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REVIEW

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Understanding the environmental impacts of facemasks: a review on the facemask industry and existing life cycle assessment studies

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Abstract

The unprecedented COVID-19 pandemic has caused socioeconomic, physical, mental, and environmental upheaval. Personal protective equipment, such as face masks, was mandatory to curb the spread of the virus. The unexpected increase in demand for face masks resulted in an alarming increase in plastic waste globally. The non-biodegradable nature of the raw materials and the potential threat of microplastic pollution amplify the problem. This puts a lot of pressure on policymakers and the global supply chain to develop long-term plans to make face masks less harmful. By reviewing existing life cycle assessment studies, this study aims to provide an overview on how sustainable face masks are. Various challenges in the facemask industry such as microplastic pollution and waste management are discussed. A critical analysis on the various process hotspots is also conducted. Recommendations from this study can motivate focused research into an important field and enable the transitions towards a sustainable facemask industry.

Keywords COVID-19, Environmental impact, Face masks, Life cycle assessments, Micro-plastic pollution, Waste management

1 Introduction

In January 2020, the World Health Organization (WHO) confirmed a new coronavirus infection in Wuhan, China. Over the next two years as SARS-CoV-2 swept the globe, the world experienced a pandemic comparable to the Spanish flu of 1918 [1]. As of May 2022, the WHO says there have been over 521 million confirmed coronavirus infections and over 6.2 million confirmed deaths due to the pandemic [2]. The pandemic has caused problems for the global economy, supply chain systems, public health, and everyday life that have never been seen before. Several precautionary and preventive measures were put in place at the national and regional levels to stop the spread of the virus. There were multiple stages of lockdown and legislative changes to ensure social distancing and adoption of personal protective equipment (PPE). Social awareness campaigns at the global level were also undertaken to educate the importance of personal hygiene.

Demand for protective facemasks had gone through the roof during the pandemic. Single-use facemasks provided a convenient way to ensure sufficient protection from infection. Najmi et al. [3] showed that the adoption of communal face masking was key to stopping the pandemic. Using face masks by at least 60% of the population was a critical control strategy while opening up the economy, especially since compliance with face masking is easier to achieve than social distancing. The demand for face masks is also clear from the WHO study, which found that the US needed nearly 89 million masks to deal

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with the pandemic [4]. Also, the Japanese Ministry for Finance, Trade, and Industry noted that almost 600 million face masks would be required in April 2020 [5]. The figures seem consistent compared to China's production capacities, which make it a significant supplier of masks globally. Chinese production of face masks increased to 110 million d^{-1} in 2020 to meet this demand [6].

The impending crisis following the pandemic would be the management and safe disposal of used protective facemasks. While countries have laid out regulations and guidelines for plastic waste management, most countries lack a centralized regulation on the management and disposal of used face mask waste [7]. The primary concerns about face mask end-of-life options are (i) the ecotoxicological aspect, where the full facemask or micro- and nano-plastics originated due to their degradation disrupts the day-to-day lives of humans, animals, and aquatic organisms. (ii) the energy-intensive processes and greenhouse gas emissions in the manufacturing of face masks and the additional energy to be spent collecting, sorting, treating, and disposing of used face masks. (iii) the socioeconomic aspect, where more money and resources are spent to deal with PPE waste [8].

Selvaranjan et al. [7] surveyed 1033 participants from 6 different countries to study the fate of used face masks. The results showed that nearly 35% of the respondents just discarded the used face masks with mixed waste, and nearly 20% threw away the masks. This is especially worrying because the polymeric materials in the facemask will not break down in nature. The study by Knicker and Velasco-Molina [9] conducted a microcosm experiment to analyze the mean residence time (MRT) associated with the microbial activity to degrade the polypropylene (PP) layer of the face masks. It was seen that even with feasible microbial degradation, the MRT was between 7 and 28 years. This is enough time for the low-tensile-strength spunbond or melt-blown polymeric material to be degraded into micro- or nano-plastic, which can then cause detrimental impacts to the ecosystem.

Several studies have been undertaken to this effect. A study by Spennemann [10] conducted field observations in Albury, New South Wales. It could be seen that most of the mask debris collected was below 10 mm^2 in size and had been shredded by leaf blowers or lawnmowers. These tiny microfibre materials can easily evade the traditional waste collection and sorting system and end up in the soil or aquatic ecosystems. Hasan et al. [11] surveyed 30 ponds in Muktagacha Upazila, Bangladesh, and found that 76.7% had plastic debris either directly in contact with the water body or within 1 m of it.

In a similar study, Thiel et al. [12] surveyed the tourist beaches in Chile to determine the amount of discarded PPE. The average density of discarded face masks across Chile was calculated to be 0.006 face masks m^{-2}. The same study found that these values were higher than beaches in Peru and lower than some beaches in Kenya. A critical analysis study by Kutralam-Muniasamy et al. [13] compiled several other surveys conducted in South Africa, the Persian Gulf, Chile, Indonesia, Bangladesh, Peru, Canada, Kenya, and Morocco, all of which reported the presence of PPE litter in the environment. Akber Abbasi et al. [14] said that Saudi Arabia and Qatar could be responsible for almost half of the microplastic pollution in the Arabian Peninsula. Chowdhury et al. [15] conducted a study across the coastal regions of 46 countries. It is estimated that 0.15 to 0.39 Mt of plastic debris could end up in the ocean next year. PPE usage during the pandemic was a significant contributor to driving up the numbers. Cudjoe et al. [16] found that Asia's average daily accumulation of single-use face mask waste accounted for 19.12 kt d^{-1}. It is also estimated that the world consumes 129 billion single-use face masks monthly [17]. This shows how important it is to identify sustainable options to recover and dispose of used facemasks and PPE, backed up by stringent enforcement.

It is then imperative to raise awareness about the harmful effects of facemask waste and to devise effective strategies to manage them. Life Cycle Assessment (LCA) is a sustainability tool that comprehensively evaluates a process or product to analyse its environmental impacts in a standardized manner [18]. The results of an LCA study can identify the "hotspots" in a process that cause significant impacts, which can then be optimized as required or aid policymakers in making sustainable decisions.

Over the last few years, there has been an increased focus on pandemic-related research. This is also reflected in the increased number of studies on the LCA of PPE and facemask. However, there has been a lack of studies focusing solely on the environmental impacts of facemasks. This study aims to bridge that knowledge gap by reviewing existing LCA studies to better understand the environmental impacts of face masks. This is achieved by providing an overview of the protective face mask industry, and discussing the challenges due to micro-plastic pollution and facemask waste management in Sect. 3. Further, a critical analysis of existing LCA studies on facemasks is provided in Sect. 4. Recommendations from this study can guide future directions and aid in policy legislation for a sustainable facemask industry.

2 Methodology

Google Scholar and Scopus were the primary sources for gathering scientific information. Search strings "life cycle assessment" and "face masks" were used to find LCA studies. Google Scholar returned 795 results, and

Scopus returned 94 results. These were then filtered to find results that were:

- Published in a peer-reviewed journal or underwent a peer-review process
- Primarily involved in assessing the environmental impact of different types of face masks (studies involved in assessing the environmental impacts of PPE without explicitly defining the impacts due to face masks are excluded)
- Conducting a LCA study to analyze the environmental impacts
- Assessing the global warming potential (GWP)/climate change impact (in a mass of CO_{2eq})
- Published in English

The literature review was conducted following the above steps. A total of 18 studies were found that satisfied the mentioned selection criteria.

3 Protective facemasks

Facemasks are an effective control strategy against infectious diseases that are predominantly spread through airborne, droplet, or aerosol transmission [19]. In the case of COVID-19, many precautions were taken, like limiting physical contact, social distancing, maintaining hygiene, and wearing protective facemasks [8]. However, the lack of community compliance limits the absolute benefit of face masks. The following sub-sections provide an overview of how face masks are fabricated and its various types available on the market. Concerns about the facemask industry, microplastic pollution, and waste management are also raised.

3.1 Fabrication of facemasks

In order to understand the source of the environmental impacts, it is important to understand the raw materials and production process involved in the fabrication of facemasks. The basic structure of facemasks includes filtration layers, ear loops, and a nose wire. The ear loops are generally made of elastic materials like polyester and spandex [20]. The nose wires are made from aluminum, high-density polyethylene, or polyvinyl chloride [21]. Meanwhile, the filtration layers are made from "nonwoven" materials to provide minimal airflow resistance and better particle filtration efficiency [8]. These nonwoven materials are characterized by the entanglement of polymer fibers resulting in web-like structures. Depending on the type of manufacturing process selected for web formation, the quality of the web will vary, which in turn determines the final quality of the face mask [22]. Three widely used processes include spunbonding, melt-blowing, and electrospinning [23]. The basic idea behind the three processes is that some liquid polymer of choice is transformed into fibers that form web-like structures within a single step. Depending on the desired specifications, multiple polymers such as PP, polyethylene, polyesters, polyamides, cellulose acetate, polylactic acid, polytetrafluoroethylene membranes, and polymer composites like nylon six could be used to manufacture face masks [23].

To improve the filtration efficiency of the face mask or to impart specific characteristics like antiviral, antibacterial, or self-cleaning, multiple layers of filtration material produced from different polymer feedstocks or through different processes could be combined [8]. The typical surgical mask consists of a spunbond absorbent PP fabric inner layer, a melt-blown electrically charged PP fabric middle layer and a spunbond hydrophobic PP fabric outer layer. A typical N95 mask has the following combination of filtration layers: spunbond PP outer layer; cellulose/polyester second layer; melt-blown PP third layer; spunbond PP inner layer. Unlike N95 and surgical masks, there is no standardized method aiding in the choice of materials, layering, or threads per inch (TPI) in assembling a cloth mask [24]. Ideally, a cloth mask should have a comfortable, absorbent inner layer; a woven or nonwoven middle layer that facilitates filtration (preferably electrostatic); and a hydrophobic outer layer that could be aesthetically designed [8].

3.2 Types of face masks

Depending on the requirements, several face masks are available on the market. Pandit et al. [25] group them into three main types: surgical face mask, respirators, and cloth masks. Surgical masks are typically loose-fitting and disposable. They protect the wearer from splashes or large airborne particles coming into contact with their mouth, nose, or respiratory tract. Most of the time, healthcare workers and patients use these since they are more likely to get sick. At the same time, respirators enable their wearer to withstand harsh conditions and inhale a toxic or hazardous atmosphere (such as biological contaminants, gases, mist, dust, or an oxygen-deficient atmosphere). These close-fitting masks are further categorized based on their type and usage. They generally exhibit an efficacy of 95–99% against the particulate matter of size ranging from 0.01–0.3 μm. The commonly used N-series, R-series, and P-series masks fall under the subcategory "disposable air-purifying respirators." They are predominantly helpful in multiple industrial settings.

Surgical masks and respirators are regulated using regional standards and guidelines across the globe. Contrary to this, cloth masks do not conform to guidelines or standards, making it hard to evaluate their efficacy. They should be multi-layered (hydrophobic, electrostatic, and absorbent) to offer protection. During the COVID-19 pandemic, cloth mask sales went through the roof when surgical and respirator masks were hard to find [26]. Furthermore, the need for cheap, affordable, and reusable masks has increased. Figure 1 shows the classification of various types of face masks.

3.3 Micro- and nano-plastic pollution

The exponential increase in facemask usage foreshadows an impending plastic pollution crisis. During the COVID-19 pandemic, the demand for plastic went up by 370%, which can be directly linked to medical waste. Simultaneously, the demand for plastic packaging went up by 40% [27]. The current waste management system is designed to handle the average amount and type of medical waste. The pandemic, on the other hand, pushes the waste management system past its limits [28]. Pathogens in used face masks add to the difficulty of dealing with waste, which is already complicated by the amount of waste being made. The uninformed disposal of facemasks and PPE poses several environmental and health concerns. Studies have shown the presence of active SARS-CoV-2 on plastic surfaces after three days [29], whereas, on the outer layer of surgical masks, it was present even after six days [30].

When facemasks are exposed to prolonged durations of ultraviolet radiation and visible light, along with fluctuating temperatures, the tensile strength of the PP mask fibers is reduced. This leads to the separation of individual fibers and fragmentation. Eventually, brittle fracturing produces micro- and nano-plastic fibers [10]. It could take 450 years for these microfibres made of medical-grade PP to break down in nature [31]. They can be easily mistaken for food by both land and aquatic animals due to their bright colors. Once eaten, it can't be broken down, causing the animal to die of starvation.

Another common problem is that the face mask wastes wrap around the animal's body, making it hard for it to breathe [32]. Marine plastic, on the other hand, pulls all toxins and other pollutants to its surface, where they form a layer. This toxic film can poison marine animals, rendering them weak and vulnerable. Selvaranjan et al. [7] say that these toxins make it hard for them to reproduce slowing their growth and metabolism. Chemicals like phthalate, nonylphenol, organotin, triclosan, and polybrominated biphenyl ether are also released from microplastics when they break down chemically or biologically [33].

Multiple studies have been conducted to evaluate microfibre release from facemasks, which provides a basis to estimate the extent of the resultant microplastic pollution. The artificial withering experiments by Saliu et al. [34] showed that up to 173,000 fibers d^{-1} could be released from face masks submitted to 180 h of UV irradiation and vigorous stirring in artificial seawater. In a similar experiment, Chen et al. [35] shook both new and used facemasks in deionized water for 24 h. Results showed that new facemasks released fewer microfibres (183 ± 78 particles $mask^{-1}$) than used facemasks (1246 ± 403 particles $mask^{-1}$). A similar mechanical agitation study on different types of single-use facemasks by Dissanayake et al. [27] showed that the highest microfibre release was from surgical masks (202 fibers $mask^{-1}$). This was followed by KF-94 (161 fibers $mask^{-1}$) and FFP1 (160 fibers $mask^{-1}$) masks. Others [36–42] also conducted similar studies. All noted-down results depict concerning levels of microplastic release from face masks. Finally, Shen et al. [43] studied the impact of natural and induced withering using detergent or alcohol solutions on

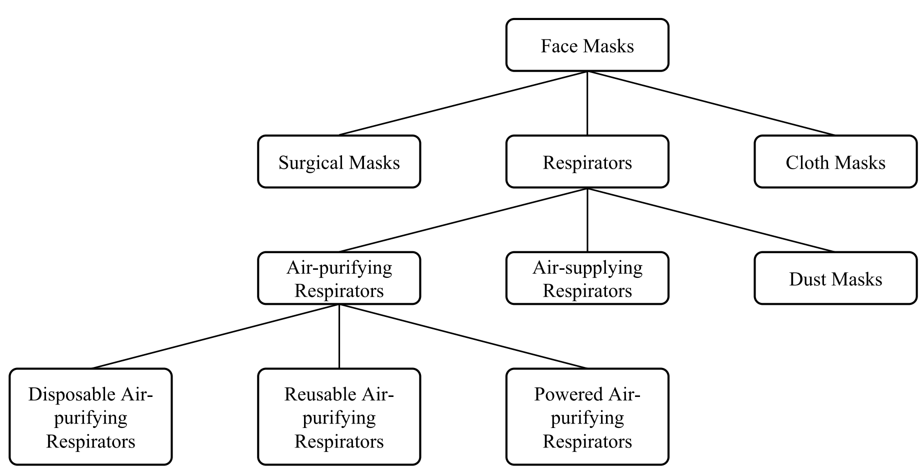

Fig. 1 Classification of facemasks

facemasks. It was seen that the addition of detergents and alcoholic solutions sped up the degradation process and released a higher quantity of microfibres. Subsequently, the broken fragments had a higher exposure area which exponentially increased the release of microfibers.

Microplastics and nano plastics are a concern because they can get through layers of biological barriers and stay in the body of an organism. These occurrences are concerning as these microplastics can bioaccumulate in the food chain through tropic transfer and eventually move up to higher organisms. Researchers are still trying to figure out the long-term effects of consuming microplastics, but they have been seen to get into cells. They accumulate in the bloodstream, brain, and placenta, posing immunosuppression and psychological burdens [44]. A recent study by Amato-Lourenco et al. [45] found the presence of microplastics in human lungs, possibly inhaled. A study by Cox et al. [46] estimates microplastic ingestion in the US population. In their study, which evaluated 3600 processed samples representing approximately 15% of Americans' calorific intake, the annual microplastic ingestion is estimated between 39,000 and 52,000 particles. Inside the human body, these microplastics can break down and release toxic chemicals like organophosphate esters, which have been shown to interfere with the way the endocrine, nervous, and reproductive systems work [13]. They are also linked to a drop in the quality of sperm and cause asthma and allergies. Figure 2 provides a summary of the various public health impacts due to micro- and nano-plastic pollution from discarded facemasks. Face masks are essential for stopping the spread of COVID-19, but they are slowly becoming a big problem regarding waste management and the subsequent rise of micro- and nano-plastics. It then becomes essential to analyze and improve the face mask life cycle to align with the circular economy and resource conservation principles.

3.4 Reuse, reduce & recycle

In situations like the COVID-19 pandemic, there is a sudden rise in the demand for facemasks. This demand and other socioeconomic factors put much pressure on the supply chain, which could cause a shortage and make face masks more expensive in some markets [47]. Generally, reusing and recycling medical waste such as syringes and PPE may not be preferred due to concerns over secondary infections [48]. However, preserving life takes precedence in trying times when there is physical,

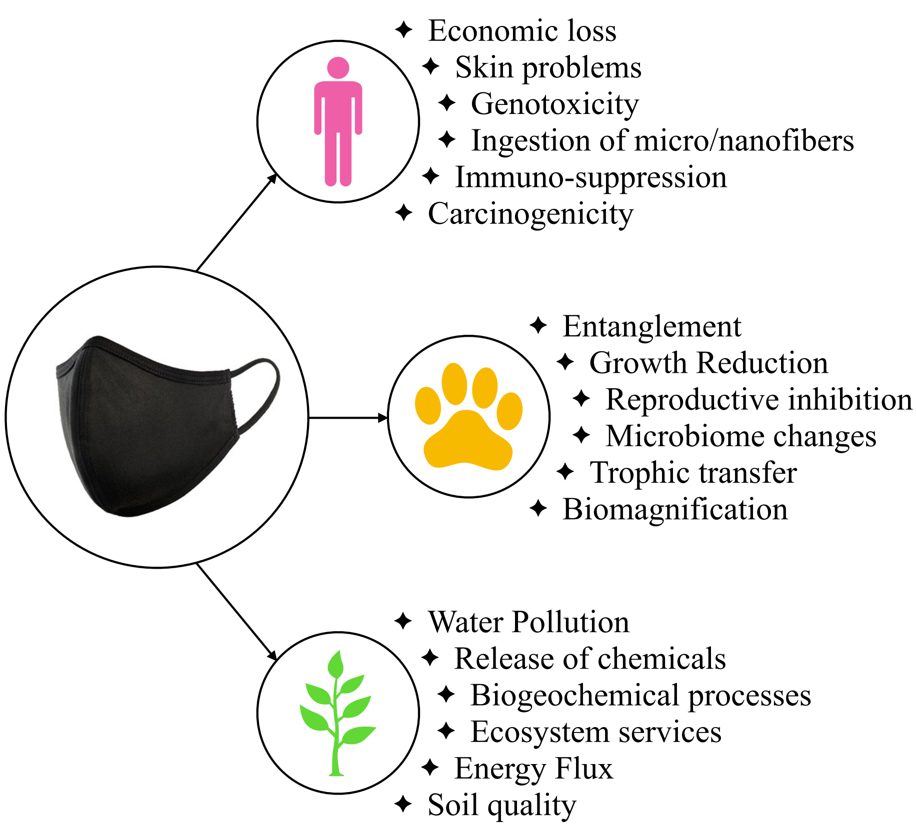

Fig. 2 Various public health impacts due to micro- and nano-plastic pollution from discarded facemasks

mental, and economic turmoil; as such, multiple studies have been conducted to evaluate the feasibility of various decontamination strategies and their effectiveness. There are several tested and available methods for decontamination, such as heat treatment, chemical disinfection, UV irradiation, microwaving, or washing with detergent. In their paper, Ogbouji et al. [23] put together a detailed table of research on decontamination strategies. While reusing face masks does provide significant environmental benefits, as discussed in the next section, exercising caution while decontaminating face masks and adhering to the WHO guidelines is strictly recommended [49].

Even though face masks are unavoidable in times of crisis like the COVID-19 pandemic, it is essential to look for ways to make them less harmful. One approach could be to extend the usable lifetime of facemasks so that fewer facemasks are used up or to substitute sustainable alternatives for facemasks' raw materials. Several studies have looked into the possibility of new biomaterials with similar properties that could be used instead of non-sustainable plastic-based raw materials [50]. A summary of this research is provided in Table 1. Studies have also explored materials that impart favorable characteristics such as antiviral, antibacterial, self-cleaning, self-sanitizing, and superhydrophobicity. These make it easier to use a face mask and could extend the usable lifetime of facemasks [51]. A summary of this research is provided in Table 2.

The already strained plastic waste economy has been put under much stress by the sudden increase in PPE waste. The pandemic increased the number of single-use plastic products, most of which have a useful life span of hours or days [26]. Only a fraction of these masks is collected back at the waste treatment facilities, while the majority are just thrown away to end up in the soil or water bodies. Hence, it is critical to investigate innovative end-of-life options for a used face mask to reduce its impact and, if possible, establish a circular economy [83].

Studies have assessed the feasibility of using shredded mask fibers in concrete material. It was shown that adding 0.2% [84] to 1% [85] improved the mechanical properties of concrete. Yu et al. [86] investigated the possibility of recycling used face masks into a carbon nanotube–nickel hybrid through catalytic conversion to be used in microwave absorption. The study concluded it was an environmentally friendly, scalable, and cost-effective recycling strategy. Fabiani et al. [87] studied the possibility of turning used face masks into panels that could be used for building construction. The novel panels were seen to have improved both thermal and acoustic performances. Another study by Pulikkalparambil et al. [88] recycled face masks as a matrix material to reinforce sisal and hemp fibers used in packaging materials. The composites exhibited increased tensile strengths of 197 and 305%, respectively. Other creative ideas include the French company Plaxtil, which turns used face masks

Table 1 A summary of existing and potential biomaterial applications in face masks

Type	Biomaterial	Application	Reference
Protein	Keratin/polyamide 6 nanofiber	Water & Air filtration	[52]
	Soy protein isolate/polyvinyl alcohol hybrid nanofiber	Air filtration mask	[53]
	Gluten nanofiber	Face mask	[54]
	Electrospun Sericin nanofibrous mats	Air filtration mask	[55]
	Silk nanofibers	Air filtration mask	[56]
Cellulose	Nanomembrane lyocell fibrous	Surgical face mask	[57]
	Fungal hyphae and cellulose fibers (Wood and Hemp)	To substitute synthetic melt and spun-blown materials	[58]
	Cellulose acetate (CA) nanofibers	Air filtration mask	[59]
	Cellulose non-woven layers	Surgical face mask	[60]
	3-ply cotton-PLA-cotton layered	Face mask	[61]
	Non-woven cellulosic fiber	Face mask	[62]
	Banana stem fiber	Face mask	[63]
Polylactic Acid (PLA)	3D printed and electrospun polylactic acid	Face mask filter	[64]
	Poly(lactic acid) fibrous membranes	Air filtration mask	[65]
Polyhydroxyalkanoates (PHAs)	Nano fibroustructure	Face mask	[66]
Chitosan	Chitosan nanowhiskers and poly(butylene succinate) -based microfiber and nanofiber	Face mask filter	[67]
	Nanofibrous chitosan non-woven	Water & Air filtration	[68]
Gelatin	Gelatin/β–cyclodextrin composite nanofiber	Respiratory filter	[69]

Table 2 Summary of possible face mask modifications to increase their usability

Characteristic Property	Material added	Reference
Antibacterial	Quaternary Ammonium	[70]
	N-halamines	[71]
	Metal nanoparticles (eg. Ag)	[72]
	Electrospun polylactic acid (PLA) membranes	[65]
	Extracts of *Vitex tri- folia, Punica granatum, Allium sativum, Acacia nilotica, Andrographis paniculata, Sphaeranthus indicus, Strobilanthes cusia, Chromolaena odorata, Aloe barba- densis, and Azadirachta indica*	[19]
	Graphene & Graphene oxides	[73]
	Mangosteen extract	[74]
Antiviral	Metal & metal oxide nanoparticles (eg. Zn, Cu, Ag)	[75]
	Sodium chloride	[76]
	Poly(ethylenimine) (PEI)	[77]
	Poly-phenol	[62]
	Ginkgo extract with Sumac	[78]
	Iodine	[79]
	Graphene oxide	[80]
Self – cleaning, Self – sanitizing, Super-hydrophobicity	Graphene nanosheet embedded carbon	[81]
	Laser induced transfer of graphene	[73]
	Shellac & copper nanoparticles	[82]

into plastic visors [89]. The study by Battegazzore et al. [90] has shown that the mechanical recycling of used face masks to form materials that are not subjected to shocks or significant deformations, like furniture, is a cheap and straightforward solution to managing face mask waste.

Even if the 3 R's (reuse, reduce, and recycle) are given the most attention, there has been much waste from face masks already generated over the years. It is just as essential to study and understand how to manage this waste while minimizing the impact on the environment. The waste hierarchy places landfilling as the least favorable alternative [91]. Incineration remains the primary option for eliminating medical waste contamination [48]. But it is also essential to think about how the different emissions from incineration affect the environment. Zhao et al. [92] did an LCA study to compare the effects of five medical waste disposal techniques. Results show that medical waste disposed of after being sterilized in a microwave is the best for the environment. Conversely, when energy recovery is prioritized, rotary kiln incineration shows the best performance (38.2%), followed by pyrolysis (33%). After process optimization, these go up to 63.6% and 55%. The conclusions from the study also recommended the co-incineration of medical waste with municipal solid waste. Under an optimized situation, this scenario showed > 83.4% energy recovery potential. Since then, several studies [16, 93] have used the waste-to-energy route to turn face masks into power or fuel. Thermochemical conversion of facemasks using incineration, pyrolysis, and gasification all show good energy recovery potential.

4 LCA of protective facemasks

A literature review was conducted according to the steps mentioned in the methodology. Table 3 provides a summary of all the literature collected as part of this review.

4.1 Trends in literature

All the LCA studies were undertaken within the last three years, starting with Schmutz et al. [94]. This is likely because of the pandemic and the subsequent realization of an environmental impact crisis, which caused more PPE and facemasks to enter the economy. All eighteen studies primarily evaluated some form of disposable single-use surgical or medical masks. In most cases, this was compared to the effects of a reusable mask. Thirteen studies looked at the effects of cloth facemask, whether hand-made or bought from a store, but only six looked at the effects of N95 facemask. Other facemasks being evaluated were embedded filtration layer reusable facemask, 3D printed masks with valves, FFP3 masks, and rigid half masks. Even though these are all common types of masks, some commercially available ones, like activated carbon facemask and polylactic acid facemask, still need to be looked at. Most studies utilized dedicated LCA software such as SimaPro, GaBi, or OpenLCA. The exceptions of Schmutz et al. [94] and Bouchet et al. [95] utilized MS Excel, but their studies were justified as simplified LCA

Table 3 Summary of LCA studies evaluating face masks

Year	Article	Country/Region	Software	Type of LCA study	Types of face masks	Functional Unit	Method of LCA	GWP for Functional Unit (in kg of CO_2)	Main Conclusions
2020	[94]	Switzerland	Excel	Cradle to grave	Surgical & 2-layered cotton	1 person wearing facemask for 1 week	IPCC, VDI definition, AWARE	0.23–0.24	• Both masks had high impacts in depending on the impact category considered • User behavior determines the environmental impact of facemask • The production phase is a hotspot
2021	[21]	UK	GaBi	Cradle to grave	Single use & reusable cotton	1 yr of facemask use by UK population	Environmental Footprint 3.0	1.47E+09	• Use of 4 facemasks in rotation without filters and machine washed had the lowest impact • Hot spot analysis showed that import of facemasks from China was the major impact category
2021	[95]	Europe	Excel	Cradle to grave	Disposable single-use, Cloth & Reusable	Facemask required by 1 person in 1 month	UBP	0.4–1.3	• Most favourable scenario is a homemade cotton mask • Importing disposable masks by plane was the most impactful scenario • GWP reduction of 50–90% can be achieved by switching from single-use to reusable facemask • Reusing medical masks with a 'wait and reuse' strategy is most appropriate as it balances between protection achieved and environmental impact
2021	[96]	Italy	SimaPro	Cradle to grave	Cloth, Surgical, & FFP2 with & without valves	Facemask used in 306 days	IPCC 2013, GWP 100a, ReCiPe 2016, IMPACT 2002+	5.36E+07–1.96E+8	• Disposable masks provide better protection • Cloth masks have 3.39 times lower impact, 85% less wastage and 3.7 times cheaper
2021	[97]	Italy	OpenLCA	Cradle to grave	Surgical & reusable	1 mask	IPCC-GWP100, CML baseline	0.327	• Major hotspot was the textile production for facemask

Table 3 (continued)

Year	Article	Country/ Region	Software	Type of LCA study	Types of face masks	Functional Unit	Method of LCA	GWP for Functional Unit (in kg of CO_2)	Main Conclusions
2021	[98]	Singapore	-	Cradle to grave	Surgical & Embedded filtration layer reusable	31 (12-h) days	ReCiPe	0.038–0.58	• EFL reusable masks has 30% lesser wastage and impacts
2021	[99]	Italy	SimaPro v9.0	Cradle to grave	3D printed with changeable valve, surgical, FFP2 with and without valves & washable	Facemask used by Italian citizen in a month	ReCiPe, Cumulative Energy Demand	1.5E + 06–5.6E + 07	• 3D printed and washable masks were most sustainable • Highest impact in all category was for FFP2 mask with valve followed by FFP2 mask without valve • Upstream production phase was a hotspot
2021	[100]	Netherlands	SimaPro 9.1	Cradle to grave	Single use & reusable	1 facemask each used 2-h for 100 health care workers	ReCiPe	2.77–6.55	• 58% lower carbon footprint for masks reused 5 times compared to single use facemasks
2021	[101]	China	SimaPro 9.0	Cradle to grave	Combined impact from surgical and N95	Sum of surgical and N95 facemask produced by China in 2020	IMPACT 2002 +, EDIP 2003	2.13E + 09	• Substituting mask 10 – 100% of mask material with bio alternatives can result in 4 – 43% reduction of environmental impacts • PP used in production was the major contributor to many impact category
2021	[102]	India	OpenLCA	Cradle to grave	Cotton & Surgical	-	CML IA baseline, ILCD 2011 Midpoint +	1.92E-2–4.89E-2	• Surgical facemask has higher impact than cotton facemask
2022	[103]	Indonesia	OpenLCA	Cradle to gate	Disposable single use	30 (12-h) days / 30 single use facemask	ReCiPe	1.82593	• Production line contributed to more than 50% of emissions • New ear-loop design is proposed to reduce emissions
2022	[104]	-	SimaPro 9.2	Cradle to grave	Single use surgical	1 single use surgical facemask	ReCiPe	3.49E-02	• Material supply and transport was major impact hotspot • Sustainable end of life options have to be developed other than incineration and landfilling • Biodegradable materials like PLA has to be considered as substitutes

Table 3 (continued)

Year	Article	Country/Region	Software	Type of LCA study	Types of face masks	Functional Unit	Method of LCA	GWP for Functional Unit (in kg of CO_2)	Main Conclusions
2022	[105]	Brazil	SimaPro	Cradle to grave	Single use & handmade cotton	90 h (1 reusable cotton mask or 30 single use masks)	ReCiPe 2016, IMPACT world +	6.05E-01–3.76E + 00	• Handmade cotton masks perform better environmentally than single use facemask • 60% of impacts were from manufacturing phase for single use facemask • After a single use the final disposal of cotton masks pose 5 times impact compared to single use masks. However with each reuse this value is compensated and finally after the recommended maximum reuse of 30 uses, single use masks have 6 times higher impact compared to reusable facemask
2022	[106]	Italy	SimaPro v8.2	Cradle to grave	Single use & Type IIR reusable	Total number of facemask used by Italian population in 2020	ReCiPe	1.47E + 08–9.04E + 08	• Reusable facemask showed less impacts for 14/18 impact categories • The 'use phase' for reusable masks, comprising of energy and washing requirements made 1/3 of the total impacts • Incineration of facemask always had a higher environmental impact than landfilling
2022	[107]	Turkey	GaBi v10.5	Cradle to grave	Single use	1 3-layer single use facemask with nose wire	CML 2001	0.02E-02	• Raw material supply (40.5%) and packaging (30%) were hotspots for GWP
2022	[108]	UK	GaBi	Cradle to grave	Surgical, Cloth, FFP3 & Rigid half mask	1 year of mask use by health care professional	Environmental Footprint 3.0	1.7–120	• Reusable alternatives generate 80–90% less waste than single use facemask • Reusable alternatives possess 3–11 times lower climate change impacts • Sourcing masks locally (purchasing from Turkey) or manufacturing in UK itself had less environmental impact

Table 3 (continued)

Year	Article	Country/ Region	Software	Type of LCA study	Types of face masks	Functional Unit	Method of LCA	GWP for Functional Unit (in kg of CO_2)	Main Conclusions
2022	[20]	UK	SimaPro 9.2	Cradle to grave	Single-use, EFL reusable & Reusable wool mask	1 year of mask used by a person	Environmental Footprint 3.0	-	• Reusable woollen facemask had 46% lower environmental impacts • The annual expenses of using woollen facemask is expected to be 54% lower than conventional PP facemask
2023	[109]	China	-	Cradle to grave	Reusable cotton, Disposable medical, Disposable surgical & KN95 respirator	Facemask used by 100 individuals over one month	Carbon footprint calculation model	1.29E3	• Cotton facemask will break even and become an environmentally friendly alternative after 17 washes • In low-risk settings, reusable cotton facemask and disposable facemask are better options • In high-risk settings, surgical facemask and KN95 respirators are better

IPCC International Panel on Climate Change, *VDI definition* Verein Deutscher Ingenieure/Association of German Engineers, *AWARE* Available Water Remaining, *UBP* Umweltbelastungspunkte/Environmental Impact Points, *EDIP* Environmental Design of Industrial Product programme, *ILCD* International Reference Life Cycle Data System evaluations or preliminary studies. Another exception is Luo et al. [109], who did not specify the use of any software. The carbon footprint calculation and evaluation model from ISO 14067:2018 was used in their study.

4.2 Functional unit and system boundary

In an LCA study, the functional unit is the necessary product or process within the system to which all other input and output flows are scaled. The idea behind the use of functional units is to represent the performance characteristic of the system, and they are chosen on a case-by-case basis that is specific to each study (e.g., producing x amount of product or consuming y amount of product in y amount of time). When comparing the life cycle of multiple products, it is essential to make sure that all of the product's life cycle characteristics are taken into account without any bias. This is more useful when comparing a single-use product to one that can be used repeatedly. This is why a time frame is chosen instead of a specific number as the functional unit, like the number of face masks used in a year, month, or week. This enables, the LCA practitioner to account for the use phase of reusable facemask and the potential savings from its life cycle. From the literature, the functional unit was mostly specified as a time frame. The exceptions are Giungato et al. [97] who compared the impacts of one single surgical facemask to a single reusable facemask, and Barbanera et al. [104] and Atilgan Turkmen [107] who studied the impact of a single surgical facemask.

The system boundary defines the limits of various input and output flows to be considered as part of the study. This is often shown as a diagram in the section of the study called "Goals and Scope." In the current list of studies, almost everyone followed a cradle-to-grave system boundary, except for Alfarisi et al. [103]. Even when all studies use a cradle-to-grave system boundary, it is hard to compare them as there is a vast disparity in the life cycle inventory due to assumptions and data gaps. While the results of the LCA study are still valid, these differences stand in the way of an adequate comparison. It is in the best interest of interested parties like LCA practitioners, manufacturers, policymakers, and consumers that the LCA studies evaluate similar or the same product with comparable functional units and system boundaries. This allows for easy translation of the results and avoids speculation.

4.3 Life cycle inventory

Data quality in an LCA is essential, as it determines the accuracy of the obtained results. Considering that many policy reformations and supply chain optimizations could be done based on the results, it becomes imperative that due diligence be practiced during the data collection and validation steps. During an LCA study, two main types of data are collected: foreground data, which is collected directly from the source or industry through surveys or direct communication, and background data, which comes from databases in LCA software or from existing literature. But collecting background data can be challenging if you do not have the right connections in the industry. It can also be hard if you need more time or money. This leads to data gaps in the life cycle inventory, which are then substituted with background data, or valid assumptions for simplification. In the current list of studies, most of them use a combination of primary and background data. The primary data included things like the mass of the facemasks, while the background data was mainly used to fill in gaps about energy use and manufacturing. The 2021 study by Allison et al. [21] had one of the complete life cycle inventories, with good explanations of assumptions and correct citations of data sources. This is probably why studies by Do Thi et al. [96] and Luo et al. [109] used their inventory as a background data source. Studies by van Straten et al. [100], Morone et al. [106], and Atilgan Turkmen [107] were able to gather and use industry data. Lee et al. [98] were able to gather information from the researchers at the Singapore Institute of Manufacturing Technology. In the case of Alfarisi et al. [103], it was seen that the collected primary data were all grouped together and not differentiated by different life cycle stages (raw material production, assembly, packaging, etc.). Transportation was not considered in any of the studies by Schmutz et al. [94], Do Thi et al. [96], and Boix Rodriguez et al. [99]. The packaging has a significant impact on the life cycle of face masks. However, only ten out of eighteen studies considered the impacts due to packaging. All of the above-mentioned data gaps and the subsequent assumptions being made can skew the results. This also voids any direct comparisons between the results of different LCA studies.

4.4 Decontamination strategies

An essential part of the face mask's life cycle is the use phase and how it is decontaminated after each use. This section briefly explains the various decontamination strategies in literature and their environmental performance. Other than the 18 LCA studies on face masks, information from other LCA studies and sources was added to this section to make it more complete.

Thermal treatment is considered the primary choice for mask decontamination as the heating equipment is readily available. Ogbouji et al. [23] looked at the effects of heat treatment on N95, surgical masks, FFPs, KN95, and KP94. The studies were modeled to include a multitude of aerosols such as SARS-CoV-2, *Staphylococcus* *aureus, Escherichia coli,* Human Adenovirus Type 2, Tulane virus, etc. Results show that the filtration performance was retained at the optimal level for several decontamination cycles (~ 10). Heating blocks, steamer cookers, water baths, steam, drying ovens, and autoclaving were all used as heat sources. All cases showed significant inactivation of microbial activity. Soares et al. [110] conducted an LCA on healthcare waste management. They discovered that autoclaving had a more significant impact on climate change (48 parts per thousand) and was more expensive (US$ 1.1 kg^{-1}) than microwaving and lime disinfection. The hotspot was identified as the electricity requirement for operating the equipment. In their study, van Straten et al. [100] saw similar trends and found that the energy needed for steam sterilization was a hotspot. Also, Allison et al. [21] showed that the heating required to prepare the water bath was a hot spot in disinfecting cloth masks.

Chemical disinfection is a standard method of choice for sterilizing various materials. Hence the potential of certain alcohols and peroxides to decontaminate face masks was also tested [23]. Studies have been modeled using *E. coli, Bacillus subtilis, SARS-CoV-2,* Porcine respiratory coronavirus, etc., as aerosol on surgical masks, N95, KN95, and FFP. While the results show microbial inactivation, the filtration performance was significantly reduced. The chemical treatment also impacted the mask morphology and surface potentials. This is a significant drawback in the utilization of chemical disinfection. Chemical disinfection affects the environment and the economy less than other methods, primarily because it uses less energy. The hotspot in chemical disinfection would be the chemical production process [111].

UV irradiation, short-wave UV light, has been used to kill microorganisms [23]. It works by stopping the organism's DNA from copying itself. However, UV light can only kill microorganisms when exposed to it. Multiple studies were modeled with *E. coli, B. subtilis, S. aureus,* Porcine respiratory coronavirus, etc., as aerosol on surgical masks, N95, KN95, and FFP. The results of UV irradiation show that microbial activity is greatly reduced while filtration performance stays the same.

Microwaving is another promising non-chemical method of choice in face mask decontamination, as it can be potentially done at home. Studies were modeled using *E. coli, B. subtilis,* and NaCl as aerosols for surgical masks, N95, KN95, and FFP [23]. A reduction in microbial activity is observed while filtration performance is retained. However, microwaving does affect the mask morphology over long periods, and in some cases, it melts the filter layer and makes holes visible. Soares et al. [110] showed that microwaving had a lower environmental impact (12 points) and cost less (US$ 0.12 kg^{-1}) in waste treatment when compared to autoclaving.

Detergent laundering is not a preferred decontamination method for surgical or respiratory masks. Ogbouji et al. [23] found that using laundry detergent to clean surgical masks, N95, and KN95 did not reduce microbial activity and decreased filtration performance after the first cycle. Yet this is still a practical method of disinfection for cloth masks at the household level. However, studies have identified the detergent manufacturing process as a hotspot that closely follows water requirements [106].

4.5 Significant observations

All studies show that single-use face masks have a higher carbon footprint and harm the environment than reusable face masks. It was observed that a 50%–90% reduction in GWP in kg CO_2 eq could be achieved by switching from a single-use face mask to a reusable face mask [95]. The major contributors were the impacts due to raw material acquisition and production lines. Maceno et al. [105] showed that the impacts of using single-use masks disposed of in landfills were five times higher than those of reusable mask that is landfilled. The impact is ten times higher if the reusable mask is recycled. Another motivation to consider reusable face masks would be the material flow analysis study by Allison et al. [21], which showed that the annual waste accumulation of single-use face masks in the UK amounts to 124 kt. This can be reduced by > 50% if reusable masks with single-use filters are used and reduced to > 85% if reusable masks are used.

However, the actual benefits of using reusable face masks heavily depend on user behaviour [94]. For example, Maceno et al. [105] found that the total environmental impact of reusable face masks is five times higher than that of face masks that are used once. This is mainly from the cotton used in the fabric materials that require large amounts of water, fertilizer, and pesticides to grow [21]. But each time the face mask is used again, the net impact is reduced. After the recommended 30 uses, a reusable face mask will have six times less impact on the environment than a single-use face mask [105]. Similarly, another critical user behavior is the preferred means of washing or disinfection. Two readily available options are hand washing with or without detergent and machine washing. The increased water consumption and use of detergents make hand washing unsustainable. Studies show a 50–66% reduction in GWP impacts when machine washing is preferred [21, 98]. The benefits of washing clothes in a machine again depend on how often and how much you wash since that decides the water and energy consumption. Thirdly, the user's perception and understanding of masking also influence the environmental benefits.

Suppose they dispose of a reusable mask after a few uses, much fewer than the recommended number of uses, or openly dispose of the mask without complying with any disposal guidelines. In that case, it may offset the potential environmental benefits. Among commercially available face masks, studies show that a single-use FFP2 mask with an exhalation valve had the highest environmental impact over its life cycle. Simultaneously, 3D-printed masks with FFP2 filters had the highest GWP impact considering the production phase; however, this was offset with each reuse [99].

Studies have looked at how the design of masks, the supply chain, and possible ways to sterilize them could be changed to make them less harmful to the environment. Even so, only a tiny number of LCA studies have looked at how their proposal affects the environment. A modified ear loop design has been proposed by Alfarisi et al. [103], which lowers the fraction of polyurethane raw material to 20% and combines the ear loop bonding and nose clip loading process. This modification resulted in an 8–34% reduction in environmental impacts for 7 out of 8 impact categories. Further, a GWP reduction of 25% can be achieved by substituting plastic packaging with cardboard boxes [107]. This is due to the low energy and material consumption in processing paper boxes. van Straten et al. [100] looked at 88 different brands of FFP2 masks and how well they worked after steam sterilization. They found that the reprocessed masks retained their filtration capacity and structural integrity, and fit for up to five cycles. New FFP2 masks had 58% more impact than reprocessed FFP2 masks sterilized with steam. While the sterilization process has a significant share in total impact contributions, it substantially reduces the impact contributions due to the production phase by 73%, transportation by 63%, and end-of-life by 62%.

Sensitivity analysis by Lee et al. [98] showed that the climate change impacts and waste generation from single-use face masks were highly sensitive to the quantity of spun-bond PP material used. In the case of reusable face masks, climate change impacts were highly sensitive to a reduction in emissions from the detergent manufacturing process (modification in its supply chain), and waste generation was susceptible to the quantity of polyester material used.

Finally, landfilling has a lower environmental impact than other end-of-life scenarios, but it needs to be more sustainable. Lee et al. [98] conducted a scenario analysis, comparing a base case against hypothetical situations. Their results show that direct landfilling of single-use face masks offered an 8% reduction in climate change impacts compared to incineration followed by landfilling. However, it exponentially increased waste generation by 3885%.

Environmental impacts can be reduced further by offsetting negative impacts through value addition, even at the end-of-life stage. For example, when the masks are burned to make electricity, the total impact on freshwater eutrophication from the rest of the mask's life cycle is less than what the electricity production makes up for [98]. Hence, there was a net positive impact in this particular scenario.

4.6 Hotspot identification

All the research that was reviewed showed that the most impactful part of manufacturing single-use face masks is the production phase, which includes sourcing the raw materials, processing, and energy requirement. On finer inspection, it can be seen that PP accounts for almost 33–90% of significant mid-point impact categories, followed by aluminum in nose clips with 42–95% in different mid-point impact categories [101]. In the case of both materials, the major impacts are from the raw material production process. The same study showed that PP was the single most damaging element in the face mask life cycle, with a 47% impact on human health, a 50% impact on climate change, and a 76% impact on resource depletion. Hence, it becomes imperative to explore the potential for reducing the quantity of raw materials or other sustainable alternatives with a lower carbon footprint. Transportation was also a big problem, especially when long-distance exporting is involved in sourcing the face masks or their raw materials. Even though transportation impacts are applicable for both single-use and reusable face masks, they are more amplified in the case of single-use facemasks due to the exponentially higher numbers [21]. Transportation impacts are also the result of a skewed supply chain system, which is prioritizing cost savings over environmental savings. Facemasks as a whole or its individual components may be mass-produced in some place like China where it is available for a fraction of the cost. This promotes manufacturers to just import the materials in bulk even when the import process adds to the environmental impacts. In such cases, supply chain optimizations have to be undertaken such that a middle ground is reached between cost and environmental savings. In the studies where end-of-life scenarios were considered, it had a significant impact closely following the manufacturing and transportation phases [97, 99, 104, 107]. Barbanera et al. [104] found that marine eutrophication and GWP were the two main types of end-of-life effects.

In the case of reusable face masks, the hotspots were found to be the cotton fabrics and the use phase. Cotton has heavy water requirements during its cultivation and commercial production. It also involves using pesticides and fertilizers, increasing environmental impacts [112].

The usage phase becomes a hotspot due to the water and detergent used to wash face masks. In cases where hot water is used, 70% of the climate change impacts are from the heating required for the tap water [21]. When a steam sterilization process was thought of, the sterilization process became the process hotspot [100].

4.7 Geographical distribution of selected regions

Two possible limitations of an LCA study are the geographical scope and time frame of the study. This is because the primary data collected will be specific to that process and region, and the background data from databases would have been modified to suit the requirement. For example, China is a leading producer and global exporter of facemasks, an LCA study for facemasks in China might find the facemask material of the production process to be a hotspot. Whereas some countries importing facemasks from China using air cargo might find long-distance air transport as the hotspot. Simultaneously, in LCA software like SimaPro there is an option to input country/region-specific data for electricity mix, fuel mix, and processes, which is being used in most studies. In each of these instances, any process optimization or recommendations made will mostly be specific to that case in that region and may not be valid when extrapolated. This can be seen from the studies by [21, 95] who found long-distance transportation from China to be the major hotspot, whereas other studies had other process hotspots. In the literature review, of the 18 studies, 17 mentioned a region where the LCA study was designed. Most of the current studies are for Italy, followed by the UK as shown in Fig. 3. Given the importance of the topic under consideration, there are very few LCA studies, which is not enough to reflect and assess the global situation.

4.8 Future recommendations

As for the future direction in this field, three major areas could be developed further. This includes increased knowledge sharing, focused research on sustainable materials and designs, and policy changes. This is explained in depth as follows:

- From inspecting the datasets used in existing LCA studies, it can be seen that quite a lot of data are based on assumptions rather than solid industrial information. This creates discrepancies in the life cycle inventory calculations. As discussed earlier, the assumptions made include oversimplifying some data or neglecting some important impact sources (transportation, packaging, certain manufacturing processes, etc.). This means that the direct comparison of an LCA that accounted for transportation or packaging and one that did not consider these sources would be impractical. There must be more open data sharing among the researchers and their industry counterparts, such that more accurate data is available for the studies. This will be reflected as valuable results that reflect real-time problems and their solutions.

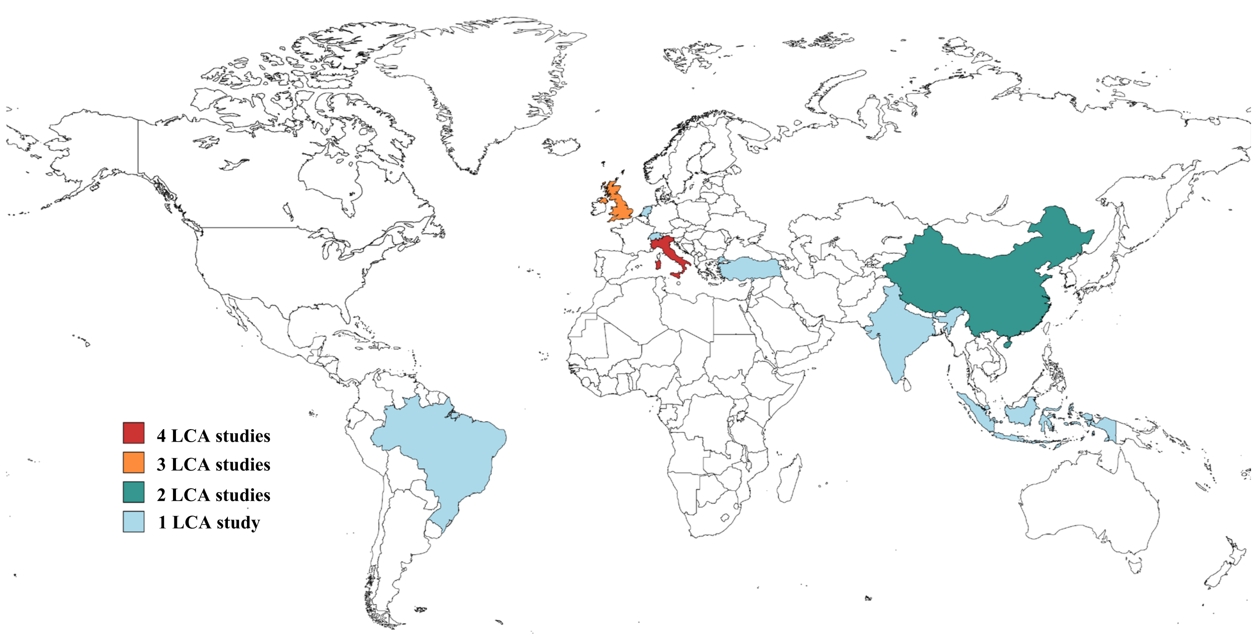

Fig. 3 Pictorial representation of locations selected for existing LCA studies

- Based on the hotspot analyses from existing LCA studies, it can be inferred that it is important to focus research on alternative sustainable raw materials (ideally, locally sourced), reducing transportation impacts, increasing the usable lifetime of facemasks, and sustainable collection and disposal methods.
- The potential benefits of partially/entirely substituting virgin mask materials with recycled or bio-based materials must be evaluated further. Tabatabaei et al. [101] already showed that substituting 10–100% of mask material with bio alternatives can result in a 4–43% reduction in environmental impacts.
- Analytic Hierarchy Process (AHP) techniques can help select a suitable mask material. It is generally used in a complex environment to select the best alternative when numerous variables are involved. Hartanto et al. [113] used AHP to show that quilt and cotton 600 TPI were the best options for non-medical face masks, offering good breathability and filtration efficiency and having the lowest impact among 26 other materials. However, it is yet to be adopted in the industry. Similar studies can be conducted for selecting a sustainable medical facemask material and design.
- Adopting design for environment principles in facemask manufacturing. This includes designing facemasks to consume fewer raw materials while retaining their functionality can significantly benefit the environment. Simultaneously, metal–organic framework such as Zeolitic imidazolate framework-8 [114] and nanofiber membranes, are potential materials that can be integrated into the mask design. This has been shown to improve the functionality of facemasks. Also, the potential of 3D printing utilizing sustainable materials could be explored further [64].
- From the existing studies, it can be seen that only a few evaluated the impacts due to facemask packaging materials. Often times there may be up to four or five layers of packaging, the requirement of which is questionable. As such, sustainable packaging solutions involving recycled materials (like paper) can be evaluated. At the same time, future LCA studies should explicitly evaluate the environmental impacts due to packaging.
- Sustainable waste management and value-addition strategies for used facemasks should be explored. The co-incineration of facemasks and PPE waste could be adopted at the municipal level as it shows the highest energy recovery potential. However, more sustainable options should be studied in the long term. Valorization techniques such as pyrolysis, carbonization, catalytic deformation, or high-solid anaerobic deformation could be utilized to produce building materials, fuel-range hydrocarbons, value-added aromatics, soil stabilizers, cathodes, adsorbent dye carriers, or anode electrodes [84, 115, 116].
- As the environmental benefits of a reusable mask heavily depend on user behavior, it is important to conduct awareness campaigns and provide clear guidance on mask usage to the public.
- Support and invest in research relating to bio-plastic and alternative materials that can replace conventional mask materials. Also, subsidizing bio-plastics in the medical industry through tax incentives or grants could provide extra motivation.

5 Conclusions

Because of the COVID-19 pandemic, there was more demand for PPE like facemasks, which hurt the environment. While there are proper regulatory guidelines relating to the standards and specifications of all medical facemasks, there must be more guidelines on how facemask waste should be managed. This could involve consumer awareness campaigns, revamping waste management infrastructure, or legislative intervention. This paper evaluated the studies involved in the LCA of face masks. All LCA studies show that a reusable face mask is better than a one-time-use face mask. The major process hotspots were the raw material acquisition and manufacturing processes. In cases where international import–export was involved, transportation was a crucial hotspot.

Furthermore, the usage phase of reusable face masks had significant environmental impacts due to the high water and energy requirements for disinfecting the face masks. However, several socioeconomic factors such as facemasks' availability, cost, and personal preferences, influence the wearer's choice in selecting a facemask. Despite the obvious, the environmental impact of face masks is ultimately a function of user behavior. Even though reusable cotton masks are better for the environment, they cannot protect you as well as surgical face masks or respirators. At times like the COVID-19 pandemic user discretion is highly advised in selecting a suitable facemask for themselves. This shows how important it is to do more focused research on waste management and alternative materials like polylactic acid that are biodegradable. It is also crucial to ensure that the biodegradability of such alternative face masks is widely applicable across existing end-of-life options and not under a constrained environment. Literature references have been used to suggest research and policymaking in this field.

Even though the topic was significant, there were only 18 LCA studies for the selected regions. More research is needed worldwide to understand better how face masks work in different places and to help make policy. This paper will likely motivate future research in such an important field.

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Authors' contributions
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Competing interests
The authors declare they have no competing interests.

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