Life cycle assessment and circularity evaluation of the non-medical masks in the Covid-19 pandemic: a Brazilian case

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Abstract
This paper aims to evaluate the life cycle impact and the circularity of face masks to support government public policies in extreme consumption of these products as in the case of the Covid-19. The reference case was the Brazilian context for using and consuming Personal Protective Equipment (PPE). Two types of face masks were defined for analysis: handmade reusable face masks made with cotton fabric and single-use face masks made with nonwoven fabric. To achieve this goal, the Life Cycle Assessment (LCA) steps following ISO 14040 and the Material Circularity Indicator (MCI) by the Ellen Macarthur Foundation were applied. The results obtained show that the reuse of face masks has a better environmental performance over five uses. The comparative analysis between the ReCiPe 2016 and IMPACT World+ methods shows that the impact categories linked to human health are the most important in terms of environmental impact. Nevertheless, the trend toward improved environmental performance for the handmade reusable face mask has continued. The possibility of recycling shows that the reintegration of material after the use of the product could improve the environmental performance of both face masks. Finally, the reuse increases the circularity of cotton fabric masks compared to nonwoven fabric masks according to MCI. In this way, it is possible to observe that the handmade reusable face mask has a better environmental performance and a higher circularity than the single-use face mask. Thus, the results of the environmental performance and circularity of the face masks may support the decision of government agents to guide the public in the use of face masks, not only contributing to the protection of health against Covid-19, but also reducing the environmental impact of PPE. Furthermore, the methodological steps adopted in the study gives greater reliability in the conclusions obtained.

Keywords LCA · Circularity evaluation · Non-medical face masks · Personal protective equipment

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1 Introduction

The first official Brazilian case of COVID-19 in the city of São Paulo dates back to February 26, 2020 (Aquino & Monteiro, 2020). The first death occurred just 15 days later, on 12 March, also in São Paulo (G1, 2020). Social isolation was adopted by Brazilian states in mid-March (Urban & Nakada, 2021). However, there has been a linear increase in confirmed cases from March to July (Our World in Data, 2020). And the number of deaths per day remained constant at the level of approximately 1,000 new deaths per day between June and October (Ministry of Health of Brazil, 2020a; Our World in Data, 2020).

With the increase in the number of cases registered, the Ministry of Health of Brazil has released the Informative Note No. 3/2020-CGGAP / DESF / SAPS / MS on April 4, 2020 (Ministry of Health of Brazil, 2020b) in recommending the use of handmade reusable face masks for the general population, as long as they are not affected by influenza symptoms, in environments with a greater flow of people. This is because the demand for medical masks had increased substantially not only in Brazil but worldwide, leading to a shortage of the product on the market. As a result, it was decided to allocate medical masks, N95/PFF2 to health professionals and those who are directly linked to infected patients (Ministry of Health of Brazil, 2020b).

The World Health Organization (WHO), in its Interim Guidance of April 6, 2020 (World Health Organization, 2020a), argued that the use of handmade non-medical face masks has, to date, no scientific evidence in favor of or against its effectiveness as a preventative measure of contagion. The WHO also encourages research in this area and supports policymakers who recommend the use of these non-medical masks by the broader community.

On June 5, 2020, the WHO updated its Interim Guidance (World Health Organization, 2020b), in which it began to recommend the use of non-medical masks (or handmade masks) to the general population in public spaces and public transport, and for those living in impoverished conditions, such as refugee camps, camp-like settings or slums (World Health Organization, 2020b). However, the report emphasized that "the widespread use of masks by healthy people in the community setting is not yet supported by high quality or direct scientific evidence and there are potential benefits and harms to consider" (World Health Organization, 2020b). The guide indicates that the medical masks are recommended for people who have symptoms suggestive of COVID-19 or vulnerable populations, as people over 60 years old, or with underlying comorbidities (cardiovascular disease, diabetes mellitus, chronic lung disease, cancer, cerebrovascular disease, or immunosuppression). (World Health Organization, 2020b). Later, on June 12, 2020, WHO updated the guide by reinforcing prevention by indicating the use of protective masks for the general population, including in public spaces where social distancing is impossible.

Since the publication of Informative Note No. 3/2020 (Ministry of Health of Brazil, 2020b), the Brazilian Secretariats of State and Municipal Governments have initially started to suggest the use of handmade masks for the general population when in agglomerations and then began to demand by decree this conduct of its citizens. State decrees were not synchronized, and the first state to adopt the mandatory use of masks was Rio Grande do Norte, on April 2, 2020 (Sistema FIEB, 2020).

On April 2, 2020, the National Health Surveillance Agency (ANVISA) published a guidance document for the community on the use of non-medical face masks (National Health Surveillance Agency 2020). In this document, ANVISA reinforces all previous Ministry of Health of Brazil recommendations and addresses topics such as recommended
fabric types, production procedures, some form of usage and warning, cleaning, and disposal of masks. The guide explains that: “unlike disposable masks, fabric masks can be washed and reused regularly, but it is advisable to avoid more than 30 washes” (National Health Surveillance Agency, 2020).

By the end of July 2020, the mandatory use of masks by the general population had already lasted around four months for the States that had adopted the measure earlier. However, even after the publication of the decrees imposing usage, part of the population remains reluctant to use them, which led to the adoption of fines by States for non-compliance with the rule, as a measure of the State of São Paulo on July 1, 2020 (Diário Oficial, 2020). On the other hand, another part of the population did not just adopt the mandatory use of handmade masks but also made them as a fashion accessory (Panda Books, 2020), an inseparable part of everyday clothing. This behavior is reinforced by the fact that reusable fabric masks, like underwear, require washing and drying care (National Health Surveillance Agency, 2020), which leads the population to have more than a single-use face mask for daily use.

Artisans and seamstresses played a major role in satisfying this demand. In a conversation with a local artisan in the city of Jaraguá do Sul, a city in the state of Santa Catarina in southern Brazil, on July 17, 2020, she alone had already sewn more than 1200 pieces since May of that year.

According to Rocha (2020), it is estimated that only the city of São Paulo, on the date of publication of the article, has already discarded around 60 million masks. Considering only the Brazilian population over 2 years old, Brazil counts approximately 207 million inhabitants (National Health Surveillance Agency, 2020). If each resident has used an average of three masks per month of the pandemic situation, with the elimination rate shown by Rocha (Rocha, 2020), nearly 1,490 million masks have potentially been discarded in Brazil since the compulsory use began. According to another study by Urban and Nakada (2021), 85 million face masks are discarded each day in Brazil.

Numerous scientific and journalistic articles have brought information and warnings on the negative environmental impacts of the pandemic on a global scale (Zambrano-Monserrat et al., 2020). For example, medical waste has increased considerably (Calma, 2020; Daryabeigi & Vaezi, 2020; Fan et al., 2021; V. Kumar, et al., 2021; Kumar, et al., 2021; Urban & Nakada, 2021). There was also a decline in the conscious consumption of plastic worldwide (Silva et al., 2020). In addition, the mask waste produced during the COVID-19 can be a potential source of plastic contamination in the environment (Fadare & Okoffo, 2020).

In this context, the purpose of this paper is to describe a comparative LCA and the Material Circularity Indicator (MCI) between the two most common types of non-medical masks used during the Sars-CoV-2 pandemic in Brazil: handmade reusable face masks made from fabric 100% cotton and single-use face masks made of nonwoven fabric.

Scientific literature examining and comparing the environmental effects of medical and non-medical face masks are shown in Table 1. This research makes it possible to determine the degree of novelty and to understand the contribution of this publication.

The current literature provides a small number of studies on reusable masks (Giungato et al., 2021; Klemeš, Van Fan 2020; Kumar et al., 2021; Kumar et al., 2021; Rodríguez et al., 2021a; Tabatabaei et al., 2021; Allison et al., 2020), and this number is even smaller for studies of handmade reusable face masks (Lee et al., 2021; Widya & Samti, 2020). It should be noted that these studies also failed to explore the various reuse options for the reusable cotton face mask, and this analysis is relevant.
| Author | Journal | Method | Objective | Results |
|--------|---------|--------|-----------|---------|
| Tabatabaei et al. (2021) | Journal of cleaner production | LCA/IMPACT 2002 + | Identify critical environmental considerations in the production and use of medical face masks. The objective was to provide solutions to minimize negative effects. | The replacement of fossil-based plastics with bio-based plastics, at rates ranging from 10 to 100%, could mitigate the total annual environmental damage of the product by 4 to 43%, respectively. |
| Lee et al. (2021) | Resources, conservation and recycling, | LCA/ReCiPe | Comparison of reusable face masks with an integrated filtration layer (EFL) and a single-use medical mask. | The reusable face mask will emit at least 30% less than the single-use face mask, in terms of waste generated and the impact categories are taken into account. |
| Kumar et al. (2020) | Environment, development, and sustainability | LCA/Método Centrum voor Milieuwetenschappen (CML 2001—janeiro de 2016) | Analyze better disposal options for different PPEs, such as coveralls, gloves, and safety glasses, as well as a face mask. Including landfill and incineration options, both centrally and decentralized. | The incineration process significantly reduced the impact on Human Toxicity Potential (HTP), Eutrophication Potential (EP), Acidification Potential (AP), Freshwater Aquatic Ecotoxicity Potential (FAETP), and Photochemical Ozone Depletion Potential (POCP) over landfill, resulting in a high overall impact of landfilling over incineration. On the other hand, the incineration process has demonstrated strong Global Warming Potential (GWP). |
| Rodríguez et al. (2021b) | Sustainably | LCA/Circularity indicator assessment (MCI). ReCiPe method and cumulative energy demand (CED) | Apply LCA and MCI to evaluate masks (i) 3D printing with interchangeable filters, (ii) a surgical mask, (iii) an FFP2 mask with valve, (iv) a non-valve FFP2 mask, and (v) a washable mask. | Reusable masks (i.e. 3D printed masks and washable masks) are the most sustainable from a life cycle perspective, significantly reducing environmental impacts across all categories. |
### Table 1 (continued)

| Author                  | Journal          | Method                                      | Objective                                                                                     | Results                                                                 |
|-------------------------|------------------|---------------------------------------------|------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------|
| Rodríguez et al. (2021a) | Procedia CIRP    | LCA/ ReCiPe                                 | Compare the environmental performance of five different types of face masks (i.e. 3D printed reusable mask with filter, surgical mask, filter face mask—FFPs with and without the valve, washable masks) | Reusable masks and masks with replaceable filters can potentially contribute to improved environmental performance across all impact and damage categories considered |
| Giungato et al. (2021)  | Sustainably      | LCA / CML baseline impact-assessment        | Compare the environmental impact of a single-use surgical mask made with a polypropylene non-woven fabric (TNT) and a hypothetical reuse situation of mask given the industrial laundry process | Fabric production and disposal were the major contributors to emissions, followed by packaging and transport. A reuse strategy based on the laundry operation was modeled, and the balance between disposal and reuse strategy with the laundry operation (environmental problems caused by the use of detergents and water) was achieved for the second option |
| Klemeš (2020)           | Energy           | Energy consumption analysis                 | Provides an overview of energy sources and environmental footprints in responding to COVID-19. Energy requirements and the use of human resources and protective equipment (PPE) and test kits were discussed. Includes masks and disinfection tests | A suitable design pattern, material selection, and user orientation are recommended. Reusable PPE is an efficient alternative with lower energy consumption and environmental footprint |
| Author                  | Journal                          | Method | Objective                                                                                                                                                                                                 | Results                                                                                                                                                                                                                     |
|-------------------------|----------------------------------|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Allison et al. (2020)   | Environment preprint             | LCA    | Comparison of the environmental impact of the manufacture, transportation, use, and disposal of single-use and reusable face masks                                                                           | Evidence suggests that reusable masks accomplish most tasks in disposable masks without the associated waste stream. Reusable masks are preferred over disposable masks. The use of reusable masks by the general public would greatly reduce plastic waste and the impact of this policy action on climate change |
| Widya and Samti (2020)  | Science of the total environment | AHP    | Use the Analytical Hierarchy Process (AHP) to identify the appropriate material for an ecological non-medical mask                                                                                           | The AHP has a priority rating for all spare materials with duvet and 600 TPI cotton are the best values and meet the demands and characteristics of material required by WHO. Followed by the quilt/cotton with a fabric structure and the polypropylene fabric is the worst material for the production of non-medical masks |
This study presents other developments in the methodology, including (i) the study of Brazilian scenario (ReCiPe 2016 method), (ii) the study of Brazilian versus Global scenarios (BR x GLO) to data of process, material, and energy, comparison between ReCiPe 2016 versus IMPACT World+ and (iii) the study of the hypothetical scenario of recycling masks and the study of the number of reuses (trend). This study is of particular interest as decision support considering three aspects: (a) the selection of the citizens through different types of face masks; (b) the structuring of public rules and policies by governments taking into account the environmental impact of sustainability; (c) and the management of masks waste in the next possible pandemic scenario (United Nations Environment Programme, 2020a).

2 Methodology

This work is divided into two main topics, comparing Life Cycle Assessment of the products handmade reusable face mask and single-use face mask, and evaluating the circularity of these two different non-medical masks.

The LCA was developed according to the principles and guidelines of ISO 14040:2006 (ISO, 2006a). Sections 2.1, 2.2, 2.3, 2.4, 2.5, 2.6 set out the steps of the LCA.

The circularity assessment was conducted using the Material Circularity Indicator (MCI) created by the Ellen MacArthur Foundation (EMF, 2015). This indicator was used because it measures circularity at the product level (Linder et al., 2017; Lonca et al., 2018). The MCI is also considered an important indicator to support decision-makers in the design phase (Moraga et al., 2020), and therefore it can make auxiliary modifications in a product to new versions of it. Finally, the linkage of the LCA and MCI could present an important analysis because the LCA provides a broader scope considering impacts on Human Health and Ecosystem Quality, while MCI can contribute to the improvement of resource use at a micro-scale of the product (Lonca et al., 2018).

The methodology steps of the MCI application are presented on Topic 2.7. Thus, to specify the methodological steps, Fig. 1 presents the sequence of actions in this work. These steps are described in greater detail in Sects. 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7.

![Diagram](https://example.com/diagram.png)

**Fig. 1** Steps of the methodology adopted in the paper
2.1 Goal and system definitions

The purpose of the LCA in this study was to identify and quantify the environmental impacts of the handmade reusable face mask made with 100% cotton fabric and to compare it to a single-use face mask made with nonwoven fabric. It is expected that the results of this objective will support the decision of the population considering the choice for face masks in Brazil and even in other parts of the world as well. In addition, these results can help governments in rules and public policies when considering the environmental bias of sustainability.

Figure 2 shows the boundary of the system studied, considered to be cradle to grave: extraction of raw materials, manufacture of components, use, and disposal.

The main feature of this process is the manufacturing step, particularly the sewing of masks manufactured in small industries such as factions or even at home. For this reason, the product used in this case study is called a handmade reusable face mask. Thereafter, the use and disposal steps differ among the masks studied, primarily because of
the possibility of cleaning and maintenance that allows the reuse of cotton fabric masks is not permitted for the single-use face mask made with nonwoven fabric.

The Ecoinvent 3.6 database was used for extracting raw materials, manufacturing processes, and processed materials. More details about Life Cycle Inventory and Ecoinvent 3.6 use are shown in 2.3.

2.2 Function, functional unit, and reference flow

The main function of non-medical masks is to prevent the transmission of infectious respiratory diseases through the filter of particles. According to the recommendations of the ANVISA (National Health Surveillance Agency, 2020), the maximum period of use of a handmade reusable face mask for a person must be 3 h and 30 reuses. For the single-use face mask, the maximum duration is 3 h without reuses.

In this way, the functional unit defined is 90 h to protect and prevent the transmission of COVID-19. The reference flow chosen is 1 unit of the handmade reusable face mask and 30 units for the single-use face mask.

2.3 Life cycle inventory (LCI)

Tables 2 and 3 show the Life Cycle Inventory (LCI) analysis phase with the parts, materials, processes, and quantities used in the production of the handmade reusable and single-use face masks, respectively. LCI is divided into three phases for each face mask, being their manufacturing, use, and end-of-life (EoL) phase.

In the manufacturing phase, the face masks are similar in size and volume. However, the only difference is in the material used in making the component with the largest weight and representativeness. For the handmade reusable face mask, cotton material was considered. For the single-use face mask, was used the nonwoven material. These are materials that have different mechanical properties and densities, and nonwoven has a higher density. For the remaining parts of these two face masks, the technical specifications of the materials were maintained.

In the use phase, the handmade reusable face mask owns two processes to enable its reuse. On the other hand, for single-use face masks, there are no actions that demand materials and/or energy during this phase.

Finally, in the end-of-life (EoL) phase, both face masks are destined for landfills. However, due to the possibility to recycle the handmade reusable face mask, this EoL also was considered when building the analysis scenarios. More details about these scenarios are shown in 2.5.

As additional information, the cotton material and batch dyed have been adapted to Brazilian electricity (BR). The changes in these processes/materials occurred by applying a cut-off criterion of 5% in the cumulative contribution by the environmental significance (ISO, 2006b; Zampori et al., 2016). Finally, as stated in Sect. 2.2, the Ecoinvent 3.6 database has been used as it is considered the most consistent and transparent database in the world (Ecoinvent, 2020).
| Life cycle phase | Item*/product | Material (Ecoinvent) | Process | Quantity |
|-----------------|---------------|----------------------|---------|----------|
| Manufacturing   | Cotton fabric (4 pcs 15×15 cm) | Textile, knit cotton (GLO) | Textile production, knit cotton, batch dyed | Cut-off, U | 9.72 g |
|                  | Lateral elastic (2 pcs 18 cm) | Polyester resin, unsaturated | Spinning, bast fiber (RoW) | Cut-off, U | 5.67 g |
|                  | Sewing thread (L = 1 m) | Polyester resin, unsaturated | Spinning, bast fiber (RoW) | Cut-off, U | 2.94 g |
|                  | Reusable face mask | – | – | 20.76 g |
| Use             | Iron clothes | – | Electricity, low voltage (BR) | 1.12 kWh |
|                 | Washing house clothes | – | Tap water (BR) | 7.77 kg, 0.019 kWh |
| End-of-life**   | Landfill | – | Municipal solid waste (RoW) | 1 product |
| Recycling       | Avoided materials (Textile, knit cotton, Polyester resin, Synthetic rubber) | – | – | 1 product |

*Item is a part (pcs) of a product (manufacturing phase) or a process (use phase). ** End-of-life (EoL) phase may vary depending on the simulated scenario.
Table 3  LCI to the life cycle of the single-use face masks

| Life cycle phase | Item/Product | Material (Ecoinvent) | Process | Quantity |
|------------------|--------------|----------------------|---------|----------|
| Manufacturing    | Nonwoven     | Polypropylene, granulate (RoW) | Blowing, granulate (RoW) | 5.40 g |
|                   | (4 pcs 15 × 15 cm) | production | 1 Cut-off, U | |
|                   | Lateral elastic | Polyester resin, unsaturated (RoW) | Spinning, bast fiber (RoW) | 5.67 g |
|                   | (2 pcs 18 cm) | production | 1 Cut-off, U | |
|                   |              | Synthetic rubber (RoW) | production | 2.43 g |
|                   |              | 1 Cut-off, U | |
|                   | Sewing thread | Polyester resin, unsaturated (RoW) | Spinning, bast fiber (RoW) | 2.94 g |
|                   | (L = 1 m)    | production | 1 Cut-off, U | |
|                   |              |              | |
| Use               | Single-use face mask | – | – | 16.44 g |
| End-of-life       | Landfill     | – | Municipal solid waste (RoW) | 30 products |
|                   |              | treatment of, sanitary landfill | 1 Cut-off, U | |
2.4 Life cycle impact assessment (LCIA)

LCIA translates the environmental impacts of the life cycle stages for a product or service into a limited number of scores (Huijbregts et al., 2017). This analysis presents a set of environmental impacts indicators by characterizing them in the midpoints and endpoints, which are complementary.

In this context, to assist in the process of data collection and organization, the definition of processes, the registration of materials, and the analysis of the results and graphs, the software SimaPro v. 9.00.49 was used, and the methods ReCiPe 2016 and IMPACT World+ were chosen. Midpoints and endpoints were used in both approaches to analyze environmental impacts.

For Recipe 2016, the following midpoints were examined: Global warming, Stratospheric Ozone Depletion, Ionizing Radiation, Ozone formation (human health and terrestrial ecosystems), Fine particulate matter formation, Acidification, Eutrophication (freshwater and marine), Ecotoxicity (terrestrial, freshwater, and marine), Carcinogenic and Non-carcinogenic toxicity, Land use, Mineral resources, Fossil resources, and Water consumption. Furthermore, the following endpoints for this method were analyzed: Human Health, Ecosystem, and Resources Consumption. For the normalization and weighting processes, the set of factors World 2010 H (PRé Sustainability, 2020) has been used in this study.

The choice of the ReCiPe 2016 was made because it provides global scale factors and shows the impact of water consumption in the midpoint category (Huijbregts et al., 2017). The direct visibility of the impact of water consumption is important in this case study as the handmade reusable face mask requires washing during its life cycle, as recommended by ANVISA (National Health Surveillance Agency, 2020). Furthermore, ReCiPe 2016 owns a high number of impact categories providing a holistic assessment to evaluate products (Ferrara & De Feo, 2020).

In addition, the IMPACT World+ has been used to compare results with the ReCiPe 2016 method. This method is the first regionalized method worldwide that incorporates the latest developments in LCIA research, increasing the accuracy of the LCA impact assessment (Bulle et al., 2019). In other words, IMPACT World+ presents regionalized indicators (Bulle et al., 2019), the region of resource extraction or emissions, for example, has a major effect on the impacts generated. This is a global approach, covering data from around the world.

IMPACT World+ combines indicators of damage to human health, ecosystem quality, and ecosystem services and resources. However, it adds impacts from water and carbon emissions on human health and ecosystem quality. Thus, the impacts of water use on human health and the long-term effects of marine acidification on the ecosystem are also evaluated as global potential damages. Finally, short- and long-term damage indicators are also presented (the latter, more than a century after their issuance) (Bulle et al., 2019).

For IMPACT World+, the following midpoints were considered: Climate change, Fossil, and nuclear energy use, Mineral resources use, Photochemical oxidant formation, Ozone layer depletion, Freshwater ecotoxicity, Human toxicity (cancer and non-cancer), Water scarcity, Acidification (freshwater and terrestrial), Eutrophication (freshwater and marine), Land transformation, Land occupation, Particulate matter formation, and Ionizing radiations. Furthermore, the following endpoints were analyzed: Human Health and Ecosystem quality. For the normalization and weighting processes, Stepwise 2006 values (Weidema, 2009) have been used in this study.

It is important to note that the second approach of the LCIA method (IMPACT World+) was chosen to evaluate an alternative response to potential environmental impacts and,
consequently, validate the results taking into account the convergence between these results obtained for each method. This procedure is aimed at increasing the reliability of the LCA results.

2.5 Sequence of analysis in this study

This study was organized in a sequence of analyses to obtain greater reliability in the results of the potential of environmental impacts, and also to endorse the decision of potential stakeholders (citizens and governments) in the results of this study.

First, the two different types of non-medical face masks relevant for evaluation have been defined, taking into account the current situation of their use in Brazil. In this context, handmade reusable face masks and single-use face masks were selected to assess the potential environmental impacts and their circularity.

In the sequence, 5 different steps of the analysis in LCA were defined according to Fig. 3.

- **In step 1 (Study of Brazilian scenario (ReCiPe 2016)), the comparison between the handmade reusable face mask and the single-use face mask was made simulating the environmental impact with the ReCiPe 2016 method. The composition of the Brazilian scenarios in this step was made by considering the face masks with different disposal situations: handmade face mask with landfill EoL phase, handmade face mask with recycling, and single-use face mask with landfill. About handmade face masks with recycling, the avoided materials in this approach are shown in Table 2. This first analysis is intended to produce a first idea of the environmental impact of the scenarios and to understand the reasons behind this result.**

- **In step 2, the behavior of the reuse was analyzed considering that the handmade reusable face mask could have up to 30 reuses while a single-use face mask is disposable. Thus, the following simulations were carried out to understand the influence between the number of reuses of the handmade reusable face masks, and their environmental impact: 1, 5, 10, 15, 20, 25, or 30 single-use face masks vs. 1 handmade reusable face mask with landfill or recycling in the EoL phase.**

- **In the sequence, given that one of the limitations of this study is not consider the logistical processes throughout the life cycle of each face masks life, step 3 aims to understand the behavior of the environmental impact when reviewing global data in Ecoinvent with Brazilian scenario data. The global data in Ecoinvent usually uses logistics processes for the global market.**

- **In step 4, the results of the LCA have been confirmed. In this context, it was used another global LCIA method for simulating the environmental impact, namely IMPACT**

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**Fig. 3 Sequence adopted to the LCA analysis**
World+. This enables an understanding of the trends in environmental impact predicted by the two different methods (ReCiPe 2016 and IMPACT World+), to make the conclusions of the results of the LCA clearer and more precise.

Finally, step 5 was made to analyze a hypothetical situation in which a single-use face mask can be recycled. As that the handmade reusable face mask owns the possibility of recycling, it was created this last scenario to analyze whether recycling would be a process with significant environmental impact results to improve the performance of the nonwoven fabric mask or not. This analysis allows consequently us to understand whether a single-use face mask could have a lower environmental impact than handmade or not.

2.6 LCA assumptions and limitations

For this paper, transport analysis is a step out of scope. However, Sect. 3.3 complements the study to identify the impact of the logistics and consumption scenario by considering a global average (GLO).

The nonwoven and cotton materials have been defined for convenience as they are the most recommended for making handmade reusable face masks.

Recycling scenarios, however, have been considered in this study as hypothetical scenarios since medical and government guidelines do not suggest this possibility.

Additionally, for handmade reusable face masks, new processes have been created in SimaPro: washing, ironing clothes, and sewing machine at home.

2.7 Circularity evaluation

The circular economy is a systemic perspective aimed at decoupling economic growth from practices of extraction, use, and disposal, a current and unsustainable model, then known as the circular economy. It is intended to improve practices and ensure the sustainability of reuse and recycling of materials, component refurbishment, and design to increase service life and facilitate maintenance (EMF, 2015). In this respect, this study presents the results of simulations conducted with handmade reusable face masks and single-use face masks using the Material Circularity Indicator (MCI) developed by the Ellen Macarthur Foundation (EMF, 2015). The MCI is an indicator of circularity that helps companies to improve their product design and material supply. This tool takes into account the amount of recycled raw material added to the virgin raw material (Recycled Feedstock;), the ratio of material/product sent for recycling (Recycling Collection Rates), the variable $E$ which represents the efficiency of the recycling process (Recycling Process Efficiencies), the useful life of the product (Utility Lifetimes and Functional Units), how much the product may be shared during use (Shared Consumption Business Models) and the consumables associated with to the product (Consumables Related to a Product). (EMF, 2015).

Equation 1 (adapted from EMF, 2015) presents the main variables to obtain the MCI result. In Eq. 1, $F_R$ is the percentage of recycled feedstock, $F_U$ is the percentage of reused feedstock, $C_R$ is the percentage of recycling in the end-of-life phase, $C_U$ is the percentage of reused in the end-of-life phase, $E_F$ is the efficiency in the percentage of the recycling process to produce the recycled feedstock, $E_C$ is the efficiency in the percentage of the recycling process to transform the product after use in recycled material, and $X$ is the lifespan to the product in analysis.

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To obtain each variable of Eq. 1 and consequently calculate MCI for each face mask, LCI elaborated to the life cycle assessment method has been used. The numbers for each variable are shown in Sect. 3.6.

Finally, it is worth noting that the MCI is widely used to measure product circularity (Saidani et al., 2019) because it considers the amount of virgin and not virgin raw materials, recycling efficiency, and unrecoverable waste, in addition to considering the duration and intensity of use of the product over its lifetime or functional unit (Parchomenko et al., 2019).

Thus, this study aimed to simulate the circularity of products handmade reusable face masks and single-use face masks to complement the results of the LCA according to quoted by Saidani et al. (Saidani et al., 2019). The use of LCA and MCI together needs to better support the decision when analyzing the environmental performance of the products compared. To that effect, the results are presented in Sect. 3.7.

3 Results and discussion

Simulations were developed to assess face masks and the following scenarios were considered:

(1) SU-LD: Single-use face mask with Landfill Disposal;
(2) RE-LD: handmade Reusable face mask with Landfill Disposal;
(3) RE–RE: handmade Reusable face mask with Recycling;

3.1 Study of Brazilian scenario

The results for each impact category using ReCiPe 2016 Midpoint and Endpoint methods are shown in Table 4 and Fig. 4. In Fig. 4, the milipoint unit (mPt) has been used as a way to represent the results after normalization and weighting to the impact and damage categories. This unit is common to the normalization and weighting sets of the ReCiPe 2016 (PRé Sustainability, 2020).

According to ANVISA (National Health Surveillance Agency, 2020) recommendations, mentioned in Sect. 2, handmade reusable face masks can be reused up to 30 times. Thus, a comparative analysis of scenarios 1 and 2 was performed considering the disposal of 30 units of single-use masks and 1 unit of handmade reusable face masks (Fig. 2).

When analyzing the data in Table 4, it is noticed a predominance of the greatest impacts to the single-use face mask (SU-LD). In Fig. 4, SU-LD owns almost five times more impact than the handmade reusable face mask (RE-LD) with an impact of 159.12 and 26.31 mPt, respectively. Looking for the results of single-use face masks, it has the greatest impact on human health, representing 95% of an impact considering all endpoint categories. According to (Huijbregts et al., 2017), the human health category is related to the increase in respiratory disease, various types of cancer, increased malaria, diarrhea, malnutrition, and natural disasters due to increased global mean temperature.
Within the human health category, the midpoints of global warming, fine particulate matter formation, and human non-carcinogenic toxicity are the most affected midpoints and together they correspond to 90% of the impact generated by the single-use face mask.

As a way of understanding better the environmental impact behavior of each face mask, it was analyzed the environmental impact for each life cycle stage of them. In this context, Fig. 5 shows that for single-use face masks the most important stage to environmental

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**Table 4** Midpoints to Brazilian scenario considering ReCiPe 2016 Midpoint method: Comparison between single-use face masks, and handmade reusable face masks with recycling and landfill disposal

| Impact categories                                      | Unit                  | SU-LD     | RE-LD     | RE–RE     |
|--------------------------------------------------------|-----------------------|-----------|-----------|-----------|
| Global warming, Human health                           | kg CO₂ eq             | 3.76E+00  | 6.05E-01  | 3.33E-01  |
| Global warming, Terrestrial ecosystems                 | kg CFC11 eq           | 1.65E-05  | 2.38E-06  | 6.36E-07  |
| Global warming, Freshwater ecosystems                  | kBq Co-60 eq          | 1.53E-01  | 4.24E-02  | 2.86E-02  |
| Stratospheric ozone depletion                          | kg NO₃ eq             | 6.53E-03  | 1.12E-03  | 5.45E-04  |
| Ionizing radiation                                     | kg PM₂.₅ eq           | 4.78E-03  | 9.69E-04  | 5.16E-04  |
| Ozone formation, Human health                          | kg NO₃ eq             | 6.93E-03  | 1.15E-03  | 5.58E-04  |
| Fine particulate matter formation                      | kg SO₂ eq             | 1.11E-02  | 2.71E-03  | 1.35E-03  |
| Ozone formation, Terrestrial ecosystems                | kg P eq               | 7.08E-04  | 1.46E-04  | 4.13E-05  |
| Terrestrial acidification                              | kg N eq               | 6.12E-04  | 5.37E-04  | −2.36E-05 |
| Freshwater eutrophication                              | kg 1,4-DCB            | 8.44E+00  | 1.87E+00  | 1.23E+00  |
| Marine eutrophication                                  | kg 1,4-DCB            | 4.20E-01  | 6.97E-02  | 4.25E-02  |
| Terrestrial ecotoxicity                                | kg 1,4-DCB            | 5.43E-01  | 8.47E-02  | 5.25E-02  |
| Freshwater ecotoxicity                                 | kg 1,4-DCB            | 9.81E-02  | 1.69E-02  | 8.89E-03  |
| Marine ecotoxicity                                     | kg 1,4-DCB            | 7.70E+00  | 7.34E-01  | 2.66E-01  |
| Human carcinogenic toxicity                            | m²a crop eq           | 1.44E-01  | 8.77E-02  | 1.09E-02  |
| Human non-carcinogenic toxicity                        | kg Cu eq              | 1.34E-02  | 1.55E-03  | 6.72E-04  |
| Land use                                               | kg oil eq             | 1.32E+00  | 1.34E-01  | 6.94E-02  |
| Mineral resource scarcity                              | m³                    | 1.15E-01  | 8.82E-02  | 2.98E-02  |
| Fossil resource scarcity                               | kg CO₂ eq             | 3.76E+00  | 6.05E-01  | 3.33E-01  |
| Water consumption, Human health                        | kg CFC11 eq           | 1.65E-05  | 2.38E-06  | 6.36E-07  |
| Water consumption, Terrestrial ecosystem               | kBq Co-60 eq          | 1.53E-01  | 4.24E-02  | 2.86E-02  |

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**Fig. 4** ReCiPe 2016 Midpoints (%) and Endpoint (mPt) to Brazilian scenario: Comparison between single-use face masks, and handmade reusable face masks with recycling and landfill disposal
impact is manufacturing. For handmade reusable face masks, the stages of manufacturing and use, the latter because the process of Iron clothes is the most significant to environmental impacts. Besides this, SU-LD masks have the greatest impact when compared to the other masks. Manufacturing processes account for 82% and waste disposal for 18% of the entire impact generated.

To understand better these results, it is elaborated Fig. 6 which presents the environmental impact for each material/equipment/process considered in the most important stages found in Fig. 5, being their manufacturing for all face masks and Use considering Iron clothes process for Reusable face masks.

Analyzing the results, the most significant material is the Elastic band for sewing, which is a material obtained by processing polyester and synthetic rubber materials. It is interesting to observe Nonwoven material owns a result of 61% less than the Elastic band for sewing, and it represents only 16% of the total impact in the Manufacturing stage for this type of mask. In contrast, for handmade reusable face masks, at this stage of manufacture, Cotton knit was the material with the greatest environmental impact, possibly due to its cotton origin. It is worth mentioning that handmade reusable face mask owns the same quantity of Elastic band for sewing than single-use face mask, however, the impact of this material is considerably inferior in the handmade reusable face mask because of the reuse process. Thus, handmade reusable face masks have a lower environmental impact

**Fig. 5** Endpoints to Brazilian scenario comparing the impact distributed for each life cycle stage of each face mask

**Fig. 6** Endpoints to Brazilian scenario comparing the impact distributed for each material/equipment considered in the manufacturing processes for single-use face masks and Reusable face masks
than single-use face masks when regarding the reuse scenario according to the ANVISA recommendations (National Health Surveillance Agency, 2020).

3.2 Study of the number of reuses

The result of the comparison accounting for variations in the number of reuses for hand-made reusable face masks against single-use face masks is presented in Fig. 7.

As shown in Fig. 4, reuse actions to the cotton fabric mask significantly reduce environmental impact of this face mask when compared to the single-use face mask. In this sense, the greater the number of reuse cycles of the handmade reusable face mask, the greater will be the difference in environmental impacts between them.

When analyzing the situation in which each face mask own one use, it seems that the cotton fabric face masks present, whatever the type of final disposal, a total impact greater than the nonwoven fabric mask. For example, the RE-LD has an impact 5 times greater than the SU-LD.

However, after the 5th reuse, the behavior begins to reverse, and the SU-LD begins to have a more significant environmental impact. According to ANVISA (National Health Surveillance Agency, 2020), handmade reusable face masks may be reused up to 30 times before disposal. In this scenario, 30 single-use face masks are required for each handmade reusable face mask used, which results in a final impact 6 times greater for the SU-LD, as already presented in item 3.1.

This study highlights the importance of reusing the face mask and how it can be more sustainable, allowing the user to make the best purchase choice, considering the environmental aspects. However, these results are achieved in practice if the recommendations for use are properly followed, this means that if the user, for example, uses more than the recommended 30 times, it can harm their health and compromising the effectiveness and protection against Covid-19. On the other hand, if the user uses less than the recommended 30 times, the environmental benefits obtained by selecting a reusable mask are affected. It

![Fig. 7](image_url) **Fig. 7** Endpoints to Brazilian scenario: Comparison between reusable face masks with recycling and landfill disposal with single-use to different quantities of used masks
also suggests the importance of controlling the use of masks, which is an unquestionable challenge.

### 3.3 Study of Brazilian vs. global scenarios

Figure 8 presents the results of the impacts generated for the RoW scenario, where a global average of process and material data from around the globe is taken into account, except for Europe, and the electricity generation from Brazil (BR). These were replaced for the overall material and process data (GLO). These criteria helped to determine (a) what the average global outcome would be, taking into account similar mask consumption scenarios for different parts of the world; (b) if when adding the GLO, with the introduction of combined logistics processes, it would change the position of environmental performance.

The results show that in the GLO scenario, the most significant impact is on the SU-LD, 43% higher than the BR scenario. For RE-LD and RE–RE, GLO scenarios are 58% and 72% higher than the BR scenarios, respectively. A plausible explanation is that Brazil’s energy matrix is mainly composed of renewable energy sources, such as hydropower plants, which will reduce the impact on the use of the studied processes and materials.

### 3.4 Comparison with impact world+ method

Simulations were conducted using the IMPACT World+ method, comparing the SU-LD, RE-LD, and RE–RE masks, as well as simulated with the ReCiPe 2016 method in Sect. 3.1. The results are shown in Table 5 and Fig. 9. In Fig. 9, EUR2003 has been used because it is a common unit in the Stepwise 2006 normalization and weighting sets (Weidema, 2009).

In Table 5, it is possible to observe a trend of results like the ReCiPe 2016 method. This is because, for all impact categories analyzed for the IMPACT World+, the results are higher for the single-use face mask (worst environmental performance) and lower for the handmade reusable face mask with recycling (best environmental performance).

![Fig. 8 Endpoints to Brazilian and Global scenario](image-url)
When analyzing Fig. 9, which presents the normalized and weighted impacts, SU-LD has 4.5 times the impact of the RE-LD. RE-LD, in turn, has an impact twice as large as RE–RE. As a result, the impact ratio between the methods is similar. Also by comparing the two methods, the distribution of the impact among the indicators of the damage endpoints/protection areas is shown in Fig. 10.
The IMPACT World+ and ReCiPe 2016 methods have a significant difference in the distribution of their damage indicators/areas of protection, and this seems to be the biggest difference between them. Considering SU-LD, which is the face mask with the greatest impact, the IMPACT World+ owns an impact distribution ratio 13 times higher in the ecosystem quality indicator than the ReCiPe 2016, while it has an impact almost 5 times lower in the human health indicator than the ReCiPe 2016. This significant difference in the proportion of damage indicators/areas of protection is reduced when RE-LD is analyzed. In this case, it is almost 7 times greater in the Ecosystem quality while having only 2 times less impact on human health.

When analyzing the impact on a single indicator the trend between the methods was maintained, in the ratio of approximately 1:0.2:0.1 (SU-LD: RE-LD: RE–RE). However, it is noted that the IMPACT World+ method, when applying normalization and weighting steps, tends to focus more on the impact categories related to ecosystem quality, while the ReCiPe 2016 method ends up with a greater focus on human health impacts.

3.5 Study with a 4th scenario: single-use with recycling

To evaluate the effects of material circularity, a single-use face mask was simulated with a hypothetical recycling scenario known as the SU-RE masks.

The result is nearly 4 times less impact than SU-LD masks. Under this scenario, all the material is destined for recycling. Therefore, the impact of landfill disposal would not exist, and the recycled material would reduce the impact of this face mask in 116.90 mPt (Fig. 11).

Although Covid-19 waste, such as masks that have recycling or reuse recommendation (ABES, 2020; Health Department RS/BR, 2020), it is clear that the application of a certain technique of material return and reinsertion into production cycles would make a significant contribution to the reduction the environmental impact of this type of product. In this sense, this study raises the need to consider the possibilities in developing
products that lead to solutions to reduce the high flow of masks for landfills. This makes it possible to increase the environmental performance of the product, as well as its circularity.

For example, the French start-up Plaxtil is a pioneer in recycling face masks. According to the start-up, its process allows decontaminating of masks using a method based on maintaining masks in quarantine for at least 4 days and then crushes the masks into an ultraviolet tunnel for 5 s. After that, the compound of the mask remains for an extra 30 s in the ultraviolet tunnel (Lentschner, 2020).

### 3.6 Material circularity indicator (MCI)

The circularity analysis is comparative between the four scenarios presented: reusable face mask with disposal in landfill and recycling, and single-use face mask with disposal in landfill and recycling. The comparative analysis was performed using the Material Circularity Indicator-Dynamic Modelling Tool (EMF, 2014), as presented in Table 6.

In Table 6, reused feedstock and reuse in the EoL for RE-LD and RE–RE had a value used from 97% given one cycle of virgin material (1/30 or 3%) and one EoL to the landfill (1/30 or 3%). In other words, these handmade reusable face masks have the first input as virgin material, 30 cycles of reuse, and a last output to the landfill. Moreover, RE–RE owns 3% of the total mass going to the recycling because the last output goes to the recycling process. As for SU-LD and SU-RE, reused feedstock and reuse in the EoL are 0% because these single-use face masks do not own reuse processes. These types of face masks also do not own recycled feedstock material, only virgin materials (0% of recycled feedstock). However, SU-RE owns 100% of the recycling in the end-of-life after use because in this scenario all face masks are sent to recycling processes. Finally, lifespan has been considered 1 for each face mask because in this study the face masks meet the expected average lifespan for them when compared to the average lifespan of similar products on the market.
Table 6  Material circularity indicator—Comparison between all four scenarios of face masks

|                  | RE-LD |        | RE-RE |        | SU-LD |        | SU-RE |        |
|------------------|-------|--------|-------|--------|-------|--------|-------|--------|
|                  | Feedstock | End-of-life | Feedstock | End-of-life | Feedstock | End-of-life | Feedstock | End-of-life |
| Reused           | 97%    | 97%    | 97%    | 97%    | 0%    | 0%    | 0%    | 0%    |
| Recycled         | 0%     | 0%     | 0%     | 3%     | 0%    | 0%    | 0%    | 100%   |
| Recycling efficiency | 0%   | 0%     | 0%     | 100%   | 0%    | 0%    | 0%    | 100%   |
| Lifespan         | 1      | 1      | 1      | 1      | 1     | 1     | 1     | 1      |
| MCI              | 0.973  | 0.986  | 0.100  | 0.550  | 0.100 | 0.550 | 0.100 | 0.550  |
As shown in Table 6, in the case of the handmade reusable face mask, the end-of-life slightly affects the Material Circularity Indicator. In other words, the reuse in the life cycle of this face mask is predominant in its circularity result.

On the other hand, for the single-use face mask, the end-of-life of the material significantly affects the result of circularity. In the case of landfill disposal, this is the worst possible scenario in terms of circularity, presenting a minimum value for the indicator, showing that the product is highly disposable. However, in the hypothetical scenario of recycling this material, the circularity indicator increases by more than 5 times, but it remains much smaller than the indicator presented by the handmade reusable face mask.

In a study developed by Rodríguez et al. (2021b), the authors obtained similar results when comparing five different face masks containing among them single-use face masks and reusable face masks. In this study, reuse actions were the ones that most contributed to the increased circularity of the face masks. Šuškevičė and Kruopienė (2021) also demonstrated the importance of reuse for the circularity by MCI when the authors compared reusable cups vs. single-use cups.

3.7 Discussion of the results in LCA and circularity evaluation

Notwithstanding the urgent need to care about the health of the population, it is important to assess other impacts caused by the COVID-19, such as the environmental impact of overconsumption of some products, including facial masks. In this sense, the results of the LCA and Circularity assessment showed that the reuse of masks is considered an important step in achieving a better environmental performance of this product.

The LCA, in the different end-of-life scenarios, has shown that single-use face mask has its worst environmental performance in the manufacturing phase, mainly because of the presence of Elastic band for sewing, sewing thread, and nonwoven materials, which accounted for 60% of the total environmental impact of this phase of its life cycle. In terms of the handmade reusable face mask, the total environmental impact of a single-use face mask was 604% higher. Other literature that has studied the environmental impacts of face masks, corroborates this result (Allison et al., 2020; Klemeš et al., 2020; Rodríguez et al., 2021b).

It should be noted that handmade reusable face mask presented the manufacturing phase and the iron-clothing activity in the use phase as the main contributors to the environmental impact of this product. Also, given the activity of iron clothing can be an optional action to sterilize the mask because the washing with detergent already has the potential to destroy COVID-19, the difference in environmental impact between the two masks studied can be even more significant. Comparing the results of the ReCiPe 2016 and IMPACT World+ methods enhances the behavior of the single-use face mask’s environmental impact, even though the IMPACT World+ method indicates greater contributions of the impact categories related to the Ecosystem quality and the ReCiPe 2016 indicates greater contributions to the impact categories of Human Health.

The number of reuse analyses presented in Sect. 3.2 showed that only 6 reuse cycles are required for the single-use non-woven fabric mask to have a higher significant environmental impact. The Brazilian control agency recommends the possibility of reuse of up to 30 times, following the mask sanitization procedures between each use (National Health Surveillance Agency 2020). This analysis is part of what is new in this study. The environmental impact analysis of the single-use mask is compared to the reusable mask taking into
account up to 30 uses. Other published studies have compared the environmental impact of 1 (one) functional unit of different types of masks, including N95 type surgical masks, and non-medical masks made of fabric and non-woven fabric, for single-use, recycling, and different disposal proposals (Lee et al., 2021; Rodríguez et al., 2021b; Tabatabaei et al., 2021). It is worth noting that Rodríguez et al. (2021b) present an analysis on 50 times for reuses. However, the maximum recommended to Brazil according to the recommendations of the ANVISA is 30 times for reuse (National Health Surveillance Agency, 2020).

Furthermore, the evaluation of the circularity between the face masks showed that there exists a predominance of circularity in materials for the reusable mask, whereas linearity is predominant for the single-use mask, as its name already indicates. It should be noted that even a potential recycling scenario for the manufactured Nonwoven mask gives it a total environmental impact by the ReCiPe 2016 method of 39.8 mmPt against 26.3 mmPt for the handmade reusable face mask with landfill end-of-life. However, the common end-of-life for masks in Brazil, both handmade and single-use, has been the landfills (Penteado & Castro, 2021; Urban & Nakada, 2021).

Recent UNEP studies have demonstrated the need for a reduction in single-use plastic products, such as (United Nations Environment Programme, 2020b, 2021). United Nations Environment Programme (2020b) underlines the need to reduce the consumption of single-use plastic to avoid excessive volumes of such materials in oceans and landfills, with a cumulative volume of plastic waste surveyed by 2050 in landfills and an environment of 12 billion metric tons. With COVID-19, waste management has become a major problem around the world. However, there is an urgency to minimize the environmental impact of waste during this period (Fan et al., 2021), as well as the use of reusable masks. In this sense, actions related to a circular economy and waste management can be seen as very useful in the fight against reducing environmental impacts during COVID-19 (Patrício Silva et al., 2021; Vanapalli et al., 2021; Zhu & Liu, 2020), increase personal protection and contribute to lower costs and greater sustainability (World Health Organization, 2020b). In this context, this study aligns with the original findings of the studies prepared by UNEP, demonstrating the lower environmental impact and greater circularity of Cotton manufacture masks compared with single-use face masks. These results may guide governments’ public policies toward environmental issues when it comes to directing the public to the use of masks in a pandemic situation like the one we are currently experiencing at Sars-CoV-2.

4 Conclusion

This study contributes to the state of the art of environmental impact assessment and circularity of personal protective equipment through the application and analysis of LCA and MCI results.

Sars-CoV-2 has brought humanity into a vulnerable state of public health. However, it has also highlighted other problems that we have on the planet and that we must take action for a more sustainable environment. In this sense, the decision support for public policies is crucial to reducing the economic, social, and more specific impact of this study, the environment.

The sequence of analyses conducted out in this article, aimed at supporting the government’s decision to direct the population to the type of mask based on environmental performance, can be seen as a template for future studies with similar characteristics.
Regarding the main results of this study, it was concluded that the use of cotton masks and their possibility of reuse obtained the best environmental performance and the level of circularity, is considered a more environmentally sustainable solution in mass use situations during this Covid-19 period. In addition, the methodological path adopted to carry out the LCA and circularity evaluation converged toward coherent answers, giving greater reliability to the conclusions drawn throughout the study.

Finally, this study opens up work fronts to evolve, both in the expansion of types of masks or other products with the use and mass to be evaluated, as well as for the study of solutions for the recycling of masks and the subsequent assessment of the environmental impact and circularity of such solutions.

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