equipment	LCA/Global warming potential, freshwater aquatic ecotoxicity potential, human toxicity potential, eutrophication potential, acidification potential, and photochemical ozone creation potential	All direct and indirect resources use and emissions in manufacturing, to disposal of personal protective equipment	✓Metal strips in medical face masks were the most significant contributors to the human toxicity potential impact category. ✓The incineration process showed high global warming potential but significantly reduced other impact categories than disposal in a landfill.	Kumar et al. (2020)
Comparison of the environmental burdens of using single-use face masks and reusable face masks	LCA/Environmental Footprint method	A cradle-to-grave study approach from the material sourcing of medical face mask to final disposal	✓The application of reusable face masks led to an over 95% reduction in waste. ✓Transportation of single-use face masks had the largest share in climate change.	Allison et al. (2020)
Assessment of the environmental burdens of surgical and cotton face masks	LCA/Carbon footprint according to the IPCC method, water footprint according to AWARE, and non-renewable cumulative energy demand according to VDI definition	Form production of the different parts of mask to the final disposal in incineration	✓Cotton masks had better environmental performance than surgical masks. ✓Incinerating polypropylene resulted in fossil CO_2 emissions while burning cotton resulted in biogenic CO_2 emissions.	Schmutz et al. (2020)
Development of action guides to produce new eco-friendly masks to reduce the negative impacts	LCA/ReCiPe method	Mask production from material extraction, transportation, usage phase, and end of life	✓Reusable masks were the most sustainable from the lifecycle assessment perspective since they drastically reduced the environmental burdens in all categories. ✓Polypropylene fabric was the worst material in terms of environmental burdens.	Rodríguez et al. (2021b)

access to vaccines for all people worldwide, further spread of the disease is much likely, imposing more pressure on the demands for masks their consequent production.

Given the substantial environmental burdens associated with the ongoing crisis, the current study is aimed at investigating the environmental impacts of medical face mask production using the LCA approach and based on the available data. It should be mentioned that LCA, as a critical tool, could be effectively used to assess the available systems and compare the different systems from an environmental point of view (Prasad et al., 2020). Notably, LCA's role in assessing the environmental impacts of any production systems is vital both in the scientific and industrial communities (Moustakas et al., 2020).

According to the International Organization for Standardization (ISO) standards, an LCA study consists of four main steps, i.e., goal and scope definition, inventory analysis, impact assessment, and interpretation (Rajaeifar et al., 2019). Herein, the environmental impacts of medical face mask production were scrutinized to identify the associated environmental hot-spots in mask production in 2020. Subsequently, this study investigated the environmental effects of mask production if bio-based plastics are used instead of fossil-based plastics for the first time. In this study, the functional unit (FU) was defined as the sum of surgical masks and N95 masks produced in 2020 in China (from February 1 to the end of the year). The system boundaries were also limited to the extraction of raw materials used in the production of masks until their end of life. The packaging and transportation of masks for domestic consumption or export were not considered due to data deficiencies.

It should be noted that inventory analysis was carried out according to ISO (2006), and SimaPro 9.0.0 software was used to convert the inventory into environmental impacts and to calculate the magnitude of the environmental impacts. The data related to the background data, including the production of consumable inputs and energy carriers, were taken from the EcoInvent database v3.2. The average weight of each surgical mask and N95 mask was considered 5 and 10 g, respectively. The mask components' average weight values, i.e., spunbond, earloop, and nose clip made of polypropylene, polyester, and aluminum, respectively, were considered herein. Data on the production of conventional face masks, i.e., surgical masks and N95 masks containing 0–100% bio-based plastics, are presented in Tables 2 and 3, respectively.

This study also 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

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	3.12×10^{-1}	2.81×10^{-1}	1.81×10^{-1}	0	g
Aluminium, cast alloy {GLO}| market for | Alloc Def, U	3.62×10^{-1}	3.62×10^{-1}	3.62×10^{-1}	3.62×10^{-1}	g
Bio-based polypropylene[a]	0	4.33×10^{-1}	2.16	4.33	g
Polyester-complexed starch biopolymer {GLO}| market for | Alloc Def, U	0	3.12×10^{-2}	1.81×10^{-1}	3.12×10^{-1}	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	3.62×10^{-1}	3.62×10^{-1}	3.62×10^{-1}	3.62×10^{-1}	g

Jiang and Lu (2020) is the reference on which polypropylene is based.
Ingee (2018) is the reference on which polyester is based.
Bhatia et al. (2020) is the reference on which aluminum 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.
[a] Data for bio-based polypropylene production was obtained from Moretti et al. (2020) and Joosten (1998) (Table 4).

v3.2, while data for bio-polypropylene production was obtained from Moretti et al. (2020) and Joosten (1998). In their study, bio-based naphtha was produced from waste cooking oil by the hydrotreatment process and was subsequently converted into bio-propylene by steam cracking (Table 4). It should be noted that a cut-off approach was applied for bio-based naphtha due to its minor production share compared to the main product of the hydrotreatment process, i.e., renewable diesel.

Data were inventoried and analyzed in SimaPro 9.0.0 software, and the IMPACT 2002+ (Jolliet et al., 2003) and EDIP 2003 (Hauschild and Potting, 2005) methods were used to convert the inventory results into environmental impacts. IMPACT 2002+ encompasses Eco-indicator 99, IMPACT 2002, CML 2000, and IPCC methods widely used for environmental impact assessment (Singh et al., 2020). This method can also implement a combined midpoints/endpoint approach (Colangelo et al., 2020). On the other hand, the EDIP method can estimate impact categories related to waste flow, i.e., bulk waste, hazardous waste, slags/ashes, and radioactive waste (Rajendran et al., 2013).

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 plastics	50% bio-based plastics	100% bio-based plastics	
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	8.38×10^{-1}	7.54×10^{-1}	4.19×10^{-1}	0	g
Aluminium, cast alloy {GLO}| market for | Alloc Def, U	6.36×10^{-1}	6.36×10^{-1}	6.36×10^{-1}	6.36×10^{-1}	g
Bio-based polypropylene[a]	0	8.53×10^{-1}	4.26	8.53	g
Polyester-complexed starch biopolymer {GLO}| market for | Alloc Def, U	0	8.38×10^{-2}	4.19×10^{-1}	8.38×10^{-1}	g
Electricity/heat					
Electricity, medium voltage {CN}| market group for | Alloc Def, U	1.15×10^{1}	1.15×10^{1}	1.15×10^{1}	1.15×10^{1}	Wh
Waste flow					
Plastic waste	9.36	8.43	4.68	0	g
Aluminium waste	6.36×10^{-1}	6.36×10^{-1}	6.36×10^{-1}	6.36×10^{-1}	g

Jiang and Lu (2020) is the reference on which polypropylene is based.
Ingee (2018) is the reference on which polyester is based.
Bhatia et al. (2020) is the reference on which aluminum 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.
[a] Data for bio-based polypropylene production was obtained from Moretti et al. (2020) and Joosten (1998) (Table 4).

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[a] (Moretti et al., 2020).		
Materials/fuels		
Liquefied petroleum gas {RoW}| market for | Alloc Def, U	6.30×10^{-1}	kg
Steam, in chemical industry {RoW}| production | Alloc Def, U	2.90	kg
Bio-based naphtha[b]	2.67	kg
Output from system		
Steam, in chemical industry {RoW}| production | Conseq, U	5.10	kg
Emissions to air		
Nitrogen oxides	1.30×10^{-3}	kg
Carbon dioxide, fossil	1.30	kg
Carbon monoxide, fossil	7.50×10^{-4}	kg
Methane, fossil	1.90×10^{-5}	kg
Dinitrogen monoxide	8.50×10^{-5}	kg
Particulates, < 2.5 um	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).		
Materials/fuels		
Steam, in chemical industry {RoW}| production | Alloc Def, U	4.87×10^{-1}	kg
bio-based propylene	1.02	kg
Electricity/heat		
Electricity, medium voltage {CN}| market group for | Alloc Def, U	2.14	MJ

[a] 20% of the impacts are allocated to bio-propylene based on energy allocation (Moretti et al., 2020).

[b] Bio-based naphtha comes into the system as an "emissions-free" input based on Moretti et al. (2020).

Table 5
Results of mid-point impact categories achieved for annual medical face mask production in China in 2020[a] (based on IMPACT, 2002+).

Impact category	Unit	Surgical mask	N95 mask	Total
Carcinogens	kg C_2H_3Cl eq	2.13×10^8	3.24×10^6	2.16×10^8
Non-carcinogens	kg C_2H_3Cl eq	3.16×10^7	5.57×10^5	3.22×10^7
Respiratory inorganics	kg PM2.5 eq	1.86×10^6	3.11×10^4	1.89×10^6
Ionizing radiation	Bq C-14 eq	2.22×10^9	3.71×10^7	2.25×10^9
Ozone layer depletion	kg CFC-11 eq	9.49×10^1	1.46	9.63×10^1
Respiratory organics	kg C_2H_4 eq	2.10×10^6	3.56×10^4	2.14×10^6
Aquatic ecotoxicity	kg TEG water	4.30×10^{10}	6.82×10^8	4.36×10^{10}
Terrestrial ecotoxicity	kg TEG soil	1.16×10^{10}	1.77×10^8	1.18×10^{10}
Terrestrial acid/nutri	kg SO_2 eq	3.19×10^7	5.31×105	3.24×10^7
Land occupation	m^2org. arable	2.97×10^7	5.48×10^5	3.02×10^7
Aquatic acidification	kg SO_2 eq	9.59×10^6	1.60×10^5	9.75×10^6
Aquatic eutrophication	kg PO_4 P-lim	2.43×10^5	4.02×10^3	2.47×10^5
Global warming	kg CO_2 eq	2.10×10^9	3.48×10^7	2.13×10^9
Non-renewable energy	MJ primary	5.55×10^{10}	8.74×10^8	5.64×10^{10}
Mineral extraction	MJ surplus	7.33×10^7	1.01×10^6	7.43×10^7

[a] 446,600,000 pieces of surgical masks and 3,400,000 pieces of N95 masks are produced per day (Thomala, 2020). The working day in this study from February 1 to the end of the year is estimated at 291 days.

occupation (61%) mid-point impact categories.

Although the mid-point impact categories can reveal the environmental impacts associated with resource extractions and emissions with a high level of reliability and certainty, environmental assessment using end-points damage categories could convey more appropriate data about the characterization flows and facilitate decision-making (Ismaeel, 2018). In light of that, "IMPAC 2002+" based end-point damage categories, i.e., climate change, human health, ecosystem quality, and rescores, were estimated for medical face mask production in 2020. Assuming that the current daily production rates continue, total medical face mask production in 2020 (from cradle to gate) is anticipated to cause the loss of 2.03×10^3 disability-adjusted life years (DALYs); 1.63×10^8 PDF*m^2*yr damage to ecosystem quality; the climate-damaging release of 2.13×10^9 kg CO_{2eq}; and 5.65×10^{10} MJ damage to resources (Table 6). As mentioned, the production of medical face masks in 2020 was increased about 30 times compared to 2019. Therefore, it can be concluded that the pandemics led to an almost 30-fold increase in damages to human health, ecosystem quality, climate change, and resources through increasing annual production of masks. More specifically, face mask production in 2019 approximately led to 6.77×10^1 DALY damage to human health; 5.43×10^6 PDF*m^2*yr damage to ecosystem quality; 7.10×10^7 kg CO_{2eq} damage to climate change; and 1.88×10^9 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 2.95×10^4 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 significantly decrease the associated environmental impacts, e.g., greenhouse gas emissions and energy consumption (Bilo et al., 2018). It has been reported that compared with their fossil-based counterparts, the production of bio-based polymers derived from plants leads to a reduction in carbon dioxide and fossil energy demands, respectively (Spierling et al., 2018). Accordingly, bio-based plastics can be used as a

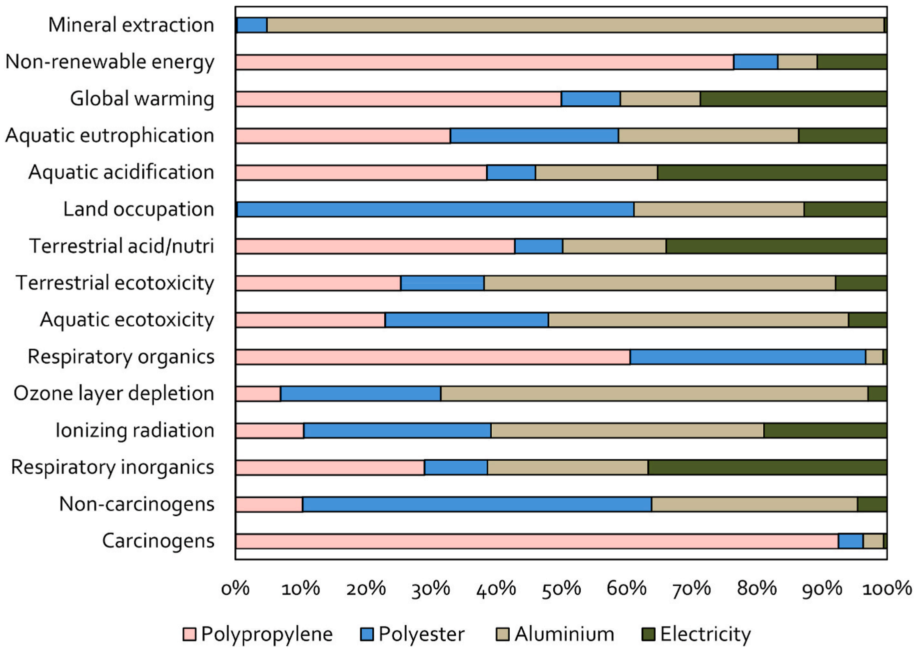

Fig. 2. Contributions of key inputs of medical face masks to mid-point impact categories.

Table 6
Results of four end-point damage categories achieved for annual medical face mask production in China in 2020[a] (based on IMPACT, 2002+).

Damage category	Unit	Surgical mask	N95 mask	Total
Human health	DALY	1.99×10^3	3.26×10^1	2.03×10^3
Ecosystem quality	PDF*m^2*yr	1.61×10^8	2.60×10^6	1.63×10^8
Climate change	kg CO$_{2eq}$	2.10×10^9	3.46×10^7	2.13×10^9
Resources	MJ primary	5.56×10^{10}	8.76×10^8	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.

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 polypropylene and polyester used in medical face mask are replaced with bio-based polypropylene and bio-based polyester, respectively. In addition, the values associated with different damage categories were weighted according to the IMPACT 2002+ method to achieve the single scores, which are presented in Table 10.

The results of the mid-point impact categories revealed that polypropylene was the environmental hotspot, emphasizing the benefit of replacing fossil-based plastics with bio-based plastic. Replacing 10–100% of plastics with environmentally friendly bio-based materials reduced the environmental impacts of medical face masks by 4–43% overall: 3–29% for human health, 0.4–3% for ecosystem quality, 3–28% for climate change, and 7–65% for resource use (Fig. 4).

It should be mentioned that primary energy consumption, also known as cumulative energy demand (CED), is introduced as one of the critical indexes in LCA studies (Frischknecht et al., 2015). Nevertheless, CExD is a more comprehensive index than CED because of the integration of non-energetic resources and the consideration of energy quality. More specifically, in the CExD assessment, the potential loss of “useful” energy resources is also measured (Ehtiwesh et al., 2016). In line with this fact, the CExD analysis for the annual production of medical face masks in 2020 was carried out in the present study, and the obtained results are tabulated in Table 11.

As shown in Table 11, the annual production of medical face masks resulted in 5.88×10^4 TJ demand for exergy in 2020 (approximately 1.96×10^3 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).

Despite the favorable environmental impacts associated with bio-based medical face masks, one of the challenges which might be encountered in the sustainable production of medical face masks with bio-based plastic is the lack of access to sufficient resources, especially in situations where the demand is too high, such as the current pandemic situation. In this context, governments’ urgent support is essential to boost national capacities for bio-based plastics production so that these commodities can compete with their fossil-based counterparts when they are vitally in demand and high quantities.

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 considered more favorable than landfilling because the energy content of plastics could be harnessed. However, incineration may lead to increases in the emission of unfavorable gases (Finnveden et al., 2005).

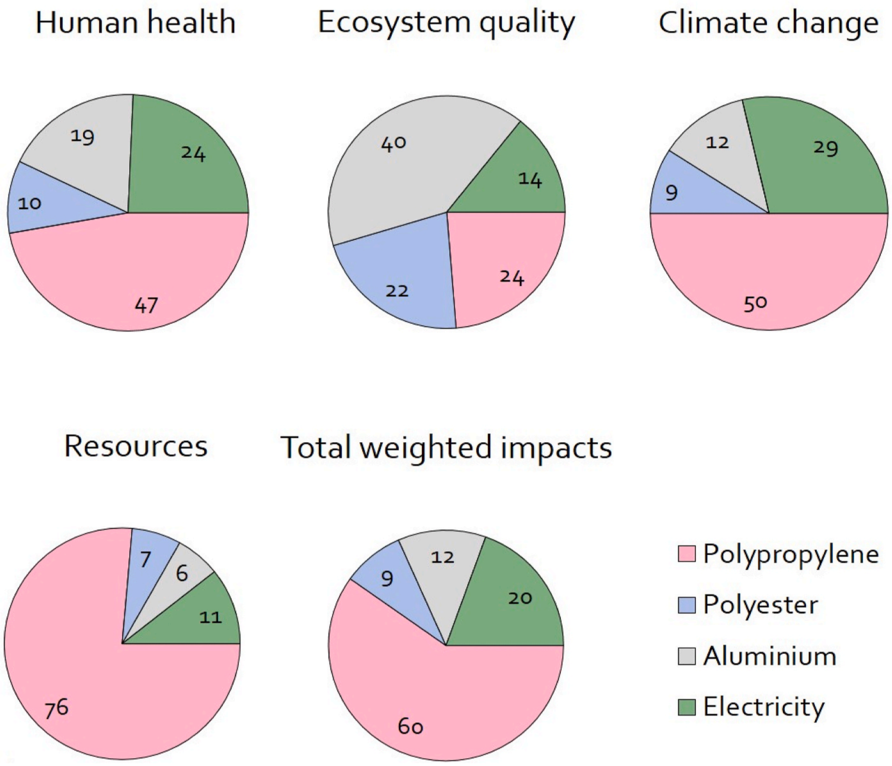

Fig. 3. Contributions of key inputs of medical face masks to various environmental areas and the total weighted impacts.

Table 7
Results of four weighted end-point damage categories achieved for annual medical face mask production in China in 2020[a] (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	2.81×10^5	4.60×10^3	2.85×10^5
Ecosystem quality	Pt	1.17×10^4	1.89×10^2	1.19×10^4
Climate change	Pt	2.12×10^5	3.52×10^3	2.15×10^5
Resources	Pt	3.67×10^5	5.76×10^3	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.

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 caloric values of 44 (Hazrat et al., 2019) and 41.8 (Wasilewski and Siudyga, 2013) MJ/kg, and, if incinerated, would generate 2.68×10^{10} MJ of energy in 2020, albeit releasing 1.43×10^9 kg CO_{2eq}. Such energy content is equal to the energy content of 5.90×10^5 tons of diesel fuel, 5.86×10^5 tons of gasoline fuel, or 5.01×10^5 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 (Aragaw, 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

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 C_2H_3Cl eq	1.95×10^8	1.08×10^8	-1.39×10^6[a]
Non-carcinogens	kg C_2H_3Cl eq	3.02×10^7	2.37×10^7	1.21×10^7
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 organics	kg C_2H_4 eq	1.94×10^6	1.21×10^6	1.50×10^5
Aquatic ecotoxicity	kg TEG water	4.23×10^{10}	3.84×10^{10}	3.02×10^{10}
Terrestrial ecotoxicity	kg TEG soil	1.17×10^{10}	1.19×10^{10}	1.11×10^{10}
Terrestrial acid/nutri	kg SO_2 eq	3.19×10^7	3.03×10^7	2.75×10^7
Land occupation	m^2org. arable	3.07×10^7	3.61×10^7	3.49×10^7
Aquatic acidification	kg SO_2 eq	9.66×10^6	9.38×10^6	8.81×10^6
Aquatic eutrophication	kg PO_4 P-lim	2.41×10^5	2.25×10^5	1.90×10^5
Global warming	kg CO_2 eq	2.07×10^9	1.85×10^9	1.53×10^9
Non-renewable energy	MJ primary	5.27×10^{10}	3.85×10^{10}	1.97×10^{10}
Mineral extraction	MJ surplus	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[a] (based on IMPACT, 2002+).

Damage category	Unit	10% bio-based plastics	50% bio-based plastics	100% bio-based plastics
Human health	DALY	1.97×10^3	1.75×10^3	1.44×10^3
Ecosystem quality	PDF*m^2*yr	1.63×10^8	1.68×10^8	1.58×10^8
Climate change	kg CO_{2eq}	2.07×10^9	1.85×10^9	1.53×10^9
Resources	MJ primary	5.27×10^{10}	3.87×10^{10}	1.98×10^{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[a] (based on IMPACT, 2002+).

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

[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 A11-A16, presented in the Appendix.

method). This damage could be reduced to 4.49×10^5, 2.52×10^5, 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 (Bátori 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 based on CExD achieved for annual production of medical face mask in China in 2020[a].

Impact category	Unit	Surgical mask	N95 mask	Total
Total	TJ	5.79×10^4	9.14×10^2	5.88×10^4
Non-renewable, fossil	TJ	5.21×10^4	8.21×10^2	5.30×10^4
Non-renewable, nuclear	TJ	3.26×10^3	5.03×10^1	3.32×10^3
Renewable, kinetic	TJ	7.25×10^1	1.39	7.36×10^1
Renewable, solar	TJ	8.47×10^{-2}	1.26×10^{-3}	8.58×10^{-2}
Renewable, potential	TJ	9.37×10^2	1.58×10^1	9.54×10^2
Non-renewable, primary	TJ	1.44×10^1	2.74×10^{-1}	1.47×10^1
Renewable, biomass	TJ	6.69×10^2	1.10×10^1	6.81×10^2
Renewable, water	TJ	7.25×10^2	1.15×10^1	7.36×10^2
Non-renewable, metals	TJ	1.78×10^2	2.51	1.81×10^2
Non-renewable, minerals	TJ	1.55×10^1	2.48×10^{-1}	1.58×10^1

[a] 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.

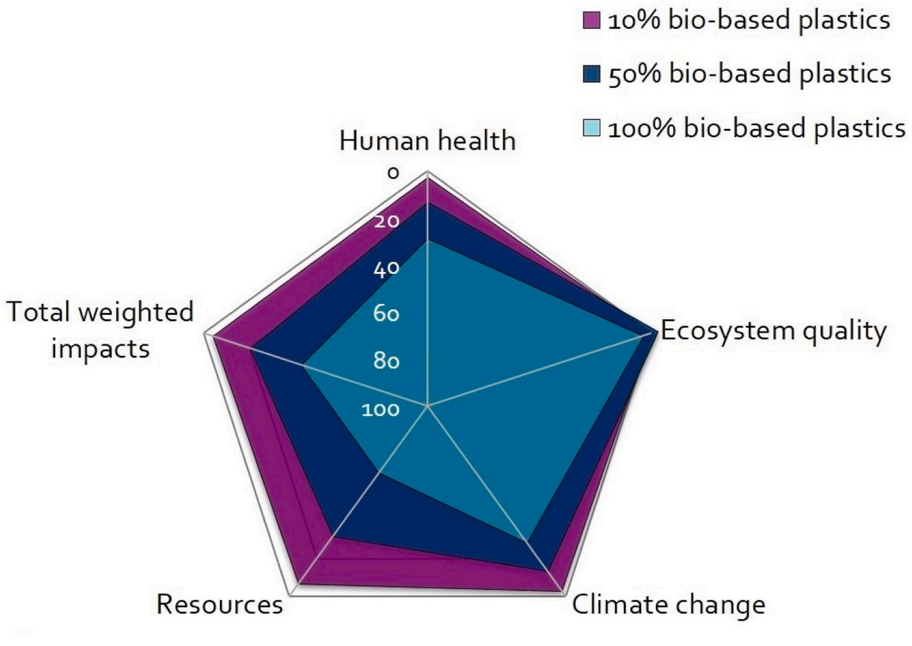

Fig. 4. Environmental benefits of using bio-based plastics in place of fossil-based plastics in the production of medical face masks.

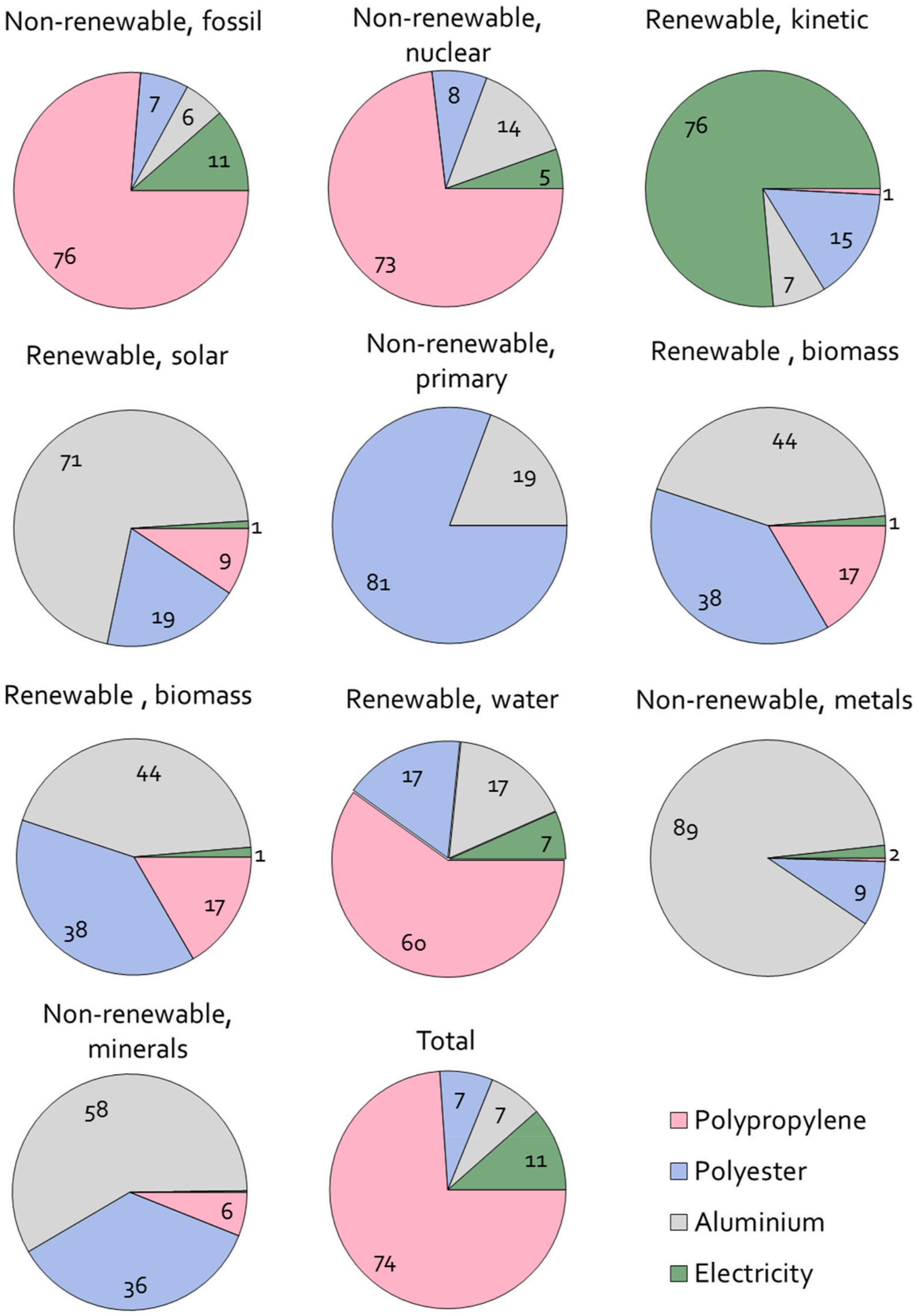

Fig. 5. Contributions of key inputs of medical face masks to various impact categories of CExD.

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.

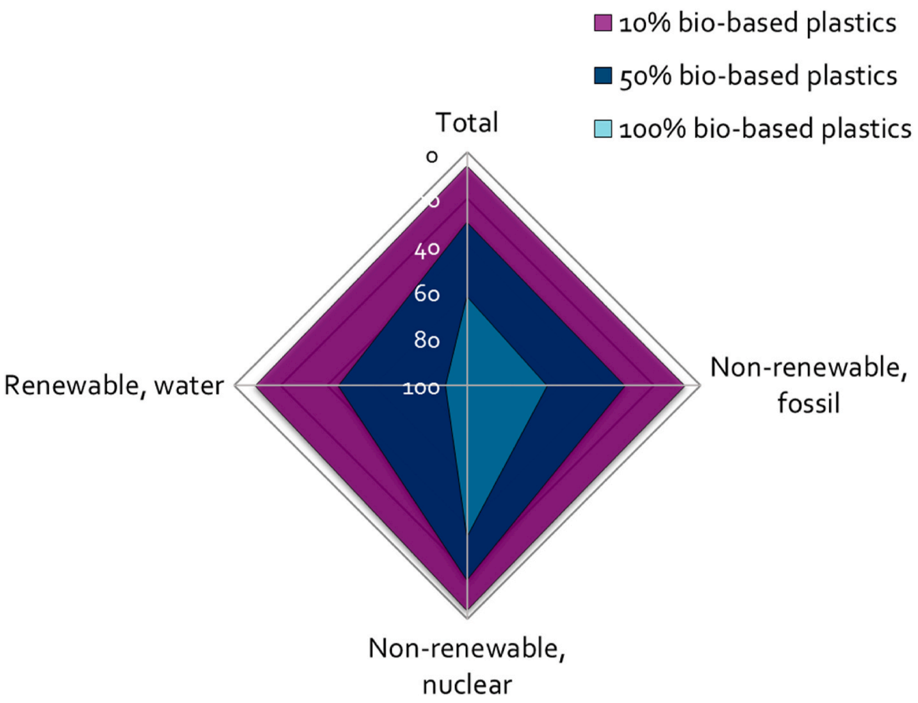

Fig. 6. Exergy demand benefits from using bio-based plastics instead of fossil-based plastics to produce medical face masks for different CExD categories.

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 toward 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 and 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 4.99×10^5 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

(Aghbashlo et al., 2019b; Soltanian et al., 2019), exergoenvironmental (Aghbashlo et al., 2017; Soltanian et al., 2020), and exergoecono environmental (Aghbashlo and Rosen, 2018; Rosen, 2018) approaches. The availability of biomass in sufficient quantities and a cost-effective manner throughout the year with similar qualities is one of the main prerequisites for increasing bio-based plastics production, especially for large-scale operations. Therefore, the search for suitable sources of biomass for bio-based plastics production should be considered by future studies.

On the other hand, due to the enormous demand for face masks caused by the COVID-19 pandemic, the possibility of reusing the used medical face masks made of polypropylene should be investigated by future studies. Dry heat, moist heat, hydrogen peroxide vaporization, and UV treatment are the methods suggested for re-processing/decontamination of medical face masks (Selvaranjan et al., 2021) and should be future investigated in the future. Finally, given the magnitude of the environmental impacts of the production and use of disposable medical face masks, it is imperative to develop washable medical face masks with high safety features to meet the needs during the current COVID-19 pandemic and to reduce the existing massive pressure on disposable items.

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.

Declaration of competing interest

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

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Appendix

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^{-8}	7.25×10^{-9}	1.52×10^{-9}	2.85×10^{-9}	3.72×10^{-9}
Ecosystem quality	PDF*m^2*yr	1.24×10^{-3}	2.94×10^{-4}	2.66×10^{-4}	5.00×10^{-4}	1.76×10^{-4}
Climate change	kg CO_2 eq	1.61×10^{-2}	8.08×10^{-3}	1.46×10^{-3}	1.99×10^{-3}	4.61×10^{-3}
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^{-9}	5.01×10^{-9}	9.50×10^{-9}
Ecosystem quality	PDF*m^2*yr	2.62×10^{-3}	5.79×10^{-4}	7.15×10^{-4}	8.79×10^{-4}	4.50×10^{-4}
Climate change	kg CO_2 eq	3.51×10^{-2}	1.59×10^{-2}	3.92×10^{-3}	3.49×10^{-3}	1.18×10^{-2}
Resources	MJ primary	8.85×10^{-1}	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 to weighted end-point damage categories (based on IMPACT, 2002+).

Damage category	Unit	Total	Polypropylene	Polyester	Aluminium	Electricity
Total	μPt	1.42×10^{1}	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^{-9}
Ecosystem quality	PDF*m^2*yr	1.23×10^{-3}	2.64×10^{-4}	2.39×10^{-4}	5.00×10^{-4}	4.83×10^{-6}	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^{-3}
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^{-2}

Table A6
The contributions of the various inputs of one piece of N95 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	3.19×10^{-8}	1.29×10^{-8}	3.67×10^{-9}	5.01×10^{-9}	7.18×10^{-10}	1.85×10^{-10}	9.50×10^{-9}
Ecosystem quality	PDF*m^2*yr	2.63×10^{-3}	5.21×10^{-4}	6.43×10^{-4}	8.79×10^{-4}	9.52×10^{-6}	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^{-2}
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^{-1}

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^{-9}	8.80×10^{-10}	2.85×10^{-9}	1.82×10^{-9}	3.99×10^{-10}	3.72×10^{-9}
Ecosystem quality	PDF*m^2*yr	1.27×10^{-3}	1.47×10^{-4}	1.54×10^{-4}	5.00×10^{-4}	2.41×10^{-5}	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^{-9}	5.01×10^{-9}	3.59×10^{-9}	9.24×10^{-10}	9.50×10^{-9}
Ecosystem quality	PDF*m^2*yr	2.66×10^{-3}	2.90×10^{-4}	3.57×10^{-4}	8.79×10^{-4}	4.76×10^{-5}	6.33×10^{-4}	4.50×10^{-4}
Climate change	kg CO$_{2eq}$	3.03×10^{-2}	7.97×10^{-3}	1.96×10^{-3}	3.49×10^{-3}	4.37×10^{-3}	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^{-1}

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	Aluminum	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^{-9}
Ecosystem quality	PDF*m^2*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	Aluminum	Bio-based polypropylene	Bio-based polyester	Electricity
Human health	DALY	2.35×10^{-8}	5.01×10^{-9}	7.18×10^{-9}	1.85×10^{-9}	9.50×10^{-9}
Ecosystem quality	PDF*m^2*yr	2.69×10^{-3}	8.79×10^{-4}	9.52×10^{-5}	1.27×10^{-3}	4.50×10^{-4}
Climate change	kg CO_{2eq}	2.55×10^{-2}	3.49×10^{-3}	8.73×10^{-3}	1.53×10^{-3}	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^{-1}

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	3.61	5.13×10^{-1}	8.14×10^{-1}	1.37×10^{-1}	2.92×10^{-2}	1.30
Human health	μPt	2.10	9.20×10^{-1}	1.92×10^{-1}	4.02×10^{-1}	5.14×10^{-2}	9.70×10^{-3}	5.24×10^{-1}
Ecosystem quality	μPt	8.99×10^{-2}	1.93×10^{-2}	1.75×10^{-2}	3.65×10^{-2}	3.53×10^{-4}	3.44×10^{-3}	1.29×10^{-2}
Climate change	μPt	1.58	7.35×10^{-1}	1.33×10^{-1}	2.01×10^{-1}	4.48×10^{-2}	5.74×10^{-3}	4.66×10^{-1}
Resources	μPt	2.63	1.94	1.70×10^{-1}	1.75×10^{-1}	4.08×10^{-2}	1.03×10^{-2}	3.00×10^{-1}

Table A12
The contributions of the various inputs of one piece of N95 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	1.36×10^{1}	7.11	1.38	1.43	2.71×10^{-1}	7.84×10^{-2}	3.33
Human health	μPt	4.50	1.81	5.17×10^{-1}	7.06×10^{-1}	1.01×10^{-1}	2.61×10^{-2}	1.34
Ecosystem quality	μPt	1.92×10^{-1}	3.80×10^{-2}	4.69×10^{-2}	6.41×10^{-2}	6.95×10^{-4}	9.24×10^{-3}	3.29×10^{-2}
Climate change	μPt	3.45	1.45	3.57×10^{-1}	3.53×10^{-1}	8.82×10^{-2}	1.54×10^{-2}	1.19
Resources	μPt	5.45	3.82	4.58×10^{-1}	3.07×10^{-1}	8.05×10^{-2}	2.77×10^{-2}	7.66×10^{-1}

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	2.01	3.31×10^{-1}	8.14×10^{-1}	6.87×10^{-1}	1.69×10^{-1}	1.30
Human health	μPt	1.87	5.11×10^{-1}	1.24×10^{-1}	4.02×10^{-1}	2.57×10^{-1}	5.63×10^{-2}	5.24×10^{-1}
Ecosystem quality	μPt	9.31×10^{-2}	1.07×10^{-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	4.08×10^{-1}	8.56×10^{-2}	2.01×10^{-1}	2.24×10^{-1}	3.33×10^{-2}	4.66×10^{-1}
Resources	μPt	1.92	1.08	1.10×10^{-1}	1.75×10^{-1}	2.04×10^{-1}	5.98×10^{-2}	3.00×10^{-1}

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	1.12×10^{1}	3.95	7.66×10^{-1}	1.43	1.35	3.92×10^{-1}	3.33
Human health	μPt	3.98	1.01	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}	2.11×10^{-2}	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	8.05×10^{-1}	1.98×10^{-1}	3.53×10^{-1}	4.41×10^{-1}	7.71×10^{-2}	1.19
Resources	μPt	3.99	2.12	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	Aluminium	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^{-1}
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	Aluminium	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 CExD).

Impact category	Unit	Total	Polypropylene	Polyester	Aluminium	Electricity
Total	kJ	4.46×10^{2}	3.30×10^{2}	3.22×10^{1}	3.29×10^{1}	5.09×10^{1}
Non-renewable, fossil	kJ	4.01×10^{2}	3.06×10^{2}	2.67×10^{1}	2.27×10^{1}	4.54×10^{1}
Non-renewable, nuclear	kJ	2.51×10^{1}	1.84×10^{1}	1.89	3.49	1.36
Renewable, kinetic	kJ	5.57×10^{-1}	4.64×10^{-3}	8.57×10^{-2}	4.11×10^{-2}	4.25×10^{-1}
Renewable, solar	kJ	6.51×10^{-4}	6.01×10^{-5}	1.24×10^{-4}	4.61×10^{-4}	6.42×10^{-6}
Renewable, potential	kJ	7.21	1.30	4.20 × 10-1	2.19	3.30
Non-renewable, primary	kJ	1.11×10^{-1}	2.13×10^{-5}	8.92×10^{-2}	2.15×10^{-2}	1.25×10^{-5}
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^{-1}	7.19×10^{-3}	4.23×10^{-2}	6.97×10^{-2}	2.35×10^{-4}

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

Impact category	Unit	Total	Polypropylene	Polyester	Aluminium	Electricity
Total	kJ	9.25×10^{2}	6.50×10^{2}	8.65×10^{1}	5.79×10^{1}	1.30×10^{2}
Non-renewable, fossil	kJ	8.31×10^{2}	6.03×10^{2}	7.16×10^{1}	3.99×10^{1}	1.16×10^{2}
Non-renewable, nuclear	kJ	5.08×10^{1}	3.62×10^{1}	5.08	6.13	3.46
Renewable, kinetic	kJ	1.40	9.15×10^{-3}	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^{1}	2.56	1.13	3.85	8.43
Non-renewable, primary	kJ	2.77×10^{-1}	4.20×10^{-5}	2.40×10^{-1}	3.77×10^{-2}	3.18×10^{-5}
Renewable, biomass	kJ	1.11×10^{1}	1.68	5.31	3.96	1.72×10^{-1}
Renewable, water	kJ	1.16×10^{1}	6.57	2.50	1.64	9.36×10^{-1}
Non-renewable, metals	kJ	2.54	1.26×10^{-2}	3.27×10^{-1}	2.14	6.03×10^{-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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