Carbon footprint of FFP2 protective facial masks against SARS-CoV-2 used in the food sector: effect of materials and dry sanitisation

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Abstract

Purpose – International outbreak of the SARS-CoV-2 infection has fostered the Italian government to impose the FFP2 protective facial masks in closed environments, including bar, restaurants and, more in general, in the food sector. Protective facial masks are rocketing, both in mass and in costs, in the food sector imposing efforts in fostering reuse strategies and in the achievement of sustainable development goals. The scope of the present paper is to depict possible strategies in manufacturing and reuse strategies that can reduce the carbon footprint (CF) of such devices.

Design/methodology/approach – To implement circular economy strategies in the protective facial masks supply chain, it was considered significant to move towards a study of the environmental impact of such devices, and therefore a CF study has been performed on an FFP2 facial mask used in the food sector. Different materials besides the mostly used polypropylene (PP) (polyethylene (PE), polycarbonate (PC), poly (lactic acid) (PLA), cotton, polyurethane (PUR), polystyrene (PS) and nylon 6,6) and different sanitisation alternatives as reuse strategies (both laboratory and homemade static oven, ultraviolet germicidal irradiation) readily implemented have been modelled to calculate the CF of a single use of an FFP2 mask.

Findings – The production of textiles in PP, followed by disposal was the main contributor to CF of the single-use FFP2 mask, followed by packaging and transportations. PP and PE were the least impacting, PC, cotton and Nylon 6-6 of the same weight results the worst. PLA has an impact greater than PP and PE obtained from

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crude oil, followed by PUR and PS. Static laboratory oven obtained an 80.4% reduction of CF with respect to single use PP-made FFP2 mask, whereas homemade oven obtained a similar 82.2% reduction; UV cabinet is the best option, showing an 89.9% reduction.

Research limitations/implications – The key strategies to reduce the environmental impacts of the masks (research for new materials and reuse with sanitisation) should ensure both the retention of filtering capacities and the sanitary sterility of the reused ones. Future developments should include evaluations of textile recycling impacts, using new materials and the evaluation of the life cycle costs of the reused masks.

Practical implications – This paper intends to provide to stakeholders (producers, consumers and policy makers) the tools to choose the best option for producing and reuse environmentally friendly protective facial masks to be used in the food sector, by using both different materials and easily implemented reuse strategies.

Social implications – The reduction of the CF of protective facial masks in the food sector surely will have relevant positive effects on climate change contributing to reach the goals of reducing CO_2 emissions. The food sector may promote sustainable practices and attract a niche piece of clients particularly sensible to such themes.

Originality/value – The paper has two major novelties. The first one is the assessment of the CF of a single use of an FFP2 mask made with different materials of the non-woven filtering layers; as the major contribution to the CF of FFP2 masks is related to the non-woven textiles manufacturing, the authors test some other different materials, including PLA. The second is the assessment of the CF of one single use of a sanitised FFP2 mask, using different sanitation technologies as those allowed in bars or restaurants.

Keywords Materials, Carbon footprint, Food sector, SARS-COV-2, FFP2 facial mask, Sanitization

Paper type Research paper

1. Introduction

A virus belonging to the coronavirus family, SARS-CoV-2, has been identified concerning a series of severe acute respiratory syndromes in late 2019, initially in Wuhan (PRC) and successively in the rest of the world. On March 11, 2020, the Director-General of the World Health Organization (WHO) declared that the pandemic is now known as COVID-19 (WHO, 2020). As contagion occurs through infected people by spreading droplets of saliva expelled during sneezing, talking and coughing, fundamental means of prevention are interpersonal distancing, hand washing and facial protective masks. Due to masks shortage, textile manufacturers were authorised by the government to produce facial masks, avoiding mandatory quality requirements of personal-protective-equipment (President of the Republic of Italy, 2020). The pandemic severely hit Italy in March 2020, when the country was locked down. Still, recently the use of FFP2 masks, instead of surgical and homemade masks, was mandatory in a closed environment (President of the Republic of Italy, 2021). Due to the ever-growing health risk, the norm establishes that it is mandatory to wear FFP2 masks for shows in theatres, concert halls and cinemas and, for all sports competitions, both in sports halls and stadiums. In all these places, it is also forbidden to consume food and drinks indoors. The use of FFP2 is also mandatory on all means of transportation. The obligation to wear FFP2-type respiratory protection devices was expected in the following cases: for access to aircraft in commercial passenger transportation services, ships and ferries used for interregional transportation services, trains, buses used for passenger transportation services, buses used for rental services with driver, vehicles used in local or regional public transportation services and schools. The use of FFP2 was mandatory in shows open to the public that take place indoors in theatrical halls, concert halls, cinemas, entertainment and live music venues and other similar venues for indoor sports events and competitions, hotels, restaurants and, more in general, in the tourism industry. The mask remains mandatory for workers, guests and visitors of health, social-health and social-assistance facilities, hospitality and long-term care facilities, assisted healthcare residences, hospices, rehabilitation facilities and residential facilities for older adults. The intensive consumption and disposal of facial masks in the food sector have added to the food waste, generating great concerns about the environmental impact of the tourism industry (Amicarelli *et al.*, 2022). Life cycle assessment (LCA) is very promising and reliable and has been used by several authors to evaluate the environmental impact of protective facial masks. An LCA of reusable (polyester-made, by laundry operations) and disposable (polypropylene-made) isolation gowns in a sanitary system demonstrating, considering a functional unit of 1,000 uses of facial masks, the pre-eminence of contribution to the total impact assessment of the production phase of the non-woven textiles composing the multi-layered structure of the mask and that the reusable scenario had a lower environmental impact concerning single-use one (Vozzola *et al.*, 2018). The carbon footprint (CF) of gloves, aprons, face shields and type IIR and IIIR surgical masks made of polypropylene was computed, indicating again that local manufacturing and reuse were key strategies to lower environmental impacts (Rizan *et al.*, 2021). Reuse was suggested as a valuable alternative to lowering energy consumption and the environmental footprint of COVID-19 fighting measures, including masks, provided the efficacy of the fighting measures was retained (Klemes *et al.*, 2020). These results confirm the necessity of reducing the textiles' overall climate impacts by keeping them in use for as long as possible or reusing them (Levänen *et al.*, 2021). Textile recycling consists of reprocessing pre- or post-consumer textile waste for use in new textile or non-textile products, considering that textile reuse and recycling reduce environmental impacts more than incineration and landfilling. Reuse is more beneficial than recycling (Sandin and Peters, 2018), and mono-material products are easier to recycle than multi-material ones (Stahel, 2013). It has been demonstrated that CF of the incineration process of personal protective equipment showed higher figures than disposal in a landfill (Kumar *et al.*, 2021). Textile recycling routes are typically classified as mechanical, chemical or thermal. Facial masks are often discarded before the end of the technical lifespan, as most textiles (EEA, 2021a, b). The Istituto Superiore della Sanità (Italian Higher Institute of Health) suggested including masks coming from households as urban unsorted waste with European List of Waste Code EER 200301, whereas all others to EER 150203 "absorbents, filter materials, rags and protective clothing" (ISS, 2020). Market pressure has increased both the consumption and the production of masks and increased risks of soil and marine pollution from microplastics (Fadare and Okoffo, 2020) and recycled urban green waste (Spennemann, 2022). Disposable single-use masks provide higher protection, although carrying environmental burdens. In contrast, reusable masks have proven to reduce 85% of waste, lower climate change by 3.39 times and reduce cost by 3.7 times concerning disposable single-use masks (Do *et al.*, 2021). CF lowering of 58% was calculated for face masks reused five times (sanitised with steam in an autoclave sterilisation bag that contained up to five masks) compared to single-use disposable ones. However, costs for sanitisation make the two alternatives almost equivalent in economic terms (van Straten *et al.*, 2021). Coronavirus reduced on plastics from 103.7 to 100.6 TCID50 per millilitre after 72 h with an estimated median half-life of approximately 6.8 h, suggesting waiting as a possible reuse strategy (Liao *et al.*, 2020). Sanitisation by washing protective wear in hospitals (the same used during the pre-COVID-19 period) was also studied (Liao *et al.*, 2020). A sanitization method for FFP2 should meet several requirements the effectiveness in killing and inactivating pathogens contaminating the surface, without a related reduction of the filtering performances, the process should ensure the structural integrity of elastic strips and metallic noseband, maintain tight-fitting to the face of the users and decontamination must not leave by-products affecting human health. The sanitisation should be easily available and cheap, safe for the human involved in the process, and in hospitals, scalable to large quantities (Chua *et al.*, 2020). Heating (≤85°C, RH ≤ 100%) is the most promising and non-destructive method of sanitisation to preserve the filtration properties of melt-blown non-woven fabrics. In total, 98.5% of the filtering efficiency of N95 masks was retained after 60 min at 70°C, whereas 92.4% was retained after boiling for 5 min and then air-dried. Elastic laces should be detached and re-stapled to the mask after treatment. Masks' filtering efficiency is reduced by soap by 54% and water or medical-grade alcohol by 67% due to the neutralisation phenomena of electrets on the melt-blown layer (Juang and Tsai, 2020), suggesting dry sanitisation is the best option. UV has proven effective against SARS-CoV-2 in the literature (Gopalan *et al.*, 2021) as an effective decontamination system on the N95 respirator surfaces. For this reason, it has been chosen as a valid reuse strategy to model in this paper. Regarding the use of different materials concerning the most used polypropylene(PP) and polyester (PET), the poly (lactic acid) (PLA) has been used to make nanofibers for filtering facepiece respirators and to make an eco-friendly mask with ionic liquid functionalisation based on quaternary ammonium (Nicosia *et al.*, 2015). Both the spunbond and meltblown technologies used to fabricate the non-woven fabrics used in the assembly of multi-layered FFP2 masks can process a great variety of thermoplastics like isotactic PP, PET, polyethylene (PE), polyamide (Nylon 6 and 6,6), polystyrene (PS), polycarbonate (PC) and polyurethane (PUR). PP is the most widely used by producers because of its low cost and high yield in fibre/kg obtained from raw granulate. PET has tensile strength, modulus and heat stability superior to PP but is more expensive and difficult to process. PE is characterised by good chemical resistance and hydrophobicity, and electrical insulation. Polyamide (including Nylon 6 and 6,6) require more energy and is used for packaging materials. PUR has the required elastic properties for particular applications such as a diaper, medical tape and elastic stuff (Lim, 2020; Midha and Dakuri, 2017; Dutton, 2008). As a gap exists in the scholarly literature about the environmental issues of protective facial masks, particularly on the different materials and sanitisation techniques, in this paper, we have analysed the CF of an FFP2 mask hypothetically produced in the city of Shanghai, starting from production and ending with the disposal. A multi-layered PP-made mask used in the food sector has been reverse-engineered to retrieve the composition and weight of the assembly. Besides the most used PP, different materials composing the mask with the same weight have been modelled as PLA, PC, PE, cotton, PUR, PS and Nylon 6,6. Sanitisation with easily implemented dry processes (dry oven heat and UVGI cabinet) has been chosen to preserve filtering capacity.

2. Materials and methods

The authors decided to study the needs of the food sector as the FFP2 masks were provided directly by workers from a bar/restaurant, the type they use daily. The employed sanitisation techniques analysed in this paper comprise those that can be easily implemented in the food sector (bars and restaurants). CF was determined according to the standard norm (ISO 14067:2018) to evaluate greenhouse-gas emissions released directly or indirectly from the manufacturing of textiles, as indicated in the Kyoto Protocol, including polymer production to transportation, use and disposal (or sanitisation and subsequent disposal). The calculations were conducted using OpenLCA (OpenLCA, 2020a) with OpenLCA impact assessment methods (OpenLCA, 2020b) and the Ecoinvent 3.7 database to retrieve secondary data and background life cycle inventory (Wernet *et al.*, 2016). Data used in the paper are summarised in Tables S1–S3 reported in the supplementary files.

The characterisation step in LCA was performed using the IPCC-GWP100 model, which is included in CML baseline impact-assessment methods to convert direct and indirect greenhouse gas emissions into CO_2 equivalents over a fixed period of 100 years. International standards and guidelines were used (ISO 14040:2006; ISO 14044:2006) to perform the LCA model, considering goal and scope definition, system boundary, life-cycle inventory analysis, life-cycle impact assessment and life-cycle interpretation. The purpose of the work was to evaluate the CF of a single use of an FFP2 mask (Arya HC, T-Tex Srl, Gattico, Novara Italy) made with PP non-woven fabrics; in the case of a reusable mask sanitised with dry heat in an oven or in an ultra-violet germicidal irradiation (UVGI) cabinet, to prevent the transmission of infection, the single-use refers to the use after the sanitisation. Two scenarios were modelled for the public use of FFP2 masks. In the case of a single-use disposable mask, we identified one FFP2 mask as the functional unit, starting from raw textiles followed by transportation to the assembly site (PRC), transportation to the final user, use and disposal by waste incineration and of the packaging in municipal solid waste with energy and metal recovery. The power gained during incineration was reduced, and emissions were allocated to waste treatment processes. To evaluate the convenience of using different materials, assembling a mask with the same weight as the PP one, we modelled other materials such as cotton, PC, PE, biomass-derived LA, PS, PUR and Nylon 6,6. We hypothesised the reuse of masks by sanitising with dry heat (obtained by a static oven, one used in a laboratory and one for home use) and by UV irradiation with a UVGI cabinet. The weight of the single components of the mask that, composed of its different layers, were evaluated with an analytical balance (Ohaus Scout SKX 123, resolution 0.001 g) and component information and materials were obtained from the data fact sheet provided by the manufacturer and by analytical instrumentation as validation experiment, and Table 1 reports the characteristics of the examined FFP2 mask. It should be noted that the filtering power of masks of the type N95 (USA standard), KN95 (Chinese standard), DS/DL2 (Japanese standard) and KF94 (Korean standard) corresponds to the European standard FFP2. For this reason, the calculations made for the mask used in this paper may be extended to all the masks mentioned above belonging to different national standards. The reusable mask was assumed to undergo sanitisation 10 times before being used and then incinerated. For the packaging, a cardboard box that contained the masks wrapped in a polyethylene foil was provided by a logistics company. The cardboard and the foil were weighted, and the mass of the packaging concerning the mass of the mask was evaluated. After the use phase, packaging disposal by incineration in a municipal solid-waste plant was modelled (the base scenario in the city of Bari) with energy and metal recovery. The system boundary of the study is the same for all the modelled scenarios (single-use disposable FFP2 mask made in PP, single-use FFP2 disposable mask made with different materials and single-use FFP2 mask made in PP and sanitised 10 times) to make a valid comparison between the disposable and reprocessing face masks, is reported in Figure 1.

The system boundaries in this study comprised production, use and disposal of the masks; for the sanitised face masks, the life-cycle is extended to consider the sanitisation process. The masks were manually checked before and after sanitisation by workers, and all used masks entered into the working cycle, and none were discarded. LCA was conducted based on a 0% rejection rate of face masks which could not be reused anymore due to defects such as broken elastic laces. Transportation was computed assuming the distance from the textile-production facility to Shanghai port with a small lorry with a max payload of 5 t. The masks were transported from the port of Shanghai to Bari (Italy). The imported masks were packaged and transported to port storage and then to the final users in a range comprising the province of the city (Table 2). As it was supposed that polymer granulated or non-woven fabrics came near the site of production, no modelling of transportation was made for the raw materials. In the analysed scenario, mask manufacturing wastes were not modelled considering their impacts negligible; moreover,

Non-woven textiles	Five layers of spun-bond polypropylene
Mass (g)	5.95
Elastic laces (g)	0.93
Aluminium strip (g)	0.44
Packaging film (g/apiece)	1.49
Cardboard box (g/apiece)	1.81
Manufacturing (kWh/kg)	0.729

Table 1. Characteristics of FFP2 polypropylene mask modelled in this paper

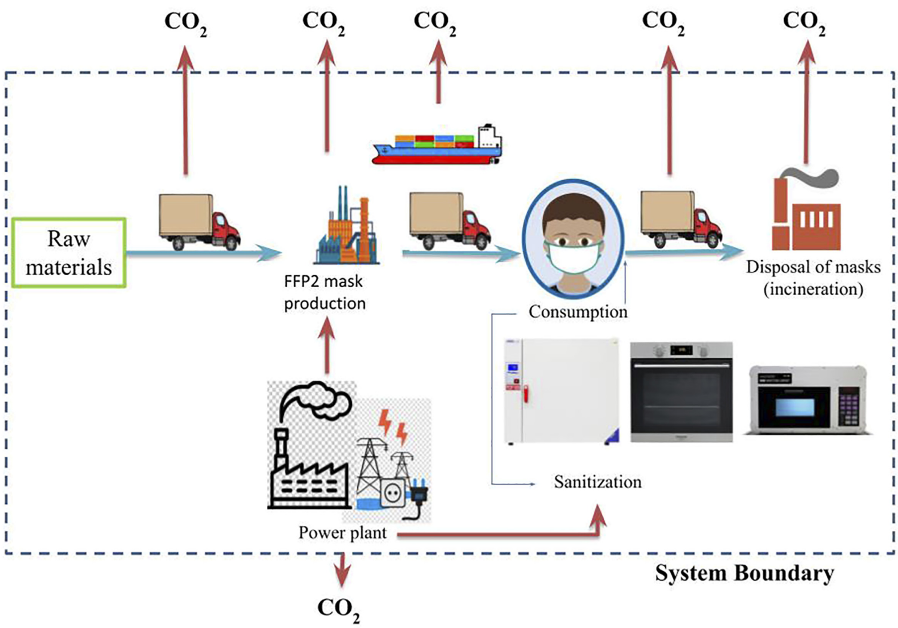

Figure 1.
System boundary

Table 2.
Transportation system of FFP2 polypropylene mask modelled in this paper

From to	Mean of transportation	Distance (km)
Plant – port (Shanghai)	Truck	100
Port (Shanghai) – port (Bari)	Container ship	26,132
Port – storage (Bari)	Truck	100
Storage – user (Bari)	Light commercial vehicle	100

the equipment is assumed to have several decades lifespan, so the environmental impact associated with the fabrication and decommissioning would be proportionally allocated, resulting in negligible. The production of machinery for the sanitisation of face masks was not included in this study for the same reasons above. The used energy mix was the PRC energy grid mix. The mask under examination was assembled by composing five layers of non-woven fabric textiles to ensure enough margins to be considered useful for personal protection against SARS-CoV-2. The mask modelled in this study conformed to the norm (EN 14683:2019). This European standard defines filtering power requirements not applicable to masks intended exclusively for the personal protection of sanitary staff but for personal protective equipment.

In this paper, the examined sanitisation processes were dry sanitisation, by laboratory static oven, homemade static oven and UVGI cabinet, applied to a PP-made FFP2 mask used in the tourism industry. This practice can be carried out up to 10 times, as further sanitisation would lead to a considerable reduction of the filtering power necessary to conform to the norm (EN 14683:2019) and obtain a classification in type FFP2. The choice of dry sanitation derives from the observation that a reduction in the filtering power of wet systems has been found in the literature (washing in an industrial washing machine, washing with hydroalcoholic solutions) due to the neutralisation of electrets present in non-woven fabric (Juang and Tsai, 2020). The masks coming from hospital environments, sanitised by washing, are reusable in the legal status of type I masks for non-sanitary use and distribute to the population to replace cotton and silk masks (Alcaraz *et al.*, 2022). In the case of the static laboratory oven, with a power output of 1.9 kW for a total of 42 min (12 min of preheating and 30 min of sanitising) of operation at 75 °C, eight masks (maximum oven capacity) can be sanitised at the same time, whereas in the case of the household static oven, with a power output 0.89 kW for a total of 35 min and 56 s (5 min and 56 s of preheating and 30 min of sanitisation) operating at 75°C can be sanitised simultaneously four masks (maximum oven capacity). Finally, in the case of the UVGI cabinet, at the wavelength of 254 nm and a power of 8 W for 30 min (no heating time), three masks can be sanitised simultaneously.

3. Results and discussion

The CF of an FFP2 single-use disposable mask made in PP was 32.05 g CO_2 eq with process contributions given in Figure 2, in which the most impactful process is the production of non-woven PP fabric with 11.16 g of CO_2 eq, followed by its disposal, 5.32 g of CO_2 eq, the production of the LDPE film for packaging, 3.98 g of CO_2 eq, the production of a cardboard box for packaging, 2.97 g of CO_2 eq and the production of elastic laces, 2.41 g of CO_2 eq.

It can be noted that transportation (by ship, trucks and commercial vehicle) does not affect (7.2%, 0.52%, 1.29%) the results (about 9% in total). Therefore the hypothesis of moving production locally (Italy) would not have a significant impact on the reduction of the CF: in other words, the zero-km mask, in this case, is not a crucial ecological choice. The result is in line with our previous calculations made on a surgical mask of almost the same weight (Giungato *et al.*, 2021), equal to 32.7 g of CO_2 eq and in alignment with work on gowns

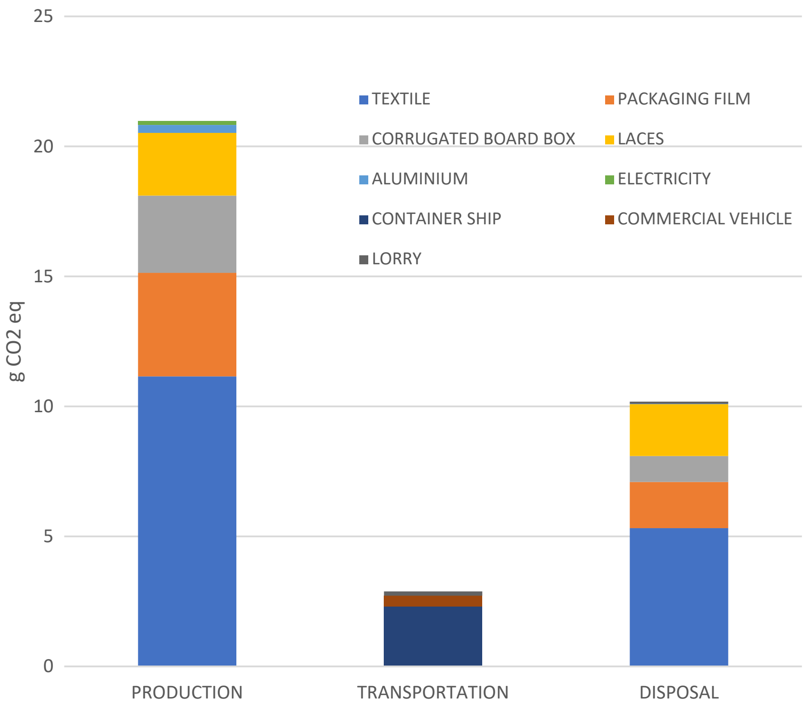

Figure 2.
Process contribution to the impact categories of the FFP2 mask per single use, made in PP

(Vozzola *et al.*, 2018) in which emissions were about 3.60 g CO_2 eq per g of mask versus 5.38 CO_2 eq per g of masks in this work. As a comparison, surgical masks made of PP were estimated to have a range of 22–31 g CO_2 eq per mask (Rizan *et al.*, 2021), whereas on an FFP2 PP-made mask, 30 g CO_2 eq apiece (van Straten *et al.*, 2021). Klemes *et al.* (2020) reported 59 g CO_2 eq per mask, whereas Allison *et al.* (2020) reported 59.5 g CO_2 eq per mask, which is slightly higher for the case under examination. Allison *et al.* (2020) obtained a value that is almost twice what we obtained because they used a completely different functional unit (FU): a year of masks used by the UK population, assuming consumption of 365 masks/year (one mask a day), and single-use surgical masks, made in PP. Such a decision has deeply influenced the final results, which have a higher CF in relation to our results.

Most greenhouse-gas emissions came from textile production (34, 8%), followed by mask disposal (28, 7%), whereas the remaining was allocated to the production of packaging and transportation. Some other processes, such as the disposal of the packaging and the electricity used for assembling and sewing the final product were negligible. The choice of materials is crucial in lowering the CF of masks, considering their life cycle. A more accurate shaping of the mask, the so-called “shape re-engineering” to reduce the area can be accomplished to reduce CF without compromising the filtration capabilities (Salman *et al.*, 2022), Suggested that also laces design and proportion of materials used to fabricate it should be changed (PUR and PET, the two primary chemicals used to manufacture laces, to 20% and 80%, respectively) with significant lowering in environmental impacts. Still, in this study the effect of laces is negligible. To calculate the overall environmental impact of those facial mask productions, if we consider only the case of Italy as an example, it is necessary to calculate the number of masks needed for each person in the country, and some hypotheses were made by Cornelio *et al.* (2022). Assuming that the masks should be changed every eight hours, for workers it was considered two masks per day, for five days/week and one mask/per day during the weekend. For non-workers (both unemployed and inactive persons as pensioners and persons, such as students, who do not seek employment), four masks/week were considered. Children under six years are not required to wear masks, so they were not considered in the study. The total number of masks consumed in one year is about 21.96 billion, but since masks became mandatory from March 2020 until the end of December 2021, 95 weeks, the masks consumed could be estimated as 40.12 billion. Based on these estimates, it can be calculated that a CF of 1,285,846 t CO_2 eq in 95 weeks is related to PP-made FFP2 masks. Analysing the relationship between the CF and materials used for the manufacturing of the non-woven layers composing the mask, PC masks of the same weight as the PP mask showed the highest CF due to the fabric manufacturing process, which includes, amongst the production of the bulk polymer, the presence of very high concerning monomers (see Figure 3).

PP is one of the least impacted, together with PE, which is not primarily used but could be an excellent alternative material to those currently used by industries (PP, PET). Although PLA is a material obtained from biomass (incorporating the environmental credentials of the fixation of CO_2 during photosynthesis), its impact is more significant than PP and PE obtained from crude oil. The production process is complex, requiring several steps and using a lot of raw material, some of which is not incorporated into the final product. The energy consumption for this production is also greater than for other productions. In the case of cotton, although it is a natural cellulose fibre or a renewable raw material, its cultivation has many environmental concerns as irrigation water is required in considerable amounts for its cultivation (Chapagain *et al.*, 2006), pesticides and insecticides are used intensively to fight pests and plant diseases (Indhu Kavi *et al.*, 2018). CF of Nylon 6,6 is slightly lower than that of PC and cotton, followed by PLA, PUR and PS. Analysing the sanitisation process by dry methods, Figure 4 reports the percentage contribution of the sanitisation processes to the impact categories of the FFP2 masks made in PP and sanitised 10 times with a laboratory

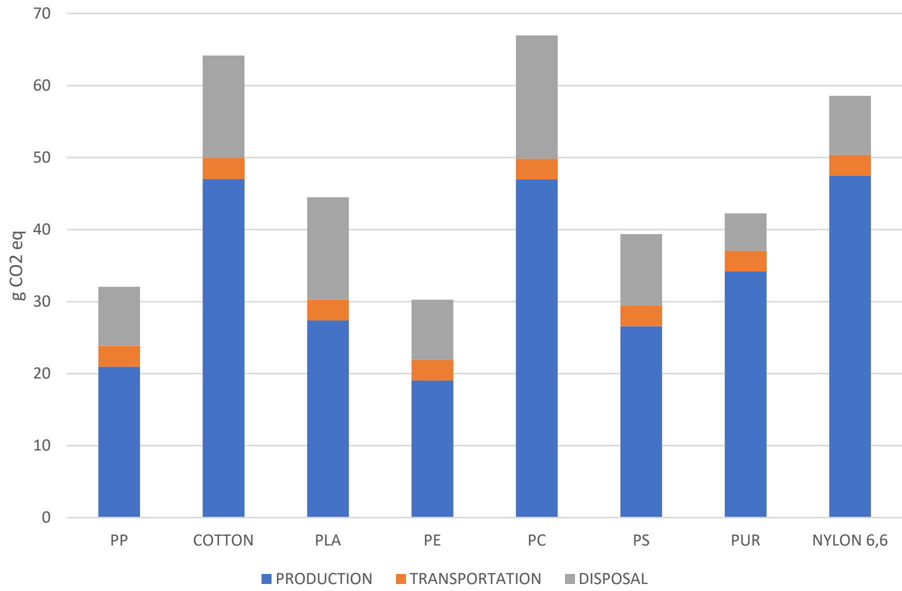

Figure 3. Comparison of process contribution to the carbon footprint of the FFP2 mask per single use made in PP, cotton, PLA, PE, PC, PS, PUR, nylon 6,6 having the same weight

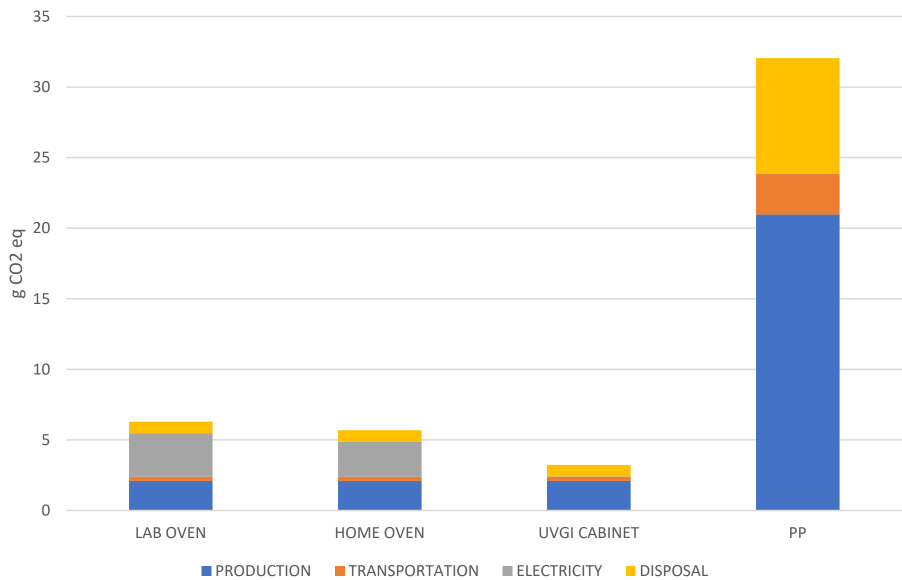

Figure 4. Comparison of process contributions to the impact categories of the FFP2 masks per single use made in PP and sanitised 10 times using laboratory oven, home oven and UV cabinet

oven, home oven and UV cabinet. Electricity consumption has the highest impact throughout the life cycle (approximately 49% and 44%, respectively, for the laboratory oven and the household oven) as expected; the greater electrical consumption of the laboratory oven is due to greater power (little more than double) concerning the home oven and UVGI cabinet.

The amount of CO_2 equivalent calculated for a single use of the mask after sanitisation is significantly lower than that of disposable masks: 6.29 kg of CO_2 equivalent per mask sanitised in a laboratory oven (an 80.4% reduction) and 5.69 kg of CO_2 equivalent for a mask sanitised in a home oven (an 82.2% reduction). Analogue reduction in CF was calculated in the case of autoclave five times sanitised FFP2 masks (van Straten *et al.*, 2021), which reported a 58% CF reduction of sanitised masks concerning single-use disposable ones. Analysing Figure 4, it can be seen how the contributions to the CF of the electricity are higher than of the PP-made single-use mask due to the energy consumption of the static ovens used, except for the UVGI cabinet whose consumption was negligible and the production of the materials remained the most impacting. Sanitisation has a significant impact on the total results of reused face masks contributing significantly, but compared to disposable single-use masks, sanitised face masks, even when including sanitisation and its electricity consumption, remain the scenario with a lower impact on climate change (see Table 3).

As a comparison, Allison *et al.*, 2020 reported a value of 4.13 g CO_2 equivalent for a single use of the mask using average household machine washing, assuming as a functional unit a complete machine wash every three days, which equates to each mask being washed 122 times in one year. Still, in this case, no certainty filtering power is retained with wet sanitisation methods. Despite everything, the disinfection procedure for single use enables a reduction in the CF of the reused mask compared to the disposable single-use mask, which is strictly related to the load capacity and capacity of the disinfection apparatus to deal with large quantities of masks per disinfection cycle.

4. Conclusions

In this work, the CF of an FFP2 mask made in PP and used in the food sector was calculated, modelling production in China (Shanghai), transportation to Italy (Bari), distribution throughout the province and finally, disposal by incineration, analysing the CF. The CF of 32.05 g CO_2 eq per functional unit (one use of an FFP2 disposable PP mask) was calculated. Production of PP non-woven fabric provides the most significant contribution, followed by disposal and transportation. The contribution of transportation (cargo ship, truck and commercial vehicle) was negligible concerning production and disposal (no more than 10%). Analysing the CF of masks having the same weight as the one in PP but made with different non-woven fabrics in the multi-layered structure, such as cotton, PC, PLA, PE, PUR, PS and Nylon 6,6, it was possible to verify that PC and cotton generate a more significant impact followed by Nylon 6,6, PLA, PUR, PS, PP and PE in the same order. Sanitisation in a dry environment, using a static laboratory oven, home oven and UV cabinet, was modelled,

Table 3.
Carbon footprint of protective facial masks per single use

Materials	CF per single-use (g CO_2 eq)
PP	32.05
Cotton	64.02
PLA	44.50
PE	30.30
PC	64.10
PS	39.37
PUR	42.24
Nylon 6.6	58.55
PP sanitised (lab oven)	6.29
PP sanitised (home oven)	5.69
PP sanitised (UV)	3.23

representing an easily implemented reuse strategy in the food sector. The values obtained for the 10 times sanitisation of one FFP2 disposable, PP-made mask are 6.29 and 5.69 g CO_2 equivalent for single use, respectively, for laboratory and home oven, values of an order of magnitude lower than those of the disposable single-use mask, despite electrical consumption. Sanitisation with UVGI cabinet is particularly convenient as consumption is particularly low, with values equal to 3.23 g CO_2 equivalent for single use. Under current conditions, for people working in the food sector (bars, restaurants), it is undoubtedly preferable to opt for the sanitisation of the masks using the dry method in a static home oven without additional costs for the purchase of a new appliance, or a UVGI cabinet with a modest expense, whereas in laboratory environments, it is preferable to use a laboratory oven with higher loading capacity. Research for new materials and reuse with sanitisation are key strategies to reduce the environmental impacts of the masks, provided their filtering capacities are retained. Future developments of this work should include evaluations of innovative materials that are better susceptible to recycling and life cycle costing evaluations to help design for the environment. Reusing facial masks will reduce the use of raw materials and foster the implementation of a circular economy model in the protective facial masks market.

Abbreviations

CF	Carbon Footprint
FFP	Filtering Facepiece
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDPE	Low Density Polyethylene
PC	Polycarbonate
PE	Polyethylene
PET	Polyethylene terephthalate
PLA	poly (lactic acid)
PP	Polypropylene
PRC	People's Republic of China
PS	Polystyrene
PUR	Polyurethane
RH	Relative Humidity
TCID50	Median Tissue Culture Infectious Dose
UVGI	Ultra-Violet Germicidal Irradiation
WHO	World Health Organisation

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Supplementary files

In Tables S1–S3 are shown the secondary data of the processes from Ecoinvent 3.7, used for the construction of the model of the life cycle of the FU.

Table S1. Inventory data related to the production phase of the functional unit

Materials	Amount	Unit	Provider
Polypropylene non-woven fabrics	4.58	kg	Textile production non-woven polypropylene spunbond – RoW
Elastic laces	0.93	kg	Synthetic rubber production – RoW
Aluminium nose	0.44	kg	Sheet rolling, aluminium – RoW
LDPE packaging foil	1.49	kg	Packaging film production, LDPE – Packaging film, LDPE – RoW
Cardboard box	1.81	kg	Corrugated board box production – RoW
Electricity	0.729	kWh	Electricity voltage transformation from medium to low voltage - Electricity, low voltage – CH

Table S2. Inventory data related to the transportation phase of the functional unit

Transportation	Amount	Unit	Provider
Transportation from factory to port of Shanghai	9.25*100	kg*km	Transport, freight, lorry>32 metric ton – ZA
Transportation from port of Shanghai to port of Bari	9.25*26,131.72	kg*km	Transport, freight, sea, container ship – GLO
Transportation from port of Bari to a generic depot	9.25*100	kg*km	Transport, freight, lorry>32 metric ton – ZA
Transportation from a generic depot to the final user	9.25*100	kg*km	Transport, freight, light commercial vehicle, unregulated – ZA

Materials	Amount	Unit	Provider
Transportation from user to waste treatment facility	9.25*100	kg*km	Transport, freight, lorry>32 metric ton, unregulated – ZA
Nose disposal	0.44	kg	Treatment of waste aluminium, sanitary landfill – RoW
Cardboard box disposal	1.81	kg	Treatment of waste packaging paper, municipal incineration – RoW
LDPE foil disposal	1.49	kg	Treatment of waste polyethylene, municipal incineration – RoW
Non-woven fabrics disposal	4.58	kg	Treatment of waste polypropylene, municipal incineration – RoW
Elastic laces disposal	0.93	kg	Treatment of waste rubber, unspecified, municipal incineration – RoW

Table S3. Inventory data related to the end of life of the functional unit

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