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Management of disposable surgical masks for tackling pandemic-generated pollution: Thermo-acoustic investigations and life cycle assessment of novel recycled building panels

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\textbf{ABSTRACT}

The COVID-19 pandemic has changed people’s habits, causing them to use large amounts of disposable items and exacerbating the already existing issue of pollution. One way to reduce the environmental impact of this shift in daily habits is to recycle these items, e.g. surgical masks that are the most common personal protective equipment against the virus, to produce panels for building applications. In this work, both the thermal and acoustical performance of such panels are evaluated using a small and a large scale investigation under real-world conditions. Small scale thermal tests are performed by means of the Hot Disk instrument while the acoustic investigations are performed by means of the impedance tube. Large scale tests are carried out in a reverberation chamber assessing both the heat flow passing through the wall and the acoustic absorption coefficient of the panels. Finally, the environmental impact of the innovative recycled panel is also investigated in a life cycle perspective. Overall, the material behavior scored well on these tests, suggesting that the proposed approach may be a good recycling method.

1. Introduction

In late 2019, humans faced an outbreak started in China by COVID-19 (COriVrus Disease 19), also known as SARS-COV-2 (Severe Acute Respiratory Syndrome Coronavirus 2). Due to the high contagiousness of the virus, the epidemic soon turned into pandemic. In order to fight the virus and avoid further contagions, policy makers all around the world imposed the lockdown, and wearing protective equipment became mandatory both indoors and outdoors. At first, the complete closure of the cities led to improved atmospheric conditions. Indeed, several studies registered an impressive drop in the greenhouse gases emissions, with a registered 30% reduction in the nitrogen dioxide emissions (NO\textsubscript{2}) (Muhammad et al., 2020) as well as reduced noise pollution in most cities, where a drastic road noise reduction was found (Caniato et al., 2021a). Despite this, the emergence of COVID-19 has also caused problems from the environmental point of view. Indeed, during the pandemic disposable items are usually preferred for hygiene reasons. Furthermore, their use was globally indicated as an effective method for counteracting the spread of the virus, essentially occurring through droplets emitted while speaking, coughing or breathing (Tanisali et al., 2021). Therefore, the demand for these protective devices became huge all around the world. A study by Ocean Asia estimated about 129 billion masks needed per month globally, which as you can imagine, if improperly disposed of, create the conditions for a possible environmental disaster (Bondaroff and Cooke, 2020). Nowadays, environmental protection is an important issue as the products used often become waste, causing problems to the ecosystem (Fuller and Ottman, 2004; Awomeso, 2010; Kaliyavaradhan et al., 2022; Rosso et al., 2014). In addition to this, some industrial processes also release waste or by-products that pollute the environment but, with the appropriate treatments, can be turned into a new resource (Sam et al., 2021; Maghool et al., 2017; Garrido et al., 2021). In this area, the reuse and recycling of system components (Thomassen et al., 2022; Gasia et al., 2021) and materials (Barros et al., 2017; Fabiani et al., 2020; Bianchi et al., 2021; Asdrubali et al., 2016) is one of the main concepts for green and sustainable construction. As a matter of fact, there are several studies that analyze the energy required for the construction of buildings and the one required during the life cycle of the structures (Buchanan and Honey, 1994), also evaluating alternative solutions for reducing the overall embodied energy of a product as well as reducing the associated...
finding good values from the energy and environmental point of view. In insulation board was compared to other commonly used materials, applications. In a similar study by Ardente et al. (2008), a kenaf-fibers identified mineral wool as the most sustainable alternative for building analysis (cradle-to-gate or gate-to-gate) (Cao, 2017). Llantoy et al. recycling of the material (cradle-to-cradle) or only partial life cycle considering the final disposal of the product (cradle-to-grave), the ISO14040 (2006) and ISO 14044 (2018) and can be carried out panels also need to guarantee low environmental impacts, mostly the previously described acoustic and thermal performance, innovative sound absorption properties, especially for high frequencies. Apart from reused polyester fibers, finding, from the acoustic point of view, good

greenhouse emissions (Cole, 1998; Ghosh et al., 2021). To achieve energy savings in the construction sector, a common approach is to improve the thermal insulation of the building envelope. Indeed, a proper designing of the most important heat transfer phenomena taking place through the building walls can reformulate the use of air conditioning systems and decrease the related energy consumption (Al-Homoud, 2005). In this view, an even more important topic for researchers worldwide is the production of good thermal insulation panels by using waste materials. There are already several studies in this area focused, for example, on reusing cellulose fibers from recycled paper products (Hurtado et al., 2016), lignocellulosic fibers from stranded driftwood residues (Pisello et al., 2016), recycled brick aggregate (RBA) from existing building elements (Mankel et al., 2021), or even recycled textiles (Islam and Bhat, 2019) or waste products from the food sector (de Albuquerque Landi et al., 2020). Insulation panels for building applications, however, also need to ensure adequate acoustic performance, for contributing to a comfortable indoor environment (Asdrubali et al., 2016; Caniato et al., 2021b). For example, Pedroso et al. (2017) analyzed the acoustic performance of commonly used materials compared to alternative solutions made from recycled products and showed that alternative materials can be a good choice for replacing common products. Another study, conducted by Patnaik et al. (2015), evaluated both thermal and acoustic performance of waste wool and reused polyester fibers, finding, from the acoustic point of view, good sound absorption properties, especially for high frequencies. Apart from the previously described acoustic and thermal performance, innovative panels also need to guarantee low environmental impacts, mostly assessed by means of the so-called Life Cycle Assessment analysis (LCA) (Miettinen and Hamalainen, 1997). This analysis is regulated by the ISO14040 (2006) and ISO 14044 (2018) and can be carried out considering the final disposal of the product (cradle-to-grave), the recycling of the material (cradle-to-cradle) or only partial life cycle analysis (cradle-to-gate or gate-to-gate) (Cao, 2017). Llanzyo et al. (2020), for example, compared the environmental impact of polyurethane, extruded polystyrene, and mineral wool using a cradle-to-grave approach. Based on the obtained results, the researchers identified mineral wool as the most sustainable alternative for building applications. In a similar study by Ardente et al. (2008), a kenaf-fibers insulation board was compared to other commonly used materials, finding good values from the energy and environmental point of view. In this context, this work proposes to find a solution to an environmental problem caused by protective devices.

Fig. 1. (a) Internal layers of the masks; mask samples: (b) stacked (c) multilayers, and (d) shredded masks; (e) mask panel.

The purpose is to recycle used surgical masks to produce panels for building applications. The use of this material can be convenient as it is available globally and in large quantities, representing a real problem in terms of final disposal. We here aim to explore the potential of this new kind of panel, which if properly communicated to the public in terms of user perception, could represent a valuable product to be presented on the market within the framework of circular economy and resource efficiency. Indeed, by using waste materials for the production of insulation panels we reintroduce them into the production cycle, with the twofold benefit of (i) reducing resource depletion and (ii) cutting down GHG emissions for their disposal. Properly stressing such aspects may lead to an improvement in the commercial attractiveness of the investigated waste material, yet acceptable thermophysical performance first needs to be achieved. To this aim, a multiphysics and multiscale experimental campaign is developed and a Life Cycle Assessment is performed to assess the performance of the panels and evaluate their potential impacts on the environment.

2. Materials and samples

2.1. Surgical mask material

Surgical masks are made of polymeric materials, usually polypropylene or polyester, and they are composed of three different layers: inner layer, filter layer, and outer layer (Fig. 1a). Spun bond technology is used for producing the inner and outer layers and the melt blow technology for the filter layer. The former creates larger microfibers than the latter, which, on the other hand, produces a combination of long and thin fibers, equipping the final product with a good filtering capacity and acceptable breathability. This type of mask has a rectangular shape and three folds designed to cover the face from nose to chin. Masks also feature elastic ear loops and a plastic or metal nose pad.

2.2. Samples production

This work focuses on the description and the evaluation of a promising recycling route for the most commonly used surgical masks available worldwide: the blue type IIR mask certified by the European
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38x354]described small scale multilayered samples on a 0.5 mm-thick squared layered panels produced by attaching two rows of the previously average size of about 1 cm and inserting them in a cylindrical sample were, instead, produced by cutting the masks into small pieces with an layered samples were produced by stacking and sewing together 8 masks small scale and large scale investigation procedures.

Fig. 2. (a) Mask sample tested; (b,c) shredded mask sample tested.

896 surgical masks were used for each panel. As regards the large scale thermal characterization, a non-destructive analysis was carried out on two types of samples: stacked multilayers with new (Fig. 1b) and used masks (Fig. 1c) and shredded masks, produced with used masks only (Fig. 1d). The stacked multilayered samples were produced by stacking and sewing together 8 masks (used or new), for a final thickness of about 5 mm. The shredded samples were, instead, produced by cutting the masks into small pieces with an average size of about 1 cm and inserting them in a cylindrical sample holder both in the case of the thermal and the acoustic tests.

Large-scale investigations were only performed on stacked multilayered panels produced by attaching two rows of the previously described small scale multilayered samples on a 0.5 mm-thick squared cardboard panel with a total surface of about 1 m², see Fig. 1e. A total of 896 surgical masks were used for each panel.

2.3. Methods for assessing thermal properties

The thermal characterization of the samples was carried out using both small scale and large scale investigation techniques. At the small scale, the Hot Disk 2500 S equipment making use of the Transient Plane Source (TPS) method was used. In this analysis, a Kapton sensor is sandwiched between two pieces of the same sample, and acts as both a heat source and a temperature probe. Based on the standard ISO 22007-2 (2015), the Hot Disk analysis allows to evaluate the thermal conductivity, thermal diffusivity and specific heat of the sample with a quick, transient measurement. The following formula is used to evaluate the thermal resistance of the sensor:

\[
R(t) = R_0 [1 + \alpha \Delta T_i + \alpha \Delta T(t)]
\]

where \(R_0\) is the resistance of the sensor before the transient recording, \(\alpha\) is the coefficient relative to TCR, \(\Delta T_i\) is the temperature relative to Kapton that after a short time becomes constant and \(\Delta T(t)\) is the average temperature increase of the TPS element assuming perfect thermal contact with the test specimen (Log and Gustafson, 1995).

As regards the large scale thermal characterization, a non-destructive analysis was carried out by using thermo-fluorometric plates. These allow to evaluate the thermal flux passing through a wall where the panel made with masks is placed. In this type of analysis, since the panel is analyzed in real conditions, there are often transient effects and it is therefore necessary to consider the average values of the phenomenon over long time periods. Therefore, the thermal conductance and thermal transmittance can be evaluated through the formulas:

\[\Lambda = \frac{1}{\sum_{i=1}^{n} (T_{pe} - T_{pe})} \]

\[U = \frac{1}{\frac{h_i}{k} + \frac{h_e}{k} + \frac{\Delta T}{\alpha}} \]

where \(h_i\) and \(h_e\) are the internal and external adduction coefficients, \(\Delta T\) is the specific heat flux, \(T_{pe}\) and \(T_{pe}\) are the surface temperatures of the inner and outer walls, \(T_i\) and \(T_e\) are the indoor and outdoor temperatures.

2.4. Methods for assessing acoustic properties

The impedance tube is used to evaluate the acoustic characteristics of the material at the small scale. Both absorption coefficient and transmission loss can be evaluated with this instrument. The tube features a source and microphones. In the case of the absorption coefficient test, two microphones are used. The source generates waves and the microphones measure the sound pressure level at these two points. By calculating the transfer function, the absorption coefficient can be evaluated. This method is described in ISO 10534-2 (1998) and ASTM E1050-12 (2012).

Transmission loss, is also evaluated using the transfer function method, however in this case four microphones and a different configuration for the impedance tube are used. This method is described in ASTM E2611-17 (2017).

The acoustic absorption performance of the recycled panels was also investigated at the large scale, based on the method described in the standard EN ISO 354 (2003). To assess the absorption coefficient of the samples, calculation is made by evaluating the difference in reverberation time measured in the reverberation chamber with and without the panel to be tested. In this case, the instrumentation used consists in a dodecahedral omnidirectional sound source and a microphone.

3. Thermal and acoustic analysis – small scale investigation

3.1. Thermal analysis

As previously explained, in the Hot Disk analysis, the sensor was sandwiched between two samples of the same material and thermal contact was maximized by using a 500 g weight (Fig. 2a). During the test, an electric current provided to the sensor, causing an increase in temperature. The material characteristics can be determined by evaluating the temperature variation. Five different tests were performed on each sample (considering a measuring time of 20 s and a heating power of 7 mW) and, finally, the average value was calculated, considering the material as isotropic.

For each test, the red Kapton 5465 sensor, characterized by a radius of 3.189 mm was used. As for shredded masks, the red Kapton 4922
sensor, with a radius of 14.61 mm, was used. In this case, the shredded material was placed inside a plastic cylindrical sample holder equipped with a hole in the lateral surface for introducing the sensor (Fig. 2b, 2c). Also in this case the average value resulting from five consecutive tests was calculated, and all experiments were carried out considering a measurement time of 160 s and a heating power of 40 mW.

3.2. Acoustic analysis

Acoustic tests were performed with the impedance tube 4206 Bruel & Kjaer, connected to a Bruel & Kjaer Pulse signal analyzer and to the Pulse LabShop software. With this tool, both the absorption coefficient and the transmission loss of the material can be evaluated. The tube comprises a sound source, two or four microphones, and a sample holder. For the absorption test, two microphones are needed to measure the sound pressure of the field generated by the source, and they are located on the opposite side of the sample (Fig. 3a). Conversely, for the evaluation of the transmission loss, four microphones are needed for measuring the acoustic pressure field downstream and an upstream with respect to the sample (Fig. 3b). Again, all samples were tested (i.e., new masks, used masks, and shredded masks). Stacked multilayered samples with a thickness of 0.5 cm, 1 cm, 2 cm, and 3 cm were tested, while for the shredded masks the 0.5 cm configuration was avoided. For testing frequencies from 50 Hz to 1600 Hz, the 10 cm diameter samples were tested in the large tube configuration, while frequencies above 1000 Hz and up to 6400 Hz, were investigated in the small tube configuration. Absorption coefficient trends are evaluated up to 6400 Hz while transmission loss trends are evaluated up to 1600 Hz.

4. Thermal and acoustic analysis - large scale investigation

4.1. Thermal analysis

To evaluate the thermal performance at the large scale under real-world conditions, the 1 m² panel was investigated following the heat flow meter method as described in the ISO 9869-1 (2014) standard for in-situ measurement of thermal resistance and thermal transmittance of building elements. The 72 hours-long test was carried out within the controlled environment of the reverberating chambers, where the mask panel was directly attached to a plasterboard plate separating the two rooms (Fig. 4). One of the rooms was kept at about 27±1 °C by using an electric heater with registered relative humidity of about 30 ±3 %. The second room was kept at ambient temperature, i.e. average temperature of about 10 °C with a relative humidity of about 35%. Surface temperature sensors (Tinytag Plus 2, model TGP-4020) were applied to the panel while ambient temperature and relative humidity were monitored inside each of the chambers using 2 Tinytag Plus 2 sensors, model 4500. Two plates were used for contemporaneously measuring the thermal flux passing through the plasterboard layer and the same component, equipped with the innovative panel. For this purpose, two different plates were calibrated and used: the first was a 150-2 Teflon plate with dimensions equal to 500 mm±500 mm 0.6 mm, while the second was a 119 Resin plate with dimensions equal to 250 mm 250 mm 1.5 mm. The larger plate allowed to evaluate the flux passing through the plasterboard with the mask panel, while the smaller plate evaluated the amount of heat passing through the plasterboard only. As a final step, the thermal transmittance and thermal conductance of the composite stratigraphy was obtained using the progressive means method according to the calculation procedure described in the ISO 9869-1 (2014) standard.
4.2. Acoustic analysis

The absorption coefficient of the panel was evaluated in real conditions, by means of a reverberation chamber test, carried out following a re-elaboration of the EN ISO 354 (2003) standard, using a 5 m² surface produced by using the 1 m² samples described in Section 2.2 (Fig. 5). In order to carry out the acoustic test, the following equipment were used: a dodecahedral omnidirectional source model DL-301 LOOKLINE with amplifier and noise generator, composed of 12 speakers; a GRAS 40 AR 1/2" microphone; a 01 dB-Stell PRE12H preamplifier; a Sinus Sound Book acquisition system.

The microphone was firstly calibrated by means of an electroacoustic calibrator (CAL01) generating a 1000 Hz signal with a sound pressure level of 94 dB. During the test, the omnidirectional dodecahedral source generated a perfectly diffuse sound field within the chamber and once the source was turned off, the reverberation time was measured considering five source and four microphone positions. The test was performed both with and without the panel in the chamber with the reduced volume of about 62 m³ and the difference in reverberation times measured in these two cases was evaluated.

5. Life cycle assessment

5.1. Goal and scope definition

In order to assess the impact of the actual production of the mask panel, a Life Cycle Assessment (LCA) analysis was carried out. In general, this assessment includes the entire life cycle of the process or activity under analysis, including the extraction and treatment of raw materials, manufacturing, transportation, distribution, use, reuse, recycling, and final disposal. Cradle-to-gate approach was used for this analysis (we stop at the panel production phase) since the study refers to an innovative product and no data is available for the use phase. The functional unit, defined as “that amount of product, which on its own or which in combination with other products, achieves a required level of performance or enables the combination to achieve a required level of performance” in the Council of European Producers of Materials for Construction EUR-305/2011 (2011), is here defined as follows:

\[ f.u. = R \cdot \lambda \cdot \rho \cdot A \]  \hspace{1cm} (4)

where \( R \) is the thermal resistance \([\text{m}^2\text{K/W}]\), \( \lambda \) is the conductivity \([\text{W/mK}]\), \( \rho \) is the density \([\text{kg/m}^3]\), \( A \) is the area considered \([\text{m}^2]\). Both thermal resistance and the area are equal to 1. This f.u. was specifically selected in order to allow the direct comparison of the environmental impact produced by the investigated panel and more common solutions, currently applied in the market. Table 1 shows the value of the functional unit of surgical masks and the materials with which they are compared in the LCA analysis. Fig. 6 provides an overview of the different phases considered in this analysis:

- Transport (T1) of the surgical masks from collection centers placed in supermarkets to GESENU collection centers. GESENU is a company that deals with the environmental hygiene services of the cities at the level of cleaning, collection and recycling of waste. It was founded in Perugia and has set up collection points scattered throughout the municipality covering its entire area. For this reason, in our study we have relied on the 5 collection points already established by this society for the collection of the surgical masks;
- Transport (T2) of the surgical masks from GESENU collection centers to the panel production center;
- Mask sterilization process (analyzed both with UV lamp and steam);
- Panel production: manual overlapping of used masks inserted as a filling of a cavity.

5.2. Assumptions and limitations

In the following, the most important limitations of the analysis are described. 1. The material flow analysis is limited to the municipality of Perugia only. 2. The impact avoided in terms of CO₂eq by not disposing surgical masks has been taken into account following the data reported in the ISPRA (2018) report related to the use of landfills and incinerators.

3. Average transport distances were taken into account considering the full area of the municipality of Perugia. 4. The study is limited to the system boundaries shown in Fig. 6. 5. The assessment of the environmental impact is done in relation to the IPCC, CED and ReCiPe methods. Focusing on the latter, the environmental impact of the panel was evaluated by means of different investigation methods in order to identify the expected impacts with respect to (i) fundamental single-purpose variables, like the expected GWP in CO₂eq emission (IPCC method) and the amount of primary energy consumed (CED method), and (ii) a broader environmental picture considering different impact categories (ReCiPe method). A similar approach was proposed also in other relevant research studies, aiming at providing a comprehensive life cycle investigation procedure (Asdrubali et al., 2016; Piasecka et al., 2020).

5.3. Life cycle inventory analysis

In this work, two types of panels were analyzed: the mask panel with UV disinfection and the mask panel with steam disinfection. For both cases, all processes between the collection of the masks and the production of the building board were considered, while the upstream steps concerning the production of a single surgical mask were not included in the study. Indeed, masks were considered as a waste material, thus,

| Materials          | Conductivity \( \lambda \) [W/ mK] | Density \( \rho \) [kg/m³] | Functional unit \( f.u. \) |
|--------------------|-----------------------------------|--------------------------|-------------------------|
| Surgical masks     | 0.049                             | 127.389                  | 6.242                   |
| Polystyrene foam   | 0.033                             | 33                       | 1.089                   |
| Foam               | 0.040                             | 110                      | 4.400                   |
| Cork slab          | 0.039                             | 110                      | 4.290                   |
| Cellulose fiber    | 0.040                             | 50                       | 2.000                   |

Table 1
Summary of the functional units compared in this study.
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6. Results

6.1. Thermal results – small scale investigation

Results from thermal characterization of the new masks show a...
rather similar thermal conductivity value \((0.0539 \pm 0.0001 \text{ W/mK for new white masks and } 0.0532 \pm 0.0003 \text{ W/mK for new blue masks})\). As for the used blue masks, in this case the thermal conductivity value drops to \(0.0494 \pm 0.0001 \text{ W/mK}\) and to \(0.0425 \pm 0.0002 \text{ W/mK}\) for the shredded masks. In general, since all the values are lower than \(0.065 \text{ W/mK}\), it is possible to define this material as thermally insulating, especially considering the shredded masks that report the lowest conductivity value (Fig. 7a). Concerning thermal diffusivity (Fig. 7b), once again, new white and blue masks, and used blue masks show similar performance, but they differ significantly from the value obtained for shredded masks, which, given the higher amounts of voids, is rather higher. As a consequence, shredded masks heat is transferred more quickly than in other types of masks. Making use of the relation that connects thermal conductivity and diffusivity, the specific heat of the same sample was also calculated (Fig. 7c). As expected, shredded masks present lower volumetric specific heat than the other types of samples.

### 6.2. Thermal results – large scale investigation

The flux detected passing through the plasterboard is equal to 20.9 W/m², while the flux through the mask panel is on average 5.5 W/m². The temperature measured on the panel side placed in the chamber with indoor conditions is on average 25.0 ± 0.8 °C, while the opposite side of the panel has an average temperature of 18.8 ± 0.5 °C (Fig. 8). The mask panel has a good behavior from the thermal point of view, reducing the amount of heat transferred through the wall of about 15 W/m² compared to a simple plasterboard wall. After the heat flux evaluation, the thermal transmittance and thermal conductance are calculated, as described in Section 2.3 and they are equal to 0.89 W/m²K and 0.72 W/m²K, respectively. These data are related to a stratigraphy composed of plasterboard, cardboard and masks: the masks are attached to the cardboard that is in turn attached to a sheet of plasterboard in order to perform the test in the two chambers.

### 6.3. Acoustic results – small scale investigation

As previously discussed, the small scale acoustic tests evaluated both the absorption and transmission loss of the materials under investigation. Regarding the absorption coefficient analysis, different thicknesses were considered, i.e. 0.5 cm, 1 cm, 2 cm, 3 cm. Also in this case, the obtained profiles are the average of five identical tests carried out in the same conditions on the different samples. As shown in Fig. 9 and as expected, increasing the thickness of the samples always improves their acoustic absorption capability at lower frequencies. The fibrous nature of the samples provides them with relatively good absorption coefficients, even when relatively low thickness is taken into account (the \(\alpha\) value is above 0.6 for frequencies above 2300 Hz with a thickness of only 0.5 cm). Used blue masks, generally show the highest absorption trend throughout the investigated spectrum, however, shredded samples show good potentials with increasing thicknesses, and could be a good solution for thicker panels. So, in general, used blue masks are the best from the point of view of the absorption coefficient, except for the frequencies after 4000 Hz for 3 cm thickness. As a matter of fact, in this case, the best performing are the shredded masks, which reach values of the absorption coefficient superior to all. In general, it is possible to conclude that there are no big differences between new and blue masks, while the absorption coefficient of the shredded masks is very different. Fig. 10 shows the average profiles from the transmission loss investigation. Evaluating the different thicknesses, it is possible to see a substantial difference between the new and used types of masks and the
shredded masks, which have a very low transmission loss value. For the 0.5 cm thickness, although there are no great differences, the most performing type is the white mask, while the least performing is the used mask. As the thickness increases, this difference gets thinner, almost vanishing in the 3 cm-thick configuration. As previously explained, with increasing thickness also the transmission loss value of the shredded

Fig. 10. Results from the small scale investigation: transmission loss of (a) 0.5 cm (b) 1 cm (c) 2 cm and (d) 3 cm thick samples.

Fig. 11. Results from the large scale investigation: absorption coefficient of the panel made of (a) one layer and (b) two layers of samples.
masks improves, however the obtained values, strongly influenced by the low mass of the samples, do not allow us to consider the panels for the acoustic insulation purposes, as expected.

6.4. Acoustic results - large scale investigation

The values obtained from the analysis performed with a single layer of masks are shown in Fig. 11a. Given the negative peaks found, a second analysis was performed with two layers of masks overlapped (Fig. 11b). By evaluating the results, it is possible to notice an increase in the performance of the absorption coefficient by increasing the layer of masks. Due also to the analyses in small scale investigation, the results allow to conclude that the increase in the number of layers of masks, also produces a general increase in the absorption coefficient calculated in diffuse field conditions, so, better performance could be achieved by increasing the number of layers in the final panel. In any case, this analysis allowed to verify the promising absorption behavior of the panel even in more realistic environment, considering a real scale application under diffuse field conditions.

6.5. Life Cycle Impact Assessment (LCIA)

6.5.1. Intergovernmental Panel on Climate Change (IPCC)

This method allows the assessment of greenhouse gas emissions and it is carried out with respect to a time-frame of 100 years. Initially, the environmental impact avoided by the non-disposal of masks, and therefore by the consequent non-use of landfills and incinerators, is evaluated. The amount of CO$_2$eq saved is estimated to be 0.58 kg for each kg of masks considered. Fig. 12a,b compares the two types of panels analyzed (UV and vapor disinfection) with and without taking into account the avoided impact for disposal. In particular, for the panel with UV disinfection a net saving of about 58% is found, while the environmental impact of the panel produced with steam disinfection reduces by 56%. The following analyses refer to the panels that take into account the avoided impact.
account the avoided impact for disposal.

After this evaluation, the mask panels are compared to the most commonly used materials mentioned previously. As shown in Fig. 12c, the obtained results in terms of global warming level, identify the foam glass panel as the most impactful solution, followed by the cork slab, and the polystyrene foam slab. In general, the innovative mask panels are always more sustainable than the competitors in the market, with exception of the cellulose fiber, which shows the best performance among the compared insulation panels.

6.5.2. ReCiPe

The ReCiPe method features three endpoint indicators (macro areas) that take into account a long list of factors (micro areas): human health, ecosystem, and resources. Fig. 13 shows the comparison among the panels and it is possible to notice that, with respect to human health, the panel with UV disinfection is the one that impacts the most, after foam glass. On the contrary, the panel featuring steam disinfection has a 30% lower impact compared to the UV panel. With respect to human health, these two panels are more impactful than both cellulose fiber and polystyrene. The panel with steam disinfection, unlike the UV panel, is better than the cork slab. On the ecosystem side, the two mask panels perform well in terms of impact and, from a resource point of view, the one that performs better from this standpoint is the mask panel with UV disinfection. Also the panel with UV disinfection performs well, while the UV-disinfection panel outperforms the other in terms of resource depletion. Globally, the best material from the ReCiPe methodology endpoint, turns out to be the cellulose fiber, followed immediately by the mask panel with steam disinfection.

6.5.3. Cumulative Energy Demand (CED)

Cumulative Energy Demand method evaluated the energy intensity required in the processes and it analyzes the production phase, the use phase and the disposal phase of the material. From the comparison with other materials (Fig. 14) it is possible to assess that the category that required the most energy is the non-renewable fossil one, associated to a global score of 86.3 MJ for the mask panel with UV disinfection and 82.7 MJ for the one with steam disinfection. In the other categories, on the other hand, both panels generate almost no impact, apart for the non-negligible 56.2 MJ score registered by the steam disinfection panel in the non-renewable nuclear category.

6.6. Life cycle interpretation

Firstly, it is possible to evaluate that, among the processes considered for the production of the mask panel, the part related to the avoided impact due to the non-disposal of masks led to a good saving of CO$_2$eq emissions, highlighting the importance of recycling. From individual analyses, it is assessed that the part related to transport produces relatively lower impacts compared to the disinfection process, that generally assumes the highest weight. With regard to the part relating to transport, the study is carried out in relation to the municipality of Perugia (Italy), so it must be considered that these could have a greater impact in relation to larger municipalities as the distances would change together with the related emissions. UV lamp disinfection is usually identified as the most impactful by the methods used to evaluate the individual impacts of the panel. Similarly, with the panel featuring steam disinfection, also owes most of the impacts to the energy used for the sterilizer. A solution to avoid all impacts related to disinfection might be to not use any processes at all. Indeed, some studies reported that infectious COVID-19 particles are no longer detected after some days on masks. In this way, disinfection processes could be avoided due to the decay of the virus after a few days. In any case, when these two mask panels are compared with the most common insulation materials in the market, they often show a good environmental behavior. In the case of the IPCC method, they even result as the best solution after cellulose fiber. This could also be due to the avoided impact in terms of CO$_2$. Also in the ReCiPe method, the two panels are always found in a median position between the most and least impacting panels. The same thing is also found in the other two methods used It should be remarked that the here proposed LCA analysis is based on a cradle-to-gate approach, i.e. it considers all impacts up to the production phase of the panel without the post-production ones. Indeed, the recycled panel is an innovative prototype and thus there are no information or data regarding its use phase. Future research studies will be specifically dedicated to the use and post-consumption impacts and will consider the panel’s durability under different climatic boundary conditions.

7. Conclusions and future developments

Turning from an epidemic into a pandemic, COVID-19 led to a greater demand for surgical masks worldwide, consequently increasing all the environmental impacts and energy consumption due to the mass production and use. As a matter of fact, the numbers of masks used per month globally reaches 129 billion (Silva et al., 2021); due to this large
The small scale tests, carried out by means of a Hot Disk and an multiphysical tests at different scales of investigation were performed. To this aim, innovative insulation panels for building applications. To this aim, number and the potential infectivity of the protective devices, disposal of these types of waste has led to management problems.

In this work, we evaluated the possibility to recycle these masks, considering their management as hazardous waste, as a secondary raw material to be re-introduced into the production cycle in the form of innovative insulation panels for building applications. To this aim, multiphysical tests at different scales of investigation were performed. The small scale tests, carried out by means of a Hot Disk and an Impedance Tube verified the good potential of the masks in terms of both thermal and acoustic absorption performance ($\lambda = 0.0425$ W/mK for shredded masks and $\lambda = 0.0494$ W/mK for used blue masks, $\alpha$ is about 0.70 for used blue masks from 4050 Hz up to 6400 Hz and between 0.90 and 0.99 for shredded masks in the range 5282 Hz - 6400 Hz, for 3 cm thickness). Large scale analyses carried out within the controlled environment of twin reverberating chambers were later used to further explore the real-world performance of the mask-based recycled panels. With this analysis, thermal transmittance (0.72 W/m²K) and thermal conductance (0.89 W/m²K) were measured on a panel characterized by a thickness of masks, a sheet of plasterboard and cardboard. Regarding the absorption coefficient, $\alpha$ peak of about 0.60 is found for frequencies around 1000 Hz using two layers of overlapped masks, and its increase was evaluated as the number of tested layers increased. In conclusion, it is possible to use this material with other commercialized products in order to increase both thermal and acoustic properties.

As for the environmental impacts, an assessment is made resulting from the impacts given by the mask panel manufacturing process. On the one hand, the disinfection process has the greatest impact on the environment and, therefore, it is the one to be evaluated with major attention. On the other hand, when comparing the mask panels with other materials, they are often on average and sometimes better in some categories. The same analysis could be carried out for other types of masks, evaluating other developments in order to improve its properties. This study can also be implemented by evaluating waste management on a larger scale with all associated processes. Doing further evaluation is important because the issue of the used masks high number is both a current and future problem as the habit of using these devices to protect oneself may remain worldwide.

CRediT authorship contribution statement

Claudia Fabiani: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. Silvia Cavagnoli: Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. Chiara Chiatti: Validation, Investigation, Data curation, Writing – review & editing, Visualization. Anna Laura Pisello: Conceptualization, Methodology, Investigation, Resources, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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Annex

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Annex

Table 2

| Processes impact avoided | Avoided products | Impact avoided | Emissions to air | Carbon dioxide | Processes UV disinfection |
|--------------------------|------------------|----------------|-----------------|----------------|--------------------------|
| Processes UV disinfection | Avoided products | Impact avoided | Emissions to air | Carbon dioxide | Processes UV disinfection |
| Products | Disinfection process UV | 1 kg | | | |
| Materials/fuels | Transport, freight, lorry 3.5-7.5 metric ton, euro3 (RER) — market for transport, freight, lorry 3.5-7.5 metric ton, euro3 — APOS, U | 8.1 kg/km | | | |
| | Ultraviolet lamp (GLO) — market for — APOS, U | 2.34 kg/km | | | |
| | Electricity/heat | 1 p | | | |
| | Electricity, low voltage (RER) — market group for — APOS, U | 0.055 kWh | | | |
| Processes steam disinfection | Avoided products | Impact avoided | Emissions to air | Carbon dioxide | Processes steam disinfection |
| Products | Disinfection process with steam | 1 kg | | | |
| Materials/fuels | Transport, freight, lorry 3.5-7.5 metric ton, euro3 (RER) — market for transport, freight, lorry 3.5-7.5 metric ton, euro3 — APOS, U | 8.1 kg/km | | | |
| | Ultraviolet lamp (GLO) — market for — APOS, U | 2.34 kg/km | | | |
| | Electricity/heat | 1 p | | | |
| | Electricity, low voltage (RER) — market group for — APOS, U | 0.055 kWh | | | |
| Processes steam disinfection with impact avoided | Avoided products | Impact avoided | Emissions to air | Carbon dioxide | Processes steam disinfection |
| Products | Disinfection process with steam impact avoided | 1 kg | | | |
| Materials/fuels | Transport, freight, lorry 3.5-7.5 metric ton, euro3 (RER) — market for transport, freight, lorry 3.5-7.5 metric ton, euro3 — APOS, U | 8.1 kg/km | | | |
| | Ultraviolet lamp (GLO) — market for — APOS, U | 2.34 kg/km | | | |
| | Electricity/heat | 1 p | | | |
| | Electricity, low voltage (RER) — market group for — APOS, U | 0.055 kWh | | | |

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