



Life cycle assessment studies to evaluate the sustainability of various facemasks used during COVID-19: A UAE case study

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ABSTRACT

The major hurdle in recovering from the COVID-19 pandemic would be the safe management of plastic waste generated from personal protective equipment and mitigating a plastic pollution crisis. Facemasks were adopted worldwide as the first line of defense against the COVID-19 pandemic, and their demand increased exponentially during the last few years. Through a life cycle assessment, this study aims to evaluate the environmental impacts of various facemasks available in the UAE market. SimaPro software was used to conduct a cradle-to-grave LCA, with a functional unit of "The number of face masks required by a person in UAE over a month (30 days)". Results show that the GWP (in kg CO₂ eq) of 1 FU of surgical FM is 0.867, activated carbon FM is 1.11, N95 FM is 1.55, cloth FM is 0.642, and PLA FM is 0.946. Packaging increases the GWP by 36–178%. Long-distance transportation from China to UAE was identified to be a significant hotspot under GWP and FRS. Other hotspots include polypropylene material in filtration layers, aluminum in nosepieces, electricity usage in cloth masks, and disposal scenarios. Multiple supply chain optimizations are suggested, such as the substitution of recycled aluminum in nose pieces, the use of sustainable transportation, and limiting the use of packaging material to a bare minimum to improve the sustainability of the face mask industry.

1. Introduction

As of October 2022, the World Health Organisation (WHO) estimates over 625.7 million confirmed cases of COVID-19 infection and over 6.5 million confirmed deaths due to the global pandemic [1]. Multiple approaches were collectively enforced to curb the spread of the virus effectively. This included several stages of community lockdown and legislative changes implementing social distancing and promoting the use of personal protective equipment (PPE) [2]. Facemasks (FM) were adopted as the first line of defense against COVID due to their efficiencies, ease of use, and availability [3]. Studies have shown the role of face masks in controlling the spread of COVID-19 [4,5], and the adoption of face mask usage by at least 60% of the population was

determined to be a crucial control strategy in opening up the economy [6]. In 2021, the protective facemask market was valued at USD 23.7 billion. Between the years 2021–2029, the compounded annual growth rate (CAGR) of the facemask market is predicted to be 9.1% [7]. The demand for facemasks over the last two years is apparent from the United Nations forecasting almost 2.4 billion surgical masks alone were needed in 2020 [8]. At the peak of the COVID-19 wave, the demand for facemasks and respirators reached a staggering 240 million masks per day. In contrast, the production capacity of China at that time, which was the largest manufacturer of facemasks, was 20 million masks per day [9].

Currently, multiple types of facemasks are available in the market. Based on their purpose and fabrication these are broadly classified into

Abbreviations: CA, Cellulose Acetate; FM, Facemasks; FPMF, Fine Particulate Matter Formation; FRS, Fossil Resource Consumption; FWET, Freshwater Ecotoxicity; FWE, Freshwater Eutrophication; GWP, Global Warming potential; HCT, Human Carcinogenic Toxicity; HNCT, Human Non-Carcinogenic Toxicity; IO, Ionizing Radiation; LU, Land Use; LCA, Life Cycle Assessment; MET, Marine Ecotoxicity; ME, Marine Eutrophication; MRS, Mineral Resource Consumption; OFHH, Ozone Formation Human Health; OFTE, Ozone Formation Terrestrial Ecosystem; PPE, Personal Protective Equipment; PE, Polyethylene; PET, Polyesters; PLA, Polylactic Acid; PP, Polypropylene; PTFE, Polytetrafluoroethylene; SOD, Stratospheric Ozone Depletion; TA, Terrestrial Acidification; TE, Terrestrial Ecotoxicity; WC, Water Consumption; WHO, World Health Organisation.

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surgical FM, respirators, and cloth FM [10]. The design criteria and quality of surgical FM and respirators are guided by various industry standards. While the fabrication of cloth FM is not regulated by any particular standards making it harder to evaluate its efficacy. Surgical FM prevents the wearer's nose, mouth, or respiratory tract from coming in contact with large airborne particles, droplets, or aerosols having a diameter of $3.0\ \mu\text{m}$ [10]. These are typically used in hospital settings. Respirators are usually prepared to withstand harsher-industrial conditions like dust, mists, biological contaminants, fumes etc. They demonstrate a 95%–99% efficacy against particulate matter size ranging from 0.01 to $0.3\ \mu\text{m}$ [10].

Polypropylene (PP), polyethylene (PE), polyesters (PET), polyamides, cellulose acetate (CA), polylactic acid (PLA), polytetrafluoroethylene (PTFE) membranes, and polymer composites like nylon six are typically being used to manufacture different types of face masks [11]. In the fabrication of face masks, multiple layers of filtration material produced from different polymer feedstock or through different processes could be combined to increase the filtration efficiency of the face mask or to impart a desired characteristic [12]. The typical surgical mask consists of a combination of spunbond (S) absorbent PP fabric inner layer – meltblown (M) electrically charged PP fabric interlayer – spunbond (S) hydrophobic PP fabric outer layer, or an SMS combination of layers. Other commercially available face masks may have a different combination of similar layers, which include SMMS, SS, SM, SSS, and SSMMS. A typical N95 mask has four filtration layers: spunbond PP outer layer – cellulose/polyester second layer – meltblown PP third layer – spunbond PP inner layer. Unlike surgical and N95 masks, there are no standardized criteria for the choice of materials, layering, or threads per inch (TPI) in the assembly of a cloth mask [13]. Ideally, a cloth mask should have a hydrophobic outer layer that could be aesthetically designed, a woven or nonwoven middle layer that facilitates filtration (preferably electrostatic), and an absorbent inner layer that is comfortable [12]. Face mask filters are made from 'nonwoven' materials to provide better particle filtration efficiency and minimal airflow resistance [12]. Three widely used processes to form nonwoven materials include – melt blowing, spunbonding, and electrospinning [11]. All three different processes start with some liquid polymer which is then transformed into fibres forming web-like structures within a single step [12]. Fig. 1 shows the various parts and layers of an N95 respirator mask.

During the COVID-19 pandemic, a 370% surge in plastic demand and

a 40% surge in packaging plastic demand was observed, which heavily impacted the medical waste crisis [14]. However, most countries lack a centralized regulation on the management and disposal of used face-mask waste [2]. Multiple studies across various regions such as New South Wales in Australia [15], Muktagacha Upazila in Bangladesh [16], Chile [17], South Africa, Persian Gulf, Indonesia, Peru, Canada, Kenya, Morocco [3], all show discarded face mask littering roads, ponds, beaches, etc. Due to withering and degradation, this PPE litter breaks down into smaller fragments. Over time these fragments transform into micro- and nano-plastics, compounding the plastic pollution crisis [18].

Multiple artificial withering experiments have been conducted to estimate the extent of microplastic pollution from facemasks. Studies showed up to 173,000 fibers/day can be released from facemasks through ultraviolet (UV) irradiation and agitation [19]. The usage duration also impacted the extent of microfibre release [20]. Surgical facemasks had the highest number of microfibre releases, followed by KF94 and FFP1 masks [14]. Detergents and alcoholic solutions were observed to speed up the degradation process, releasing a higher quantity of microfibrils. These microfibrils from medical-grade polypropylene could take up to 450 years to degrade in nature [21]. Microplastics are a matter of concern as they can quickly enter the food chain and undergo biomagnification [14]. They can be mistaken for food by land and aquatic animals, which reduces their digestive capacity, eventually leading to starvation and death [22]. Marine plastic can also attract contaminants to its surface, forming toxic biofilms which can poison marine animals [2]. A study by Holland et al. [23] reports that microplastics have been found in the intestines of 55% of aquatic birds from freshwater habitats in Canada. This number is predicted to reach 99% by 2050. Once ingested these microplastics can degrade within the human body and release toxic chemicals like organophosphate esters, which hinder the functions of the endocrine, nervous, and reproductive systems. They are also associated with declining semen quality and cause asthma and related allergies [3].

With the constant addition of facemasks and PPE in general into the ecosystem, raising awareness regarding their ill effects and devising suitable minimization and management strategies is essential. Life Cycle Assessment (LCA) is a sustainability tool that provides a comprehensive and standardized analysis of the various environmental impacts of a process or product [24]. The results from an LCA study can identify the process 'hotspots' that cause the significant impacts, which can then be optimized as required or aid policymakers in making sustainable



Fig. 1. Various parts and layers of an N95 respirator mask. (a) Elastic earloops, (b) Nonwoven spunbond PP layer (absorbent), (c) Nonwoven meltblown PP layer, (d) Hot air cotton filter layer, (e) Nonwoven meltblown PP layer, (f) Nonwoven spunbond PP layer, (g) Soft nose sponge, and (h) nose wire.

decisions [25]. Several LCA studies [26–32] conducted to evaluate the sustainability of the facemask industry have identified polypropylene / raw materials in the production phase to be the hotspot in terms of single-use facemasks. All of the literature reviewed found the production phase, including raw material acquisition, processing, and energy consumption to be the major hotspot in the case of single-use face masks. On finer inspection, it can be seen that polypropylene accounts for almost 33%–90% of major mid-point impact categories, followed by aluminum in nose clips with 42%–95% in different mid-point impact categories [28]. The same study showed that polypropylene 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. Transportation was also a major hotspot, especially when it involved importing face masks or their raw materials. While transportation impacts apply to single-use and reusable face masks, it becomes more significant in the case of single-use face masks due to the significantly higher consumption rate [33]. In the studies where end-of-life scenarios were considered, the disposal phase had a significant impact, closely following the manufacturing and transportation phase [27,30,32,34]. Marine eutrophication (ME) and Global Warming Potential (GWP) were the major impact categories for end-of-life scenarios [30].

All the existing LCA studies on FM mainly focus on evaluating the impacts of surgical FM and other forms of FM like cloth FM, N95 FM, and FM with valves. While these are some of the common types of FM, other widely available masks like activated carbon filter FM or a sustainable FM made of polylactic acid (PLA) material are not evaluated yet. As mentioned above, COVID-19 resulted in a 40% in packaging demand. Even then only 7 out of 18 LCA studies included packaging material (cardboard, paper box, LDPE covers, or shrinkwraps) along with their life cycle inventory. However, the corresponding environmental impacts and waste generation from packaging materials have not been evaluated separately. Considering the monumental rise in facemask demand and the fact that facemasks do not come without packaging, it then becomes important to analyse and understand the environmental impacts due to packaging material, which is often left out. Similarly, LCA studies are limited by the geographical region used in the study, to some extent. This is due to the specific datasets, assumptions, and values being used in the study. Hence to understand and evaluate a local scenario, a region-specific LCA study is required. None of the existing studies were conducted for the UAE or the Middle East's geographical region.

The aims of this study are:

- (i) to compare and contrast the environmental performances of activated carbon FM and PLA FM against surgical FM, N95 FM, and cloth FM.
- (ii) to evaluate the environmental impacts due to the packaging of FM.
- (iii) to conduct the LCA study for the UAE region.

2. Materials and methods

2.1. Materials

This study evaluates the life cycle impacts of 5 different facemasks available in the UAE, as shown in Table 1. Four masks have been sourced

online from an e-commerce website. Khalifa University, Abu Dhabi, provided samples of their proprietary PLA mask with antibacterial properties, NAVAmask. The life cycle study is conducted using the SimaPro v9.4 software and the Ecoinvent 3.8 database.

2.2. Goal and scope

The main goal of this study is to evaluate the environmental impacts due to the usage and disposal of a disposable surgical mask, a disposable mask with an activated carbon filter layer, an N95 respirator, a cloth mask, and a Polylactic Acid (PLA) mask available in UAE. Since there are no standards regulating cloth FM, there is a wide variety of FM with different materials and specifications available in the market. For the purpose of this study a representative cloth FM is chosen which is commercially available and has proper external packaging. To be consistent the first four FM are purchased from the same brand. The observations and analyses from this study could aid policymakers, sustainability practitioners, manufacturers, and consumers in making sustainable choices and changes. This aims to soften the impact of the plastic and medical waste management crisis through sustainable changes in manufacturing and disposal moving forward from the pandemic.

This study evaluates the entire face mask usage value chain, starting with raw material production, acquisition, mask assembly, packaging, consumer usage, and end-of-life treatment (disposal). The necessary transportation involved between the various stages is also considered. Hence, the system boundary follows a "cradle to grave" scenario, as shown in Fig. 2.

To determine the functional unit for this study, a less strict and more realistic scenario is considered (adapted from the functional units in [29, 33,35]), owing to relaxed COVID-19 restrictions across the globe. It is assumed that a person uses one single-use mask daily, which is disposed of at the end of its use. In the case of reusable cloth masks, it is assumed that one person has two masks at any time and uses them in rotation. In this case, one reusable mask is used each day, then laundered using a washing machine at the end of every day and left to dry. The second reusable cloth mask will be worn the next day, and the cycle repeats. It is also assumed that both reusable cloth masks are replaced at the end of every month. All face masks are assumed to be disposed of following locally existing guidelines to collect them for end-of-life treatment adequately. Hence, the functional unit of this study will be "The number of face masks required by a person in UAE over the time frame of a month (30 days)", equivalent to 30 single-use face masks or two reusable cloth masks.

2.3. Life cycle inventory (LCI)

The inventory assessment for this study is done through a primary collection of foreground data from mask manufacturers, from product data sheets available online, and by utilizing the background data available in Ecoinvent 3.8 database. All the masks were carefully dissected to their components and filter layers, then weighed using a 'Notebook digital scale' manufactured by United Scales. Most energy consumption data, as mentioned in the life cycle inventory (added in supplementary material), were unavailable through primary data

Table 1
Summary of facemasks used in this study [10,16].

	Surgical FM	Activated Carbon FM	N95 FM	Cloth FM	PLA FM
Testing and Approval	China: YY 0469–2011 US: ASTM F2100–19 India: IS 16289:2014	Same as surgical FM	China: GB 2626–2019 US: NIOSH 42 CFR 84 India: IS 9473:2002	none	Same as surgical FM
Filtration Efficiency	~90%	~90%	80–99%	50–90%	~90%
Price*	6 – 10 AED/ 50 pcs	50 – 80 AED/ 50 pcs	30 – 170 AED/ 50 pcs	10 – 30 AED/ pc	-

* Prices of facemasks are provided for the post-pandemic scenario.

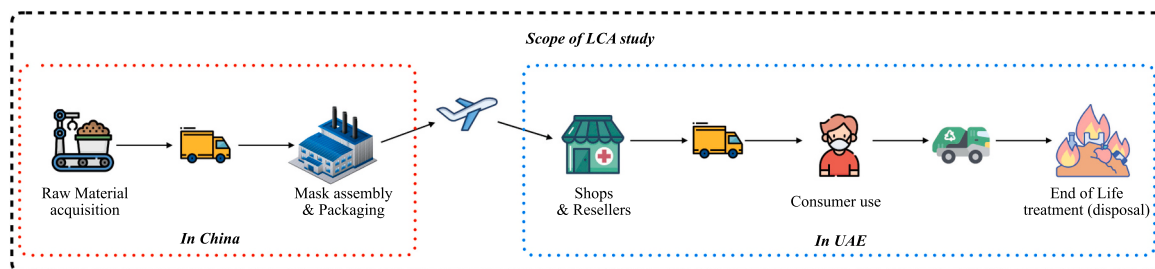


Fig. 2. Scope of the LCA study.

collection; hence approximations have been made by referring to the technical specifications of manufacturing equipment available online. It is assumed that at the end of each day, the used cloth facemasks are laundered in a 7 kg washing machine at half-load capacity (3.5 kg) for one wash cycle [33]. This means that the corresponding resource consumption and impacts due to washing one cloth mask (weighing 12.64 gms) would be 0.36% of the total resource consumption and impacts due to one wash cycle. The PLA mask used in the study is still under the commercialization process; hence, the packaging information was unavailable. The PLA mask also has antibacterial NAVAnanofibres embedded in the filtration layer; however, this was omitted in the study as it was impractical to estimate the weight of nanofibers.

China is the leading producer and largest exporter of face masks globally [36]. This study assumes that all the facemasks are manufactured in China and transported by airfreight to UAE. At the end of the life cycle, the facemasks are collected by municipal authorities at the regional (emirate) level and sent for disposal. The disposal scenario is assumed to be 60% landfilling and 40% incineration based on the medical waste management in Abu Dhabi, published in Waste Statistics by SCAD 2020 [37]. All data collected as part of LCI, the ecoinvent datasets used, and the assumptions made in this study can be found in [Supplementary Material, Tables S1 to S9](#).

2.4. Life cycle impact assessment

The life cycle assessment in the study is conducted following the

ReCiPe 2016 method available in SimaPro. ReCiPe 2016 is an updated version of its predecessors, such as ReCiPe 2008, CML 2000, and Eco-Indicator 99 [38]. Compared to the other methods, this has one of the broadest sets of midpoint impact categories (18), and the impact mechanisms have a global scope. Within the ReCiPe method, a hierarchic perspective is chosen as it is often considered the default perspective and is based on the most common policy principles concerning time frame and other issues [38]. The results from the ReCiPe methods are categorized into two sets of impact factors – at the midpoint and end-point levels. The midpoint level comprises 18 potential impact categories, which evaluates the impacts at various level along the cause-effect chain. They provide detailed insights into the life cycle and aid in identifying potential trade-offs. The end-point level consists of 3 potential impact categories, which calculate the impacts along the cause-effect chain at the end-point. These are easier to interpret; however, the statistical uncertainties at this level are higher. This study evaluates the midpoint and end-point indicators with a heirarchist perspective. [Fig. 3](#) shows the flow model of the LCA conducted in SimaPro.

3. Results

The results from the comparative life cycle assessment at the midpoint level (expressed as percentages of total impact in each category in considering 1 FU of all FM) are shown in [Fig. 4](#). The chart helps to evaluate and compare the relative impact between the different types

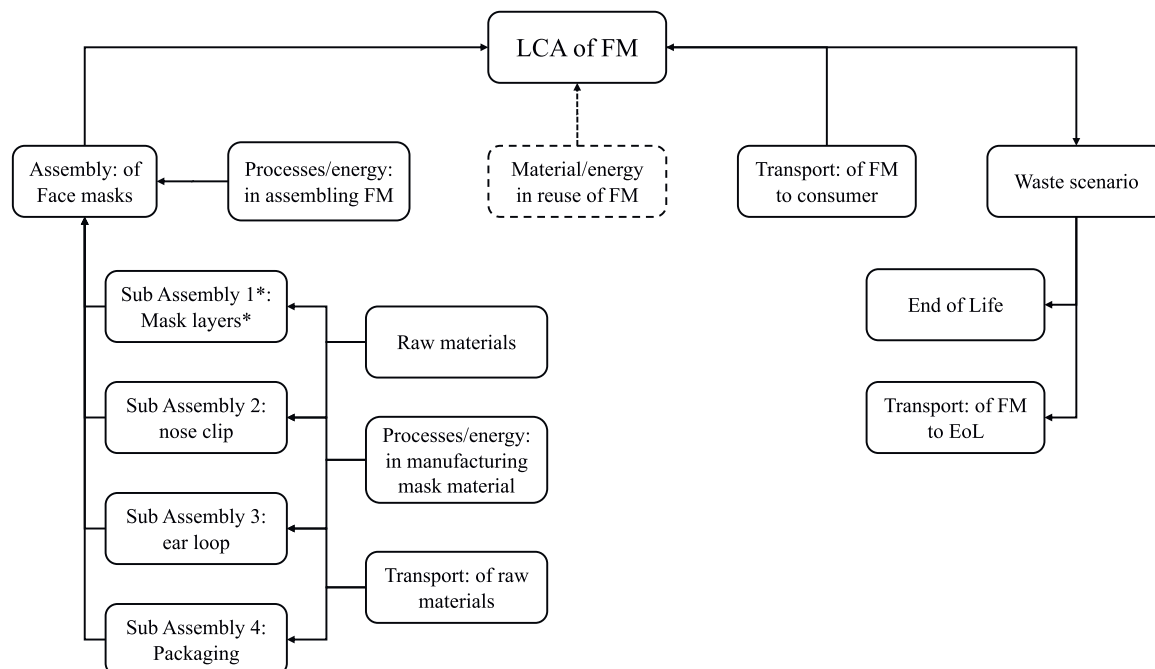


Fig. 3. Flow model of life cycle assessment conducted in SimaPro.

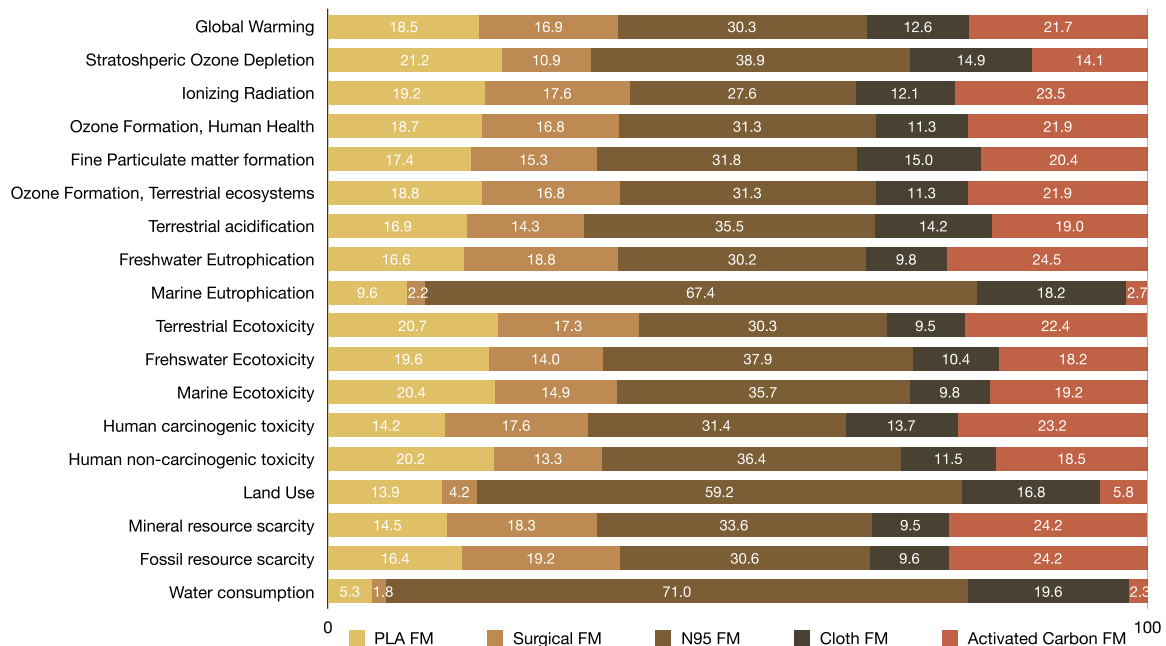


Fig. 4. Midpoint results comparing all 5 types of FM w/o packaging (values shown are in %).

of face masks within each impact category. It is easily identified that N95 FM has the highest impact in all midpoint impact categories. This is followed by the activated carbon FM, scoring the 2nd highest impact in the 11/18 categories. The PLA mask scored 2nd highest impact in the remaining 7/18 categories. Cloth FM displayed the best environmental performance, accounting for the most negligible impact in the 14/18 categories. It can also be noted that the highest environmental impact is under the human carcinogenic toxicity category, followed by significant impacts from freshwater ecotoxicity, freshwater eutrophication, marine ecotoxicity, fossil resource scarcity, water consumption, and global warming potential.

End-point impact categories aggregate the LCA results into three main categories, as shown in Fig. 5. It can be observed that N95 FM again has the highest impact in all three categories. In contrast, cloth FM has the most negligible impact in all three categories. A substantially high impact is seen under the human health category for all FM compared to ecosystems and resources.

Table 2 summarizes the LCA results for various scenarios under the global warming potential impact category. It is seen that when a single piece of FM is considered cloth FM has an 11.1x higher environmental impact in comparison to the least impactful surgical FM. When the disposable and reusable nature of the FM is accounted for, cloth FM becomes the least impactful alternative.

3.1. Human carcinogenic toxicity

Human carcinogenic toxicity is the emission of cancer-causing toxins during the life cycle. From the hotspot analysis, aluminum used to make the nosepiece's core was identified as a significant impact item, with

Table 2

Summary of GWP (Midpoint) results in kg CO₂ eq.

Scenario	Surgical FM	Activated Carbon FM	N95 FM	Cloth FM	PLA FM
One single FM	0.0289	0.037	0.0516	0.321	0.0315
1 FU (w/o packaging)	0.867	1.11	1.55	0.642	0.946
1 FU (w/ packaging)	1.18	1.78	4.32	0.761	-

*w/o – without, w/ - with.

32.2% impact in N95 FM without (w/o) packaging and 37.4% in surgical FM w/o packaging, and 30.5% in activated carbon FM w/o packaging. Filter layer material also contributes significantly to this category. In N95 FM w/o packaging, the polypropylene layers have a 20.16% impact; in surgical FM w/o packaging, the polypropylene spunbond layers have a 19.9% impact; in activated carbon FM w/o packaging, the polypropylene spunbond layers have a 15% impact. The nonwoven polyester material used in earloops is a hotspot in surgical FM w/o packaging (17.8%) and activated carbon FM w/o packaging (12.9%). Packaging only creates a significant change in this impact category for N95 FM (35.1% is packaging) and activated carbon FM (13.1% is packaging).

In the case of cloth FM, in both with (w/) and w/o packaging, the hotspots are electricity consumption (42% and 44.8%, respectively) and the cloth filter layers (cotton and nonwoven polyester), (30% and 34.9%, respectively). The hotspots in this category for PLA FM are the polylactide granules used in the filter layers (45.8%) and the nonwoven

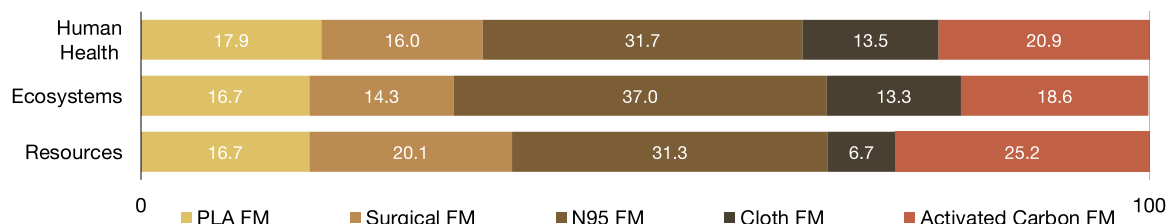


Fig. 5. End-point results comparing all five types of FM w/o packaging (values shown are in %).

polyester earloop (27%).

3.2. Freshwater ecotoxicity

Freshwater ecotoxicity measures the level of toxic chemicals and other substances released into the freshwater, disrupting the ecosystem. In all cases except cloth FM, the FM's disposal scenarios were identified as the significant hotspot. This includes both landfilling and incineration. The impacts were 41.1% and 35.3% for N95 FM w/ and w/o packaging, 41% and 29.8% for surgical FM w/ and w/o packaging, 39.1% and 29.1% for activated carbon FM w/ and w/o packaging and 44.6% for PLA FM w/o packaging. The cotton production in N95 FM (26.9%) and cotton FM (33.6%) are also significant hotspots. Other hotspots include the aluminum used to make the core of the nose piece in surgical FM (21.6%), activated carbon FM (17.9%), the polypropylene spunbond layer in surgical FM (20.5%), in activated carbon FM (18.7%), and the nonwoven polyester in activated carbon FM (17.8%), and cloth FM (15.9%). For cotton FM w/ and w/o packaging, the 2nd major hotspot was electricity (25.2% and 28%) used in its production. The polylactic acid layers had a 37.4% impact on the PLA FM. The packaging material was a hotspot for N95 FM (19.4%) and activated carbon FM (11%).

3.3. Freshwater eutrophication

Freshwater eutrophication refers to the nutrients in the water bodies resulting in an excess supply, eventually creating an algal bloom and polluting the water. The major hotspot for all FM was identified as the disposal scenario, including landfilling and incineration. The respective impacts were 59.3% w/ and 59.3% without packaging in N95 FM, 71.1% w/ and 72.3% without packaging in surgical FM, 67.9% w/ and 70.1% without packaging in activated carbon FM, 44% w/ and 41.5% without packaging in cloth FM, and 61.6% in PLA FM. This is mainly from the treatment and disposal of waste textile materials. The production and use of cotton is also a hotspot in N95 FM w/o packaging (14%) and cloth FM w/ (27%) and w/o (22%) packaging.

3.4. Marine ecotoxicity

Marine ecotoxicity measures the impact of toxin releases on the marine ecosystem. The major hotspot for all FM except cloth FM was identified as the disposal scenario, including landfilling and incineration. The respective impacts were 43.3% w/ and 39.3% without packaging in N95 FM, 42% w/ and 36.4% without packaging in surgical FM, 39.4% w/ and 29% without packaging in activated carbon FM, and 45.5% in PLA FM. This is mainly from the treatment and disposal of waste textile materials. The production and use of cotton were identified to be a hotspot in N95 FM w/ (9.23%) and w/o packaging (18.1%), and cloth FM w/ (36.8%) and w/o (26.2%) packaging. Electricity was also a hotspot for cloth FM w/ (27.5%) and w/o (31.2%) packaging. Other hotspots include aluminum used to make the core of nosepiece in surgical FM w/ (13.5%) and w/o (20.1%) packaging and in activated carbon FM w/ (11%) and w/o (16.8%) packaging. The polypropylene spunbond layers were a hotspot in surgical FM w/ (13.5%) and w/o (14.9%) packaging, in activated carbon FM w/ (10.7%) and w/o (15.3%) packaging. The use of packaging material also has a 20% impact on N95 FM.

3.5. Fossil resource scarcity

Fossil resource scarcity evaluates the fossil resources used in the life cycle and the subsequent "scarcity" it causes. The major hotspot for all FM was identified to be long-distance air transport from China to UAE. The respective impacts were 56.9% w/ and 38.3% w/o packaging in N95 FM, 36.3% w/ and 36.2% w/o packaging in surgical FM, 43.8% w/ and 36.7% w/o packaging in activated carbon FM, 26.7% w/ and 19.6%

w/o packaging in cloth FM, and 48.1% in PLA FM. The polypropylene spunbond layer has a 17.7% impact on N95 FM, 29.1% on surgical FM, and 22.9% on activated carbon FM. Electricity is the major hotspot for cloth FM w/ (34.9%) and w/o (41.1%) packaging. The use of packaging material has a 15% impact on N95 FM, 16.4% on surgical FM, and 12.4% on activated carbon FM.

3.6. Water consumption

The major hotspot for the water consumption category is the textile material in each FM. The impact of hot air cotton in N95 FM is w/ (90.7%) and w/o (96.3%) packaging. In surgical FM, the impact of polypropylene spunbond is w/ (22.9%) and w/o (34.3%) packaging, and the impact of nonwoven polyester is w/ (17.8%) and w/o (26.6%) packaging. In activated carbon FM, the impact of polypropylene spunbond is w/ (19%) and w/o (25.3%) packaging, and the impact of nonwoven polyester is w/ (30.1%) and w/o (40.9%) packaging. In cloth FM, the impact of cotton material is w/ (88.9%) and w/o (90%) packaging. The significant impact in PLA masks is from the polylactic acid layers (81.5%). The use of packaging material has a 32% on surgical FM and 23.5% in activated carbon FM.

3.7. Global warming potential

The major hotspot for all FM was identified to be long-distance air transport from China to UAE. The respective impacts were 49.1% w/ and 38.5% w/o packaging in N95 FM, 40.7% w/ and 40.7% w/o packaging in surgical FM, 45.2% w/ and 40.8% w/o packaging in activated carbon FM, 21% w/ and 14.9% w/o packaging in cloth FM, and 42.3% in PLA FM. The cotton layer has an 11.2% impact on N95 FM and 13% on cloth FM. Electricity is the major hotspot for cloth FM w/ (45.2%) and w/o (52.2%) packaging. The polypropylene spunbond has a 12% impact on surgical FM w/, and the PP meltblown has an 8.59% impact on surgical w/o packaging. The activated carbon FM also has a 12.9% impact from polypropylene spunbond material. The PLA FM has a 26.9% impact from polylactic acid layers. The use of packaging material has an 18% impact on N95 FM and 11.6% on surgical FM. Fig. 6 shows the LCA process network obtained for 1FU of N95 FM without packaging.

3.8. Impact of packaging

While face masks are the primary item of concern, the impacts due to the various forms of packaging materials should not be ignored. Multiple types of structural and aesthetic packages are being used in the life cycle of FM, which severely impacts the product's sustainability. Table 2 and Fig. 7 show that packaging material increases the GWP of N95 FM by 178%, and the packaging material becomes the 2nd most impactful process hotspot (Fig. 8). This is consistent with the other FM, surgical FM – GWP increases by 36%, activated carbon FM – GWP increase by 60.3%, and cloth FM – GWP increase by 18.5%.

Fig. 9 shows a 155.9% increase in human health impacts due to the addition of packaging material. From the previous discussion on hotspot analyses, it can be seen that the use of packaging material significantly increases the impacts and forms the major process hotspots in multiple midpoint categories.

3.9. Scenario Analysis

A case study is conducted using two scenarios to understand the environmental impact of face mask usage in recent years. The peak COVID-19 time is simulated by assuming 75% compliance with face mask usage. It is assumed that 50% of them follow a strict masking regime and 50% follow a relaxed masking regime. The relaxed COVID-19 time is simulated by assuming 60% compliance with face mask usage, and everyone follows a relaxed masking regime. The strict and relaxed

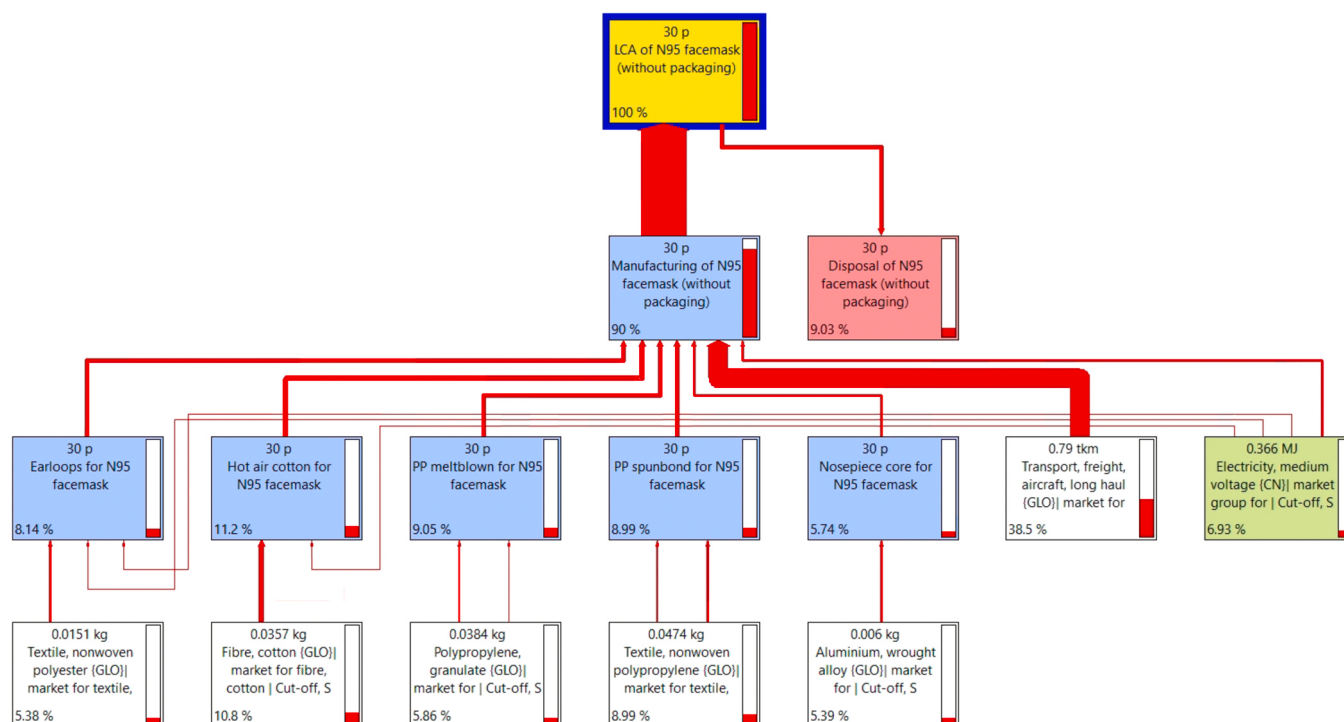


Fig. 6. LCA process network showing the GWP for 1 FU of N95 FM w/o packaging.

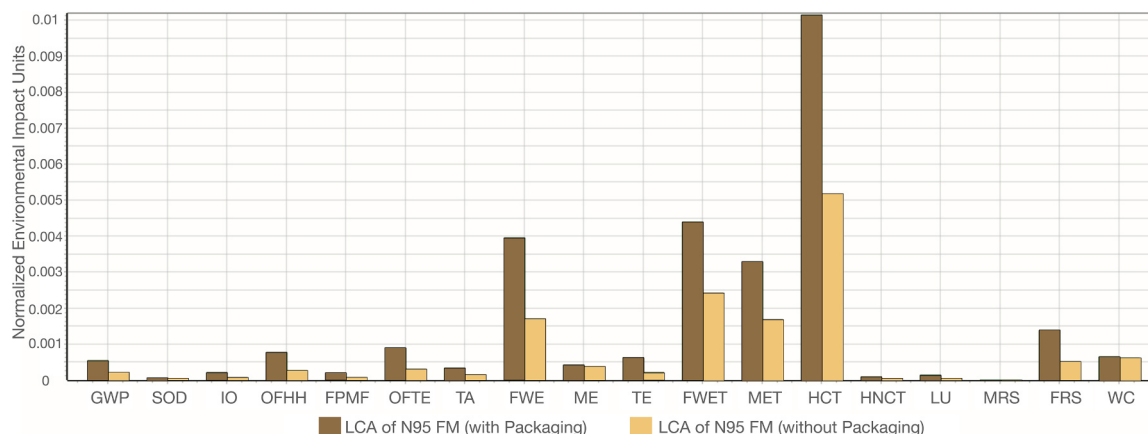


Fig. 7. Midpoint Normalization results comparing N95 FM w/ and w/o packaging. (*GWP – Global Warming potential, SOD – Stratospheric Ozone Depletion, IO – Ionizing Radiation, OFHH – Ozone Formation Human Health, FPMF – Fine Particulate Matter Formation, OFTE – Ozone Formation Terrestrial Ecosystem, TA – Terrestrial Acidification, FWE – Freshwater Eutrophication, ME – Marine Eutrophication, TE – Terrestrial Ecotoxicity, FWET – Freshwater Ecotoxicity, MET – Marine Ecotoxicity, HCT – Human Carcinogenic Toxicity, HNCT – Human Non-Carcinogenic Toxicity, LU – Land Use, MRS – Mineral Resource Consumption, FRS – Fossil Resource Consumption, WC – Water Consumption).

masking regimes are detailed in the [supplementary material](#). It was estimated that in peak COVID-19 time, UAE would need 457.6 million single-use facemasks per month or 38.126 million reusable cloth masks per month. Simultaneously during a relaxed COVID-19 time, UAE would need 183.06 million single-use facemasks per month or 12.204 million reusable cloth masks per month. This data is used to evaluate the GWP for different facemasks, and the results are shown in [Table 3](#). The weight of each FM from the life cycle inventory is then used to determine the total waste generated each month, as shown in [Table 4](#).

4. Discussion

From the results of this study, when an individual piece of face mask is considered, a cloth mask has the highest environmental impact in

terms of GWP. However, in reality, the reusability of cloth FM and the subsequent conservation of resources have to be acknowledged. For a functional unit that accounts for this reusability, cloth FM is the most environmentally sustainable alternative. Yet the actual benefits are a function of user behavior, dependent on the number of reuses, the quantity of detergent and water being used for disinfection, and finally, whether the cloth FM is hand or machine-laundried [\[26\]](#). Switching to a reusable cloth FM from single-use FM, GWP savings between 40% and 74% (w/o packaging) and 17–85% (w/ packaging) can be achieved. This is consistent with Bouchet et al. [\[34\]](#), which showed that 50–90% of GWP savings could be achieved by switching to a reusable FM. Similarly, Morone et al. [\[39\]](#) observed that cloth FM had the most negligible impact in 14/18 of the midpoint impact categories, which is also reflected in this study. The N95 FM had the highest environmental impacts

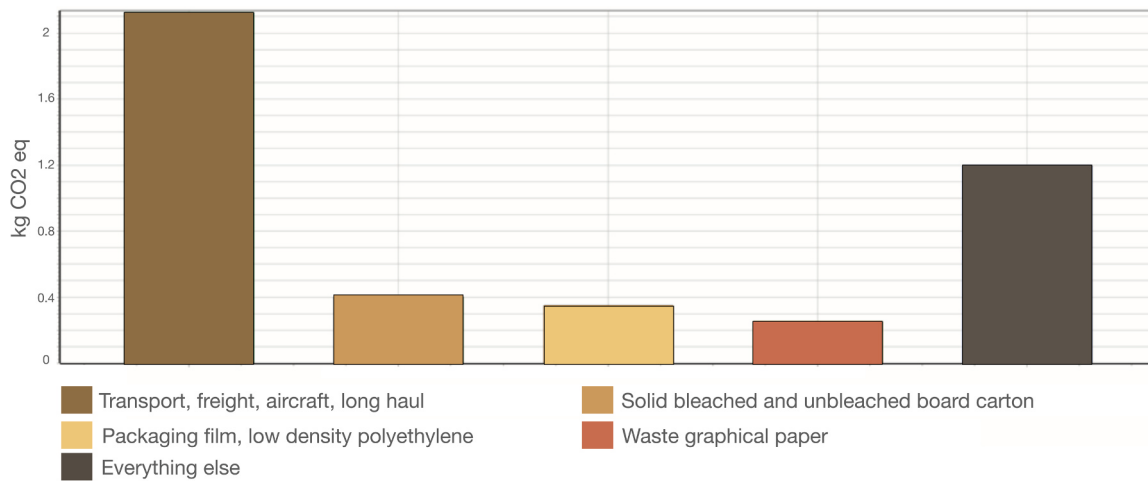


Fig. 8. Midpoint Characterization results showing the process hotspots in N95 FM w/ packaging. (In the figure, 'everything else' represents the cumulative impact from all the remaining parameters that did not have a significant impact in comparison to the other four).

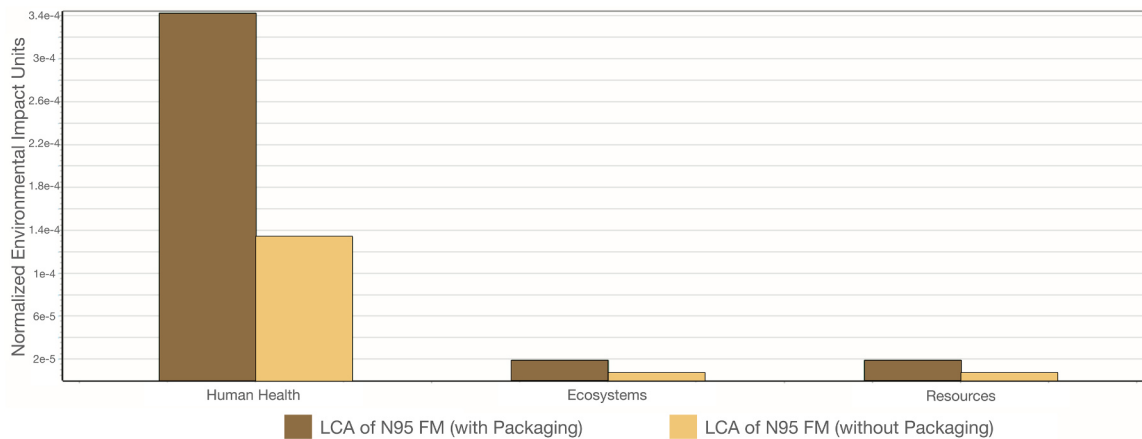


Fig. 9. End-point Normalization results comparing N95 FM w/ and w/o packaging.

Table 3

Summary of GWP (Midpoint) results in kg CO₂ eq/month for case study scenarios for FM w/ packaging.

Scenario	Surgical FM	Activated Carbon FM	N95 FM	Cloth FM
Peak COVID-19 time	1.81E7	2.71E7	6.6E7	1.45E7
Relaxed COVID-19 time	7.22E6	1.08E7	2.64E7	4.64E6

Table 4

Waste Generation per month for case study scenarios for FM w/ packaging (in a million kgs/ month). Total FM waste (FM + packaging waste) and packaging waste are shown separately.

Scenario	Surgical FM	Activated Carbon FM	N95 FM	Cloth FM
Peak COVID-19 time	1.95	3.244	8.6	0.82
Packaging waste	0.524 (26.8%)	1.485 (45.77%)	6.09 (70%)	0.337 (41%)
Relaxed COVID-19 time	0.78	1.29	3.44	0.262
Packaging waste	0.21 (26.9%)	0.567 (43.95%)	2.438 (70.8%)	0.108 (41.2%)

in all categories and was determined to be the least sustainable.

From the literature, three studies have noted the GWP for an individual piece of surgical FM. Turkmen et al. [32] estimated it to be 0.021 kg CO₂ eq, Barbanera et al. [30] estimated it to be 0.0349 kg CO₂ eq, and Giungato et al. [34] estimated it to be 0.0327 kg CO₂ eq. The present study determined the same to be 0.0289 kg CO₂ eq, which is well within the existing range. The study by Lee et al. [40] estimates the GWP due to using 31 single-use FM to be 0.58 kg CO₂ eq and GWP due to an EFL reusable mask to be 0.338 kg CO₂ eq. The difference in single-use FM values is due to the differences in the FM model and assumed manufacturing processes. The packaging materials and transportation distances could also significantly impact the results. The assumptions made during the study design could also be a deciding factor. Another critical factor would be the LCA model and software used in the process. It can be seen that Turkmen et al. [32] used GaBi v10.5 software and CML 2001 method, Barbanera et al. [30] used SimaPro 9.2 and ReCiPe midpoint method, whereas Giungato et al. [34] used OpenLCA software and IPCC-GWP100 method. The EFL masks, however, could not be compared to the cloth FM. Bouchet et al. [35] determined that 30 single-use FM had a GWP between 0.4 and 1.3 kg CO₂ eq, depending on the transportation distance. Hence reusable homemade cotton masks were suggested as the better alternative, again consistent with the present results.

The hotspot analysis in the previous section identified the long-distance air transport of FM from China to the UAE as a significant

factor in fossil resource scarcity and global warming potential. This is mainly due to the excessive need for transportation fuel and the subsequent release of greenhouse gases. In their studies, Allison et al. [32] and Bouchet et al. [34] also identified long-distance air transport as a hotspot. In the long run, the ideal solution would be to invest in and develop the local textile and FM industry. However, for the immediate future, import options from countries that are closer could be considered. Further, biofuels may be considered an alternative to conventional aircraft fuel to reduce transportation impacts. It was observed that almost 50–70% reduction in emissions could be achieved by biofuel blending [41].

The aluminum material used to make the nosepiece's core was also identified as a hotspot in multiple environmental impact categories such as human carcinogenic toxicity, freshwater ecotoxicity, and marine ecotoxicity. This is mainly from the emissions occurring along the aluminum production process from bauxite. To counter this, other possible nosepiece materials like polyvinyl chloride and high-density polyethylene were explored. However, PVC and HDPE may not be able to provide the exact structural support similar to an aluminum nosepiece. A possible solution would be to replace the aluminum material with recycled aluminum. It was observed that a 15.7% reduction in GWP can be achieved by using recycled aluminum. This eliminates the nosepiece material from being a process hotspot. Recycled aluminum can be obtained for almost 35% reduced prices, providing an economic incentive to make the change [42]. However, the possible limitation would be the need to sterilize the recycled aluminum depending on its source.

The petroleum-based polypropylene raw material used to make filtration layers in conventional FM was also determined to be a process hotspot. The PLA FM was suggested in the literature as an alternative with reduced environmental impacts [30]. In the present study, PLA FM performed better than N95 FM and activated carbon FM, but it had a slightly higher environmental impact than surgical FM. This is because the environmental savings in PLA FM are achieved from their biodegradable nature. In this study, the FM is collected at the local/emirate level to replicate the real-life scenario and sent to either municipal landfilling or incineration. This invalidates any potential end-of-life savings from the PLA FM life cycle. End-of-life disposal was also determined to be a hotspot in different impact categories, such as freshwater ecotoxicity, freshwater eutrophication, and marine ecotoxicity. Hence it is preferable to establish a specialized collection and disposal strategy for FM and similar personal protective equipment.

In the case of cloth FM, the two significant hotspots were identified as electricity consumption and cotton material. In this study, the energy requirement data was approximated from product manuals for sewing machines, and the throughput was taken to be four masks per hour, assuming manual intervention. However, in an automated setting with high throughput, the energy requirement would be significantly reduced, improving the product's sustainability. Even with this high energy consumption as per assumptions, cloth FM still performed better than all other FM in almost all categories. The impacts of cotton material are mainly from the excessive water requirement during its cultivation and the use of pesticides and fertilizers [43]. A possible solution would be to use homemade cloth masks from recycled textiles (t-shirts, shirts, etc.). WHO has published guidelines on the requirements of cloth FM made at home [44]. Recycling used cloth material to make FM at home would significantly reduce the impacts of cotton material and energy consumption.

The structural and aesthetic packaging used in FM significantly increases the environmental impacts and is often unnecessary. For example, the cloth FM used in this study had individual film packaging for each FM, which was then packed five into a cardboard box. This box is then wrapped using a shrink film. In the case of N95 FM, the packaging weighs more than the FM itself. While premium packaging can boost sales, the subsequent environmental impacts must also be considered. Table 4 estimates the total waste generated in UAE during

peak covid and relaxed covid times. It can be seen that 27–70% of the waste is just the packaging material. Especially during a pandemic when FM is in high demand, any additional waste burden should be avoided as much as possible. Bulk packaging should be encouraged, and sustainable packaging materials should be pursued. At times of high demand, administrative and legislative supervision on such issues can relieve the community of any excess burden.

5. Conclusions

As part of this study, the environmental impacts of activated carbon FM and PLA FM were successfully compared to that of surgical FM, N95 FM, and cloth FM. It was seen that both the aforementioned FM had a moderate impact in comparison to the other three. The highest impact was observed in the case of N95 FM and was determined to be the least sustainable. Conversely, cloth FM had the least impact in 14/18 midpoint categories and was determined to be the most environmentally sustainable alternative. It is suggested that when new green alternatives like PLA FM are explored, the necessary collection and sustainable end-of-life options are also provided. This is because the environmental savings from the sustainable materials being used could not be fully realized due to the existing conventional end-of-life options. Moreover, this study has clearly shown the impact of packaging material and the subsequent waste generation. From the scenario analysis, it was observed that a reduction of 22–80% in GWP could have been generated if people switched from disposable FM to reusable cloth FM during peak COVID time.

It is to be noted that while cloth FM does provide environmental benefits, it does not provide comparable protection to N95 FM or surgical FM. In situations like the COVID-19 pandemic where the objective is to ensure safety and protection, it may be advisable to use N95 FM or surgical FM as per user discretion. The users are also advised to follow the WHO and local health authority guidelines at all times. It is suggested that future LCA studies could focus on evaluating other biomaterials and multiple end-of-life options. Further, techno-economic evaluations are also required to determine the economic feasibility of biomaterials in facemasks. The findings from this study can act as a baseline in comparing the environmental impacts of different facemasks and their packaging material. The various supply chain modifications suggested could steer the facemask industry toward a sustainable enterprise.

Supplementary Materials

The following [supporting information](#) can be found in the [supplementary materials](#) file, [Table S1](#): Material and mass data for the manufacturing phase of each type of facemask. [Table S2](#): Electricity consumption data for the manufacturing phase of each type of facemask. [Table S3](#): Material data for the use phase of cloth mask. [Table S4](#): Transportation data for all facemasks. [Table S5](#): Ecoinvent datasets used to input the manufacturing phase. [Table S6](#): Ecoinvent datasets used to input the energy requirement. [Table S7](#): Ecoinvent datasets used to input the use phase. [Table S8](#): Ecoinvent datasets used to input the transportation phase. [Table S9](#): Ecoinvent datasets used to input the end-of-life disposal phase. [Table S10](#): Summary of GWP (Midpoint) results in kg CO₂ eq. All LCI assumptions and SimaPro results. References [37, 45–57] are cited in [Supplementary Material](#).

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CRediT authorship contribution statement

Rahaf Ajaj: Conceptualization, Methodology, Investigation, Data

curation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Rania Al Dweik:** Conceptualization, Writing – review & editing, Project administration, Funding acquisition. **Shafeeq Ahmed Syed Ali:** Conceptualization, Methodology, Software, Investigation, Data curation, Writing – original draft. **Mohammed Hashem Stietiya:** Writing – review & editing, Project administration, Funding acquisition.

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.

Data Availability

All the data used in the study can be found in the supplementary file attached.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.jece.2023.110491](https://doi.org/10.1016/j.jece.2023.110491).

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