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Environmental implication of personal protection equipment in the pandemic era: LCA comparison of face masks typologies

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Abstract

In the present global health emergency, face masks play a key role in limiting the diffusion of the COVID-19 pandemic, by acting as physical barriers to avoid droplets and filtrate exhalations coming from infected subjects. Since the most widespread devices are disposable products made of plastic materials, this means that relevant quantities of fossil resources will be consumed, and huge amounts of wastes will be generated. The present paper aims to compare the environmental performances of five different typologies of face masks (i.e. 3D printed reusable mask with filter, surgical mask, filtering face-piece masks – FFPs with and without valve, washable masks), considering an average Italian use scenario and the whole mask lifecycle: materials, manufacturing processes, use, sanitization, and disposal. The Life Cycle Assessment methodology has been used to assess the environmental impacts in terms of both ReCiPe midpoints and endpoints. Reusable masks and masks with interchangeable filters could potentially contribute to improve the environmental performances in all the considered impact and damage categories. Eco-design actions can be developed starting from the study results.

Keywords: face masks; life cycle assessment; personal protective equipment; environmental analysis; waste reduction; COVID-19

1. Introduction and research context

The COVID-19 pandemic caused by the new SARS-Cov-2 virus has infected several millions of people all around the world and this global emergency will continue until an effective medical treatment or a vaccine will be developed and distributed on large scale [1]. It is well known that the virus transmission can occur both for direct/indirect contact (with persons and objects, respectively) and airborne transmission (caused by droplets and aerosol) [2]. However, the latter is probably the most important cause of transmission that takes place because virus is transported from person to person by respiratory droplets (mainly of sizes minor than 5 μm) [3]. In this context, the use of face masks is largely considered the most effective way to protect people from contagion,

containing the basic reproduction number of the infection, [4][5]. A recent study discovered that the correct use of face masks is the determining factor that positively contribute in shaping the trend of COVID-19 infection worldwide [6]. Masks essentially work as physical barriers to avoid droplets and to filtrate exhalations coming from infected subjects [7]. For this reason, face masks should be worn during daily activities by a large part of the world population during the year 2020 and 2021, especially in places with reduced ventilation or confined spaces as airplanes, restaurants, etc. [8][9]. Despite the fact that the focus of governments and people must be on the protection from disease to contain the sanitary emergency, the wide application of face masks is connected to a large consumption of fossil-based materials and generation of large quantities of wastes, a derived environmental issue that should

not be forgotten. Indeed, face masks are generally fabricated using different layers of nonwoven fibers made of thermoplastic polymers (e.g. polypropylene, polyethylene, polyester) [10]. The filtering properties can be also improved by using composites, nanotechnology-based materials or anti-bacterial treatments [11][12]. The product structure of disposable face masks makes the recycling process very complicated, thus also the end of life management is a relevant issue. Even if some sustainable end of life processes are described in literature (e.g. CO_2-assisted thermo-chemical process for the production of valuable fuels), currently, end of life masks are commonly disposed in municipal/sanitary landfills or incinerated with clear impacts on the environment [13]. Moreover, recent studies demonstrated that face masks represent a primary source of sea pollution and can be ingested by higher organisms as fishes, other than representing a potential source of micro-plastics. As it is well known, the latters are very dangerous for microorganisms living in water and can re-enter in the human food chain causing severe health problems [14][15]. Such issue suggests the need to further reinforce policies on single use plastic products, because the existing legislations fail during the present period of sanitary emergency (i.e. the management of disposable plastic face masks) [16]. The extension of product lifetime, through reuse at the end of the first useful life, potentially constitutes a valuable approach toward sustainability in the healthcare sector [17]. This is confirmed by the study from McGain et al. [18] who investigated the benefits of substituting single-use anesthetic equipment with reusable ones. As outcomes they found that considering also "environmental costs" in the choice of healthcare hospital equipment could contribute to both cost savings and environmental benefits in terms of avoided CO_2 emissions. This is the reason why sanitization and reuse are "hot" topics investigated at both research and industry levels. Among the proposed sanitization methods, the most common are the use of ethanol, heat, ultraviolet radiation, ozone, etc. [19]. All of them involves additional processes that should be considered for a comprehensive evaluation of the environmental impacts of face masks lifecycle. Despite the large number of research studies developed in the last months on COVID-19-related topics, few papers are focused on the environmental assessment of face masks production, use and disposal. A recent study by Klemeš et al. [20] developed an energy and environmental footprint study of COVID-19 fighting measures. They conclude that using a proper design, material selection and user guidelines, reusable Personal Protective Equipment (PPE) lead to energy consumption and environmental footprint savings. Also Allison et al. [21] presented a study on the environmental dangers of using single use face masks as United Kingdom exit strategy from the COVID-19 pandemic, highlighting that the adoption of reusable masks significantly reduces the amount of waste entering general waste streams. However, both studies seem preliminary, they are not conducted by following the standard Life Cycle Assessment (LCA) methodology and consider only a CO_2-based indicator.

With the aim to integrate the existing state of the art on the environmental assessment of face masks, the objective of the paper is to present and discuss results obtained through a comparative ISO-compliant LCA study to establish which of the five considered alternative face masks is the most environmentally sustainable considering an average use scenario: (i) M1 – 3D printed mask with changeable filters, (ii) M2 – surgical mask, (iii) M3 – FFP2 mask with valve, (iv) M4 – FFP2 mask without valve, and (v) M5 – washable mask. The ReCiPe impact assessment methodology has been used to quantify impacts at both midpoint and endpoint levels. After this introduction that discussed the research context, the rest of the paper is organized as follows: Section 2 reports the LCA method adopted for the analysis and the related materials, Section 3 presents the results obtained for the 5 mask typologies providing a comparison among the considered alternative models, finally, Section 4 discusses final conclusions and general outcomes of the present work.

2. Materials and Method

During the execution of this project the LCA methodology has been followed, with its four corresponding phases in accordance with ISO 14040 – 14044 and ILCD Handbook: (i) Goal and Scope definition, (ii) LCI – Life Cycle Inventory, (iii) LCIA – Life Cycle Impact assessment, and (iv) Interpretation [22]. Environmental impacts have been calculated using specialized software (SimaPro 9.0.0.49). To determine the LCA goal and scope, the functional unit is defined as follow: *"The use of a face mask that prevents the emission of respiratory droplets, in a pandemic situation (March 2020 – December 2020) for Italian citizens during and after the lockdown phase"*. The specific time frame has been selected starting from initial forecast on the progress of the pandemic situation and supported literature [23]. For the comparative analysis, the reference flow is set as a facial mask made with different materials and different technologies in compliance with UNI EN 149-2009 and UNI EN 14683-2019 standards. The system boundaries include: (i) material extraction and manufacturing phases, (ii) transportation (including the route from materials production to manufacturing and assembly site, and then to the users), (iii) use phase, (iv) maintenance (i.e. sanitization, when it is necessary), and (v) end-of-life. Five different types of masks are considered for this study as depicted in Fig. 1.
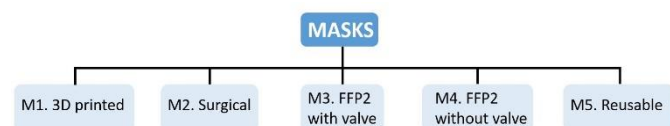

Fig. 1. Masks types studied.

First mask type (M1) is a model printed with 3D technology and uses disposable FFP2 filters. Second mask type (M2) is the surgical mask which needs to be discarded every 4 hours of use. M3 and M4 are FFP2 masks. M3 includes an exhalation valve that helps in breathing, protecting the user from external contamination (i.e., virus), but it does not protect the other persons; conversely, M4 does not have a valve and protects both the user and the other persons. Both devices (M3 and M4) need to be discarded every 8 hours of use. Finally, M5 is a

washable mask that can be reused several times since it maintains its filtering properties for at least 50 washes.

The LCI phase is divided in two parts, the manufacturing-phase and the use-phase. In both cases, all the environmental inputs and outputs associated with the product have been defined. LCI for the manufacturing-phase of the considered reference flow has been carried out by manually disassembling the five considered masks until the constituent materials (mask components). Weight of each component has been assessed by using dedicated equipment. Table 1 reports the LCI of the five different masks.

Table 1. LCI data

Mask type	Image	Material	Weight [g]
M1		PP – Polypropylene (filter)	0,50
		PE – Polyester (filter)	0,50
		PLA (mask)	30,00
		Synthetic rubber (bands)	3,00
M2		PP – Polypropylene (filter)	1,28
		PE – Polyester (filter)	1,28
		Aluminum (nose adapter)	0,44
		Cotton (bands)	0,02
M3		Synthetic rubber (bands)	3,00
		PP – Polypropylene (filter)	5,00
		Aluminum (nose adapter)	0,95
		Polyurethane foam (nose protection)	0,05
		PP (valve)	5,00
M4		Synthetic rubber (bands)	3,00
		PP – Polypropylene (filter)	5,00
		Aluminum (nose adapter)	0,95
M5		PP – Polypropylene (filter)	2,70
		PE – Polyester (filter)	2,70
		Cotton (bands)	1,00

For the inventory definition of the use-phase, the following assumptions have been done considering the Italian scenario:
- Daily need for masks is 40 million [23];
- Study period is 306 days (March 2020 – December 2020);
- Surgical masks have a lifespan of 4 h [24];
- FFP2 masks have a lifespan of 8 h [24];
- Washable masks have a lifespan of 50 washes [25];
- Raw materials are transported by ship (China – Italy);
- Masks are transported by truck inside the country (Italy).

Taking into account all the mentioned data, the need of facial masks required for the chosen time-frame (March 2020 – December 2020) is reported within the Table 2.

For maintenance phase, it has been considered that only M5 – washable mask and M1 – 3D printed mask with changeable filters require a dedicated maintenance. In particular, M5 consumes water, soap and electricity during its washing (by using a washing machine). As well as the M1 – 3D printed mask must be disinfected with ethanol.

Table 2. Masks required in the chosen time-frame

Mask type		Units [million]
M1	Mask	40
	Filter	6120
M2		12240
M3		6120
M4		6120
M5		280

Finally, for the end-of-life (EoL) phase, two different scenarios have been considered. The first scenario foresees that these devices are disposed as special wastes (sanitary landfill) due to their characteristics; while the second one considers them non-sanitary wastes (municipal landfill), due to the fact that most of population in their day-to-day lives can only have this option. Table 3 shows the scenarios studied for each type of mask.

Table 3. End-of-life scenarios

Mask type		EoL Scenario 1	EoL Scenario 2
M1	Mask	Non-sanitary	Non-sanitary
	Filter	Sanitary	Non-sanitary
M2		Sanitary	Non-sanitary
M3		Sanitary	Non-sanitary
M4		Sanitary	Non-sanitary
M5		Sanitary	Non-sanitary

Ecoinvent 3.5 – allocation, cut-off by classification-unit database was used as source of secondary data. ReCiPe was adopted as life cycle impact assessment method. This choice is justified by the fact that the study focuses on the European context (specifically in Italy), and that the ReCiPe can be considered the most appropriate impact assessment methodology to have a comprehensive overview of the environmental loads, by jointly considering a large set of different and heterogeneous indicators. In this case, both midpoints and endpoints were investigated. Midpoint impact categories allow to catch specific impacts on 18 different categories. Endpoints categories include damage on human health (HH), ecosystem (ED) and resources (RA), allowing an easier interpretation of the results for the three mentioned categories.

3. Results discussion

LCA midpoint results are reported in the following tables (Table 4 and Table 5) for non-sanitary end-of-life scenario and sanitary end-of-life scenario respectively (see abbreviations in [26]). Analyzing the results obtained for the first scenario - non-sanitary landfill (Table 4) it can be observed how for all

the impact categories M3 (FFP2 mask with valve) has the highest impact, followed by M4 (FFP2 mask without valve), M2 (surgical mask) and with significantly lower results M1 (3D printed mask with changeable filters) and M5 (washable mask). The impact category in which M3 presents the greatest difference with M4 are fossil resource scarcity – FFP (+36,5%), land use – LOP (+33,9%) and global warming potential – GWP (+32,3%), with average difference of +22,3%. These results reflect the great amount of material (Polypropylene – PP) used to produce the mask which is respectively two times and three times the amount of material used for M4 and M2. In addition, M3 is made by four different materials and a higher number of components (five).

Table 4. ReCiPe Midpoints non-sanitary (NS) end-of-life

Impact category	Unit	M1	M2	M3	M4	M5
GWP	kg CO2 eq	3,9E7	2,7E8	5,6E8	3,8E8	1,5E7
ODP	kg CFC11 eq	1,8E1	6,1E1	1,1E2	8,3E1	2,4E1
TAP	kg SO2 eq	9,9E4	8,1E5	1,5E6	1,1E6	4,5E4
FEP	kg P eq	5,9E3	5,3E4	1,0E5	7,7E4	4,2E3
HTPc	kg 1,4-DCB	8,4E5	1,9E7	2,7E7	2,4E7	5,4E5
HTPnc	kg 1,4-DCB	2,4E7	1,2E8	9,3E8	9,0E8	6,9E6
PMFP	kg PM2.5 eq	3,7E4	3,4E5	5,7E5	4,5E5	2,1E4
TETP	kg 1,4-DCB	4,9E7	2,9E8	4,8E8	4,3E8	1,9E7
FETP	kg 1,4-DCB	1,2E6	1,0E7	3,4E7	3,1E7	4,5E5
METP	kg 1,4-DCB	1,7E6	1,3E7	4,7E7	4,3E7	5,8E5
HOFP	kg NOx eq	6,4E4	5,2E5	9,6E5	6,9E5	2,8E4
EOFP	kg NOx eq	6,7E4	5,3E5	1,0E6	7,2E5	2,9E4
LOP	m²a crop eq	1,6E6	3,8E6	7,3E6	4,9E6	2,8E6
SOP	kg Cu eq	4,1E4	1,1E6	1,5E6	1,4E6	1,7E4
FFP	kg oil eq	1,2E7	7,3E7	1,7E8	1,1E8	4,1E6

Comparing M4 mask with the rest of devices, it is observed how in all cases the greatest differences are found in human non-carcinogenic toxicity – HTPnc (respectively +87% with M2, +97% with M1 and +99% with M5). Other than in HTPnc category, the greatest differences among M4 and M2 (both devices are completely discarded once their lifespan has ended) are observed in marine ecotoxicity – METP and freshwater ecotoxicity – FETP (with +68,6% and +67,2% respectively). The average difference is +35,8%. Comparing M4 with M1 and M5 (both reusable devices), instead, it is observed how the average levels of difference increase to +88,2% and +90,0% respectively. For both cases, the impacts where the greatest difference is observed are: HTPnc (as discussed before), mineral resource scarcity – SOP (+97,0% and +98,8%), marine ecotoxicity – human carcinogenic toxicity – HTPc (+96,4% and +97,7%), METP (+96,0% and +98,6%) and freshwater ecotoxicity – FETP (+96,0% and +98,5%). All the mentioned indicators refer to the toxicity which is mostly related to the product disposal (end-of-life). On the other hand, when analyzing differences between M1 and M5 (the two masks with the lower environmental impacts), it is observed how M1 can be considered the most environmental friendly device in stratospheric ozone depletion – ODP (-33,6%), and land use –

LOP (-78,0%). In all the other indicators the M1 has higher load with greater differences observed in human non-carcinogenic toxicity – HTPnc (+70,5%) and fossil resource scarcity – FFP (+65,8%), with an average difference of +52,8%. For the M5 mask the higher impact is caused by the filters (FFP2 filter made with Polypropylene – PP and Polyester – PE) that requires to be changed regularly, while the PLA – Polylactide mask is produced once at the beginning of the observation period. Since M3 is the device with the highest levels of impact, an in-depth analysis is needed. It can be seen how during its life cycle in almost all categories the greatest impact is due to the volume of masks required and so the overall amount of materials used to produce new masks. Another important issue related to the M3 mask is the end-of-life, indeed, looking at the results for each phase, some indicators (i.e., freshwater ecotoxicity – FETP, marine ecotoxicity – METP and human non-carcinogenic toxicity – HTPnc) present a big gap with the other phases, including the raw materials. Looking at the constituent materials that are used for the M3 mask, the part that has the greatest impact on almost all indicators is the nose adapter (aluminum wire) needed to accommodate the mask to the nose, while the filter has the highest level in terrestrial acidification – TAP and human non-carcinogenic toxicity – HTPnc, and the bends in land use – LOP. Finally, the valve has the highest level in fossil resource scarcity – FFP. This result is confirmed by the analysis of the endpoint damage categories for the M3 mask (Fig. 2), where it is highlighted that the wire has the highest levels followed by the valve and the filter.
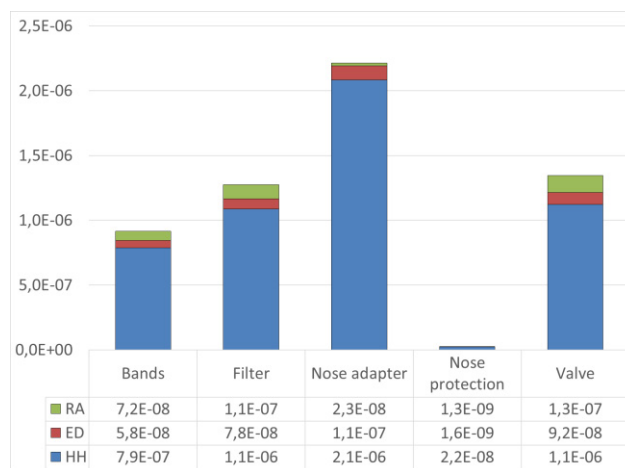

Fig. 2. ReCiPe Endpoints for M3 (split of contributions of mask components)

In the sanitary landfill end-of-life scenario (Table 5), the results are similar to those previously described. Again, M3 and M4 have the highest levels, followed by M2 and with a significant difference M1 and M5. In this case, average difference between M3 and M4 is +26,5%, being the indicators with the greatest difference fossil resource scarcity – FFP (+36,6%), land use – LOP (+34,0%) and global warming – GWP (+31,3%). By analyzing M3 mask in depth, it can be observed how, during its life cycle, the overall amount of materials used to produce the mask causes the highest impacts in almost all categories, except in terrestrial ecotoxicity – TETP, freshwater ecotoxicity – FETP, marine ecotoxicity – METP and human non-

carcinogenic toxicity HTPnc, where it is the end-of-life the phase that impacts the most compared with amount of materials (raw material phase) with a 15,4%, 46,0%, 49,6% and 21,9% of difference respectively.

Table 5. ReCiPe Midpoints sanitary (S) end-of-life

Impact category	Unit	M1	M2	M3	M4	M5
GWP	Kg CO2 eq	3,6E7	2,6E8	5,0E8	3,5E8	1,4E7
ODP	kg CFC11 eq	1,7E1	5,7E1	10,5E1	8,2E1	2,3E1
TAP	kg SO2 eq	9,9E4	8,0E5	1,5E6	1,1E6	4,4E4
FEP	kg P eq	5,9E3	5,3E4	1,0E5	7,7E4	4,2E3
HTPc	kg 1,4-DCB	8,3E5	1,9E7	2,6E7	2,3E7	5,3E5
HTPnc	kg 1,4-DCB	3,6E7	1,7E8	3,4E8	2,5E8	1,1E7
PMFP	kg PM2.5 eq	3,7E4	3,4E5	5,7E5	4,5E5	2,1E4
TETP	kg 1,4-DCB	8,1E7	4,8E8	9,1E8	6,9E8	2,8E7
FETP	kg 1,4-DCB	2,2E6	1,5E7	2,8E7	2,0E7	7,5E5
METP	kg 1,4-DCB	3,1E6	2,0E7	3,9E7	2,8E7	1,0E6
HOFP	kg NOx eq	6,3E4	5,1E5	9,5E5	6,9E5	2,8E4
EOFP	kg NOx eq	6,6E4	5,3E5	9,9E5	7,2E5	2,8E4
LOP	m²a crop eq	1,6E6	3,9E6	7,5E6	4,9E6	2,8E6
SOP	kg Cu eq	4,1E4	1,1E6	1,5E6	1,4E6	1,7E4
FFP	kg oil eq	1,2E7	7,3E7	1,7E8	1,1E8	4,1E6

M4 mask shows higher environmental burden for human non-carcinogenic toxicity – HTPnc (+33,2%) in comparison with M2, and big gap for mineral resource scarcity – SOP (+97,0% and +98,8% in comparison with M1 and M5, respectively). However, the adoption of sanitary landfill is beneficial for M3 and M4 comparing with municipal solid waste scenario, while the outcomes is quite similar for M1, M2, and M5. Environmental impacts for M1 are greater than M5 in all categories except in stratospheric ozone depletion – ODP (-29,9%), and land use – LOP (-77,1%). In particular, a big gap for M1 mask is observed for human non-carcinogenic toxicity – HTPnc (+70,5%), marine ecotoxicity – METP (+67,4%) and freshwater ecotoxicity – FETP (+65,9%), with average difference of +53,6%. Analyzing the results of the endpoints (human health – HH, ecosystems – ED, and resources – RA) it is observed clearly that M3 and M4 masks present the highest load, followed by M2 and with a great difference the M1 and M5. The washable mask (M5) shows the best performance among the other mask types. Same trend is observed in the sanitary end-of-life scenario. Fig. 3. shows the comparison in terms of endpoints of all types of masks studied and the two considered end-of-life scenarios. The non-sanitary landfill (NS) leads to higher impacts for the M3 and M4 masks, in comparison with sanitary landfill (S). For the remaining masks results are quite similar for both the EoL scenarios. This outcome refers to the fact that sanitary landfill provides a credit to the environmental burden coming from the energy production in waste incineration after the special treatment required to sanitize the waste. In particular, M3 and M4 masks produce the highest quantity of plastic waste (i.e. Polypropylene) in the considered timeframe and the adoption

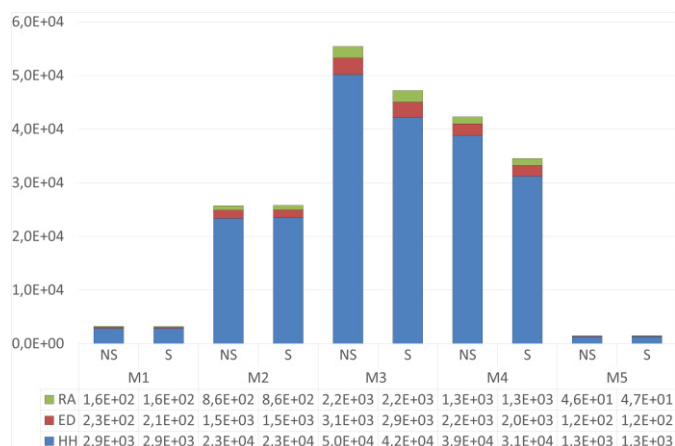of the sanitary landfill as end-of-life scenario is beneficial to the environment.

Fig. 3. Endpoints comparison (non-sanitary– NS vs. sanitary – S landfill)

4. Conclusions

The present work provides a comparative environmental analysis of five different face masks that can be used in the COVID-19 pandemic period: (i) M1 – 3D printed mask with changeable filters, (ii) M2 – surgical mask, (iii) M3 – FFP2 mask with valve, (iv) M4 – FFP2 mask without valve, and (v) M5 – washable mask. The work was carried out by using a ISO-compliant methodology (ISO 14040 – 14044). Results highlight how the most impactful masks, in terms of environmental impacts, are the ones that requires to be discarded after their use (i.e., M2, M3 and M4). In particular, FFP2 masks (M3 and M4) are less sustainable than surgical masks (M2) due to the fact that the amount of material used for their production is more impactful compared with the total amount of masks required in the given time-frame. This issue provides an important insight in the development of eco-design actions oriented to the production of FFP2 that requires a lower amount of raw material (PP and PE). Conversely, it is well-known how FFP2 mask has better performance to prevent the virus from spreading compared with surgical mask. Another important remark about the material used for the production of filters and masks is the possibility to use a single material (i.e., only PP or only PE) to produce non-woven fabric. In particular, the adoption of only PP material for non-woven fabric will allow to decrease the environmental load for M2, M3 and M4 masks. In addition, literature studies demonstrate that PP performs better in terms of droplet blocking efficiency [27].

On the other hand, reusable masks, both M1 and M5 shows very important benefits in terms of environmental burden compared with the other ones. Washable masks seem more beneficial that 3D printed mask, however, several eco-design actions based on the LCA results, can be put in place to reduce the environmental impacts of this type of masks. The first one is the reduction of the filtering area, indeed the reduction of the filtering area is connected with the overall amount of material required to produce the filter. By adopting this action, an environmental benefit is provided both for the raw material phase (less plastic required for filter manufacturing) and for the end-of-life phase (less plastic material to discard). The second

one is related to the manufacturing process. As a prototype, this type of mask is currently manufactured with additive manufacturing technology which is time and energy-consuming. Due to the high volume of mask required to face the pandemic situation, more sustainable manufacturing processes (i.e., injection molding) can be adopted.

Finally, eco-design actions concerning the EoL phase could be focused on two main streams. The first one concerns the possibility to adopt a dedicated EoL scenario for material recycling. As reported in the discussion of the results, a sanitary landfill, which includes energy production from waste incineration is beneficial in particular for M3 and M4 masks. A more promising scenario could be the possibility to recycle plastic materials from this special waste. However, material recycling starting from sanitary waste requires the implementation of a system for waste collection (i.e., "door to door" waste collection system or distributed collecting points) as well as a dedicated treatment to sanitize this kind of waste (to make it "safe" from the sanitary perspective). The second one, strongly related to the first one, concerns the possibility to develop a product structure that facilitates the component disassembly and material separation. In this sense, classic FFP2 masks (as M3 and M4) are very problematic since the different layers and materials are coupled together in a univocal structure, thus it is difficult (or even impossible) to optimize them following the design for disassembly/EoL approach. Regarding surgical masks (as M2), improvements could regard the fixing of aluminum wire and rubber bands in order to favor their disassembly from the core structure of the mask. This latter, instead, could benefit from the use of a single polymer (e.g. PP) that allows an easy recycling. However, the most promising actions could be implemented in case of reusable masks with filters (as M1). The use of a single material, as well as the use of easy to disassemble joints among the structure and the filter support (e.g. snap-fit), allow to improve the recyclability of the mask at the end of its useful life, other than simplifying the maintenance (i.e. filter substitution).

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