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Evaluation of the Environmental and Economic Impact Deriving from the Adoption of a Reuse Strategy for Disposable FFP2

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ABSTRACT

The COVID-19 pandemic has exposed the vulnerability of emergency response systems to personal protective equipment shortages, particularly FFP2 masks. In that context the Milan Fire and Rescue Service has developed a novel method for regenerating and reusing disposable FFP2 masks, evaluating its safety and effectiveness through comprehensive biological, mechanical, and stress tests, guaranteeing this way up to 10 safe reuses per mask. The method not only ensures personnel safety and uninterrupted emergency service but also yields significant environmental and economic benefits, minimizing the environmental footprint associated with masks life cycle and leading to substantial financial savings to the entities willing to adopt it, through reduced procurement and disposal costs. Benefits linked to the regeneration method are validated in this work by three distinct case studies, conducted within the Milan province and encompassing three distinct entities. This study provides evidence that through regeneration it is possible to achieve environmental and economic impact reductions of up to 90% across various operational settings and presents a groundbreaking and sustainable approach to FFP2 mask reuse, offering a viable solution to address potential shortages during future pandemics.

1. INTRODUCTION

In 2020, the COVID-19 pandemic created a global emergency and a momentary the personal protective equipment (PPE) supply chain, especially in the disposable face mask field. Such protective devices were mandatory for first responders to perform emergency and supportive functions [1]. In March of the same year, at the epicenter of the pandemic in Milan, the Fire and Rescue Service (FRS), to avoid being disconnected from the supply chain of disposable FFP2, designed and implemented a method for their regeneration and thus multiple reuses. This method was utilized in the daily activities of the Italian provincial command and supported by a standard operating procedure (SOP), which allowed the disposable FFP2 to be decontaminated, analyzed for suitability for reuse, and then returned to their operators. The reuse approach was fundamental to guarantee to continuity in first responders' activities, especially to those operators in direct contact with the population. Without this disruptive approach, the city of Milan, at the beginning of the pandemic, would have suffered much many losses due to the virus spread.

This study comes then as the consequence of the pandemic period-related FRS activity and the identified necessity of guaranteeing FFP2 supply-chain continuity to cope with first responders needs.

COVID-19 itself in its early stages, generated a monthly global demand of 129 billion disposable face masks [2]. This unthinkable short-term increase in such PPE demand led firstly to a world-wide shortage situation and afterwards, to an overabundance of disposable face mask which created an enormous environmental pollution problem considering that as from what reported by the recent scientific knowledge it is estimated that face mask production requires 15 g fuel-based polymers and releases (mean value) 32.7 g CO_2 equivalent and that during the pandemic 15 trillion face masks (mean value) have been used globally each year, resulting in 2 megatons of waste [3] impacting both land and aquatic environment [4]. It is hence clear then to mitigate the environmental impact associated with disposable FFP2 masks, the implementation of circular economy principles is imperative. These principles advocate for sustainable production, re-utilization, and end-of-life management strategies, promoting resource conservation and minimizing waste generation.

In this context, the Chemical, Biological, Nuclear, Radiological (CBNR) unit of the FRS of Milan, first of all, to prevent FFP2 shortage during emergency services and to find a viable solution to face mask environmental pollution, which was already clear along the landscape of the city, developed a method able to reduce the bacterial and viral load on the masks while preventing filtration fit and seal properties loss, allowing further re-use. The method, was characterized by a ventilated dry heat process and simultaneous use of ozone, applied through an industrial dryer technology, capable of simultaneously treating hundreds of FFP2 per batch. After each treatment, the regeneration method verifies, through a series of mechanical-physical tests applied following European [5] and other international regulation [6], that the disposable FFP2s possess sufficient protective and mechanical performances to be reused. The method itself was made possible thanks to a cooperation with numerous partners including the department of materials chemistry and chemical engineering of the Politecnico di Milano, the face masks manufacturer BLS s.r.l. and research institutes such as the Sacco hospital of Milan.

The very objective of this study is to identify and display the environmental and economic impacts and savings deriving from the adoption of the disposable FFP2 masks regeneration method, in contrast with single use practice.

1.1 Extending disposable FFP2 service life

Being the average weight of a disposable FFP2 5g, it is possible to estimate the Italian plastic waste production deriving from single use in pandemic period. Considering 1 mask per day per citizen for an average number of 59 million people, a rough estimation could amount to 108,000 t/y, a large part of which could have ended up dispersed into the environment as many studies suggests [7], or incinerated [8], generating 1.5 billion t of CO_2. Adding to this consideration that average cost of a disposable FFP2 is about 0.40€ per citizen [9] (while the price for companies is estimated to be 0.2 €), it is possible to calculate that the average expenditure by the Italian population could have been of roughly 8.6 billion €/y. Regenerating a disposable mask reduces such impacts, since it allows the devices to be reused n-times (if filtering and mechanical properties are retained above certain values required by the European regulation for their certification as FFP2). Regenerating a disposable mask means to avoid the CO_2 emissions related to its production and disposal together with the economic expenditure related to the mask disposal and repurchase and ultimately to greatly reduce the volumetric waste produced upon landfill or prior incineration. To better understand the advantages related to the use of the regeneration approach it is useful to contextualize its application within the disposable FFP2 mask life cycle.

1.2 The regenerative method interfaced with the life cycle of a disposable FFP2

The following paragraph introduces the concept of regeneration by inserting it within the hypothesized life cycle of a disposable FFP2 mask. Figure 1 shows such life cycle steps. The steps following the red arrow represents the general life cycle of a disposable FFP2 mask, from production (P), use (U) to the end of service life (EL), i.e. the exhaustion of filtering and protective capabilities, followed by disposal (D), which can either end in incineration (I) or landfill (L), according to World Health Organization guidelines for material contaminated with hazardous biological residues [10]. This quasi-linear path can be ideally replaced by another one, by adding a bioburden abatement treatment BA (green and blue arrow), which allows the mask waste exploitation through recycling of the polymeric fabric. The focus of Figure 1 is to show how the BA, key element of the regeneration method (green frame), allows multiple reuses of the same disposable FFP2 mask before reaching its EL. This means, for each reused mask, a reduction in the environmental footprint due to P and D and a reduction in the economic expenditure since reusing means significantly reducing purchasing (although the BA itself has costs which is negligible if compared to disposal's and repurchase). A further step of BA (blue arrow) applied at disposable FFP2s end EL, eliminates the danger of cross contamination, and allows recycling of masks component materials (CS) into mixed type polymers. This way the disposable FFP2s acquire an added value, as its own component materials can be reused in the manufacture of new products instead of being disposed.

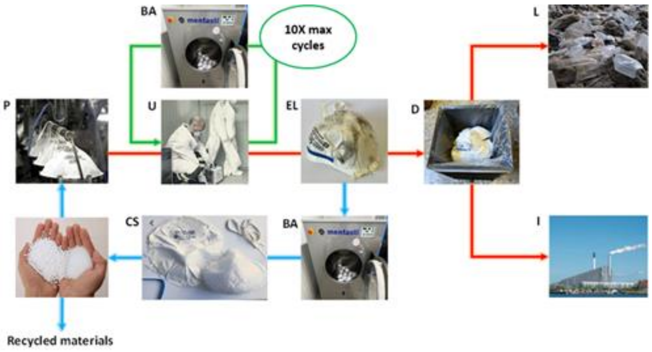

Figure 1. Life cycle hypothesis for disposable FFP2

The result of the recycling process is a series of polymers such as Polypropylene, Polyethylene Terephthalate, Polyester, Polyethylene [11]. These polymers can be used both in the production cycle of new masks as demonstrated by a recent study by Procter and Gamble [12] or in the creation of new polymeric blends for lower mechanical properties objects development [13]. It is important to underline that regenerating a FFP2, through the BA treatment, allows to convert a biological contaminated waste (in case of SARS-CoV-2 or other pathogens) into a common waste, allowing the application of recycling procedures (following the European directives on COVID-19 waste [14] implemented in Italy by the Istituto Superiore di Sanità Ambiente [15] during the pandemic period) which otherwise would be legally not applicable. Thanks to the regeneration method it is possible to make the most out of the residual protective potential of the disposable FFP2 masks, reducing their environmental footprint and the economic impact on the buyer related to purchase and disposal. The following section shows the equations used for the calculation of the environmental and economic impacts deriving from the practice of single use, repurchase and disposal versus the use of the regeneration method on FFP2 disposable masks.

1.3 Biological and mechanical tests to allow re-use

The tests framework encompassing the regeneration method is made-up of different stages below showed.

Mask conditioning. The objective of the conditioning procedure is to simulate the stress due to daily use (8 hours of wearing and breathing) and decontamination treatment, on the components of the FFP2 masks. A system characterized by an artificial lung (Hydraltis 9500fm) connected to a test head

(Scheffield Head) on which the FFP2 mask is placed (Figure 2) is used. The mask is then fluxed with air with a content of humidity equal to the human breath and respiration is simulated for 8 hours. The following phase of the conditioning involved applying a Dry heat plus ozone treatment to the mask with the timing and temperature which were identified to be the most suitable to abate the biological and viral load.

Figure 2. Mask conditioning test apparatus comprising an artificial lung, a water condenser and a testing head

Deactivation processes of the micro-organisms. For the deactivation of the bio-burden on FFP2 masks, E.Coli and SARS-CoV-2 were used. A ventilated drying treatment (VDH) and a ventilated drying treatment with a simultaneous flow of ozone (VDHO3) were used, varying temperature and operating time (Figure 3).

Figure 3. Interior of the VDHO3 system with FFP2 masks and their cover

Verification of inactivation of micro-organisms. After application of the inactivation treatments to the masks inoculated with E.Coli or SARS-CoV-2 the inoculum area was cut out and treated under Bio Safety Level 3 hood (BSL3). Both E.Coli and SARS-CoV-2 were abated with a >Log 4 reduction.

Filtration performance test. The filtering performance of disposable FFP2 masks were tested on new samples and samples treated with 0-30 cycles of conditioning by VDHO3 and 0-10 cycles of SU+VDHO3. The filtering performance after conditioning is verified by two tests, taken from the reference standard for the certification of disposable FFP2 EN 149:2001+A1 2009, namely filtering efficiency and breathing resistance. Both tests are performed using the FMP03 testing apparatus - Lorenz Meßgerätebau.

Tensile strength to breakage loading test. This test was made to verify that FFP2s rubber bands were not detrimentally affected by the conditioning procedure (simulating stressful conditions related to breathing, wearing, and the bioburden deactivation treatment) to which a disposable FFP2 is subjected during and after an 8-hour working day. The test procedure follows ISO1924/2. A 50mm length of elastic is taken from a new mask and from masks that have undergone 10, 20, and 30 cycles of VDHO3 conditioning and 5, and 10 cycles of mask conditioning + VDHO3 conditioning. The rubber band is stretched at a rate of 500 mm/minute and the resistance offered by the rubber band at the breakage moment is measured. The apparatus used for the tests is the Advanced Materials Testing System LS1.

Fit test. To check the sealing capability of the FFP2 mask that has been conditioned using VDHO3 or the mask conditioning + VDHO3, the Fit test is carried out, following the Anglo-Saxon regulations, United Kingdom HSE protocol 282/28, and using the PortaCount® TSI instrument S/N 8048194009.

Following this method, when the bioburden is abated and mechanical properties are retained above the threshold level presented in the EU and international reference standards, the FFP2 mask is considered re-usable for another 8-hour working shift.

Limitations of the FFP2 mask regeneration method. The FFP2 mask regeneration method presents primarily aesthetic limitations. As a dry process, it does not remove dust residues or stains that may have accumulated during use. Consequently, regenerated masks may appear stained or dirty, potentially discouraging adoption among users other than the original owner.

To address this limitation, the method is designed for use within structured organizations of first responders. A barcoded pouch system ensures that the regenerated mask is returned to the same operator, maintaining personal association with the mask. While the regenerated mask meets the mechanical requirements of reference standards and eliminates bioburden, its appearance may still be perceived as unappealing to some users.

2. ANALYSIS METHODS

This section inspired by the study of Rodríguez et al. [16] on disposable FFP2 masks life cycle and environmental footprint, reports simplified equations aimed at calculating environmental, economic, and volumetric impacts linked to the disposable FFP2 masks after the application of the regeneration method. These equations allow, through substitution of specific factors, to calculate the impact degree for each category as both whole number and percentage.

2.1 Generic equations: calculation of the impact related to disposable face masks single use

The following equation describes the impact generated by a disposable mask:

$$I_{impact}=P_{roduction}+D_{isposal} \quad (1)$$

From which derives the impact per personnel:

$$I_{\frac{m}{p}} = (P + D) \cdot N_A \quad (2)$$

where, P is the impact that derives from all those processes related to the disposable FFP2 mask production starting from polymers formation, refining, material molding, assembling, and manufacturing of the final product. Depending on the case, P acquires an economic (€), environmental (t of CO_2 equivalents) or volumetric (m^3) values. D is the impact generated by the end life of a disposable mask and it is as well linked to an economic (€), environmental (CO_2 equivalent) and volumetric (m^3) value. N_A is the number of masks purchased in a defined working period and identified as: $N_A=(n_{\Delta T}\cdot 11)$ being $n_{\Delta T}$ an integer variable ranging from 1, 2, 3 ...to 24, and corresponding to the intervals into which (for convenience of this study) a working year can be divided. Given that, a month consists of an average of 22 working days. The number 11 was chosen as the smallest integer number a working month can be divided into. The assignment $n_{\Delta T}=1$ will therefore correspond to 11 working days and consequently $N_A=11$, i.e., 11 disposable masks purchased.

Eq. (2) quantifies the impacts resulting from the production and end of life of a disposable mask. It is possible to extend the service life of a disposable mask by including the additional parameter called regeneration, within Eq. (1). Eq. (2), in the case of regeneration addition becomes:

$$I_{mpact}=P_{roduction}+R_{egeneration}+D_{isposal} \tag{3}$$

where,

$$\text{Regeneration}=[c\cdot n_{\Delta T}\cdot(N_R+1)\cdot\left(\frac{N_M}{N_b}\right)] \tag{4}$$

By adding the contribution of (4) to (2) and making the necessary simplifications, it is possible to obtain the general equation for the calculation of the impacts associated with a disposable mask in case of its regeneration:

$$I_{\frac{m}{p},Reg}=(P+D)\cdot\frac{N_A}{N_R+1}+[c\cdot n_{\Delta T}\cdot(N_R+1)\cdot\left(\frac{N_M}{N_b}\right)] \text{ with } N_R\neq 0 \tag{5}$$

where, $\frac{N_A}{(N_R+1)}=N_{AReg}$ is a corrective factor which indicates the impact reduction, given by the regeneration of the disposable masks (reuse=lesser impact).

$[c\cdot n_{\Delta T}\cdot(N_R+1)\cdot\left(\frac{N_M}{N_b}\right)]$ is the contribution directly linked to the use of the technology for the application of regeneration $\left(\frac{N_M}{N_b}\right)$.

where, N_R is the number of possible regenerations cycles; N_M is the number of regenerating technologies (machines used to apply the regeneration process); N_b is the number of masks that can be loaded for each regeneration cycle (per batch); c is the impact deriving from a regeneration cycle and is equal to: $c=P_M\cdot\Delta Ts\cdot k_{conv}$.

where, P_M is the electrical power required by the regeneration technology in kWh (being the regenerative technology power requirement equivalent to 8 kWh).

ΔTs is the duration of a regenerative cycle in hours (for the calculation of the impacts presented in this study, an operating time of 30 minutes was used).

k_{conv} is the conversion factor, which varies according to the impact category considered (economic K_{eco}, environmental K_{env}). By subtracting (5) from (2) it is possible to derive the equation that identifies the savings resulting from the use of regeneration (and hence multiple re-use):

$$\Delta S_p=I_{\frac{m}{p}}-I_{\frac{m}{p},Reg}=(P+D)\cdot N_A-[(P+D)\cdot\frac{NA}{N_R+1}+c\cdot(N_R+1)\cdot\left(\frac{N_M}{N_b}\right)] \tag{6}$$

Multiplying $\Delta S_p\cdot N_P$ the equation for total savings is obtained:

$$\Delta S_{(ToT)}=\Delta S_p\cdot N_P \tag{7}$$

where, N_P is the number of personnel using disposable masks for which the regeneration process is used.

The percentage savings deriving from the use of regeneration can be then quantified as:

$$S_{(\%)}=\frac{\Delta S_p}{I_{m/p}}\cdot 100=[1-\frac{I_{\frac{m}{p},Ri}}{I_{\frac{m}{p}}}]\cdot 100 \tag{8}$$

The following section focuses on the application of general equations from (1) to (8) to the three categories of impacts (environmental, economic, and volumetric) related to the use of disposable FFP2 masks.

2.2 Calculation of the environmental footprint

The environmental footprint of a disposable mask corresponds to the t of CO_2 emitted during the various phases of its life. For example, the CO_2 deriving from the production of the materials that compose it, their transport, assembly, manufacturing processes, up to the CO_2 deriving from its end of life which generally corresponds to incineration. The total impact is therefore composed of three terms P, D and R (in case regeneration). Regeneration reduces the impact for each category by a fixed amount in relation to the number of regeneration cycles applied (N_R). Substituting to the generic Eq. (6) the following variables:

- P, impact in terms of t CO_2 eq. resulting from the production and assembly of the components of the disposable mask [17].
- D, impact ton CO_2 eq. for the end of life (incineration).
- k_{env}, the value linked to the conversion of 1 kg of material into t CO_2 eq.=0.53 [18].

It is therefore possible to obtain:

$$\Delta S_{CO2\,/\,p}=(P+D)\cdot N_A-[(P+D)\cdot\frac{NA}{N_R+1}+c\cdot n_{\Delta T}\cdot(N_R+S)\left(\frac{N_M}{N_b}\right)] \tag{9}$$

Which expresses the savings in t of CO_2 equivalent, deriving from the use of regeneration.

Eqs. (7) and (8) for the calculation of the savings remain applicable also in this case.

2.3 Calculation of the economic impact

The economic impact generated using a disposable face mask can be quantified by summing three different contributions included in the parameters P, R and D as:

$$P+R+D \tag{10}$$

where, P is the cost of the mask defined as C_{Mask} (data acquired on July 2022 from BLS s.r.l company mask manufacturer: 0.20 to 0.35 €/mask); R is the cost of the Regeneration, $=[c\cdot n_{\Delta T}\cdot(N_R+S)\cdot\left(\frac{N_M}{N_b}\right)]$; D is the cost of mask disposal as solid waste, $=(C_{Sw}\cdot w_{Mask})$.

Parameter D varies according to the type of waste, for example:

• A disposable mask that does not encounter biological organisms, pathogenic to humans is assimilated to a solid urban waste (suw) associated with a disposal cost given by ($C_{suw} \cdot w_{Mask}$);

• Disposable masks in the event of ascertained contact with pathogenic biological agents (used for example in hospitals, emergency rescue operations, etc.) are considered special infectious waste (siw) and their disposal corresponds to higher costs, identified as $C_{siw} > C_{suw}$ and therefore in this case to ($C_{siw}w$) being w_{Mask} the weight of the disposable mask (mask model used is BLS O2 102 w_{FFP2}=0.007 kg, BLS ZERO w_{FFP3} =0.0126 kg, generic surgical w_{surg}=0.0035 kg).

By replacing the new terms P, D, R in (7) we obtain the specific equation to calculate the economic savings deriving from regeneration (considering that the regenerative process reduces the biological pathogenic load and returns the masks to conditions like those of a solid urban waste):

$$\Delta S_{\frac{€}{p}} = [C_{Mask} + (C_{sw} \cdot w_M)] \cdot N_A - [(C_{Mask} \cdot \frac{N_A}{N_R+1}) + (C_{sw} \cdot w_M \cdot \frac{N_A}{N_R+1}) + c \cdot n_{\Delta T} \cdot (N_R + 1) \cdot \left(\frac{N_M}{N_b}\right)] \tag{11}$$

with k_{eco}=0.2 €/kWh [19] and C_{suw}=1.5 €/kg, C_{siw}=4 €/kg (data coming from a private waste management company from Lombardy region - July 2022).

where, $c = P_M \cdot \Delta Ts \cdot k_{eco}$.

Eqs. (7) and (8) for the calculation of the total and percentual savings remain applicable also for this case.

2.4 Calculation of the waste volumetric impact

The waste volumetric impact, related to the end of life of disposable FFP2 masks is given is expressed by Eq. (12) which refers to the volume of FFP2 waste that is produced in absence or avoided in presence of regeneration:

$$\Delta S_V = (N_A - N_{AReg}) \cdot V_{Mask} \tag{12}$$

where, V_{Mask} is a volumetric value typical for each type of disposable face mask marketed. Eqs. (7) and (8) for the calculation of the total and percentage savings remain applicable also for this case.

3. RESULTS AND DISCUSSION

The equations described in section 2. ANALYSIS METHODS are now applied to real data coming from three case studies, each one involving a specific user operating over Milan central and suburban area. The final output of these calculations is expressed by means of visual representations and displays data relevant to the regeneration process influence on environmental, economic, and volumetric impacts related to the use of disposable FFP2 masks. Results comparison in absence and presence of the regeneration process highlight the amount of saving related to the reuse versus single use practice.

3.1 Application of the regeneration process to disposable FFP2 masks used by public and private institutions

Input data for section 2 equations are directly derived from three case studies where reference entities, differing for personnel size and scope are presented. In the pandemic time frame to carry out their service activities and duties, these entities have consumed daily a fixed amount of disposable FFP2. To understand how far the reusability potential of such disposable masks can stretch and hence how to exploit it, it is necessary to consider that each mask, depending on its typical use, undergoes different kind of stress loads which can alter or impair its protective functions. This evidence must be considered when identifying a proper number of maximum regenerations (N_R) and hence reuses, ultimately enabling the impact and savings calculations. Specific parameters to be considered when identifying an appropriate maximum regeneration number (N_R), are related to the type of use (e.g., against dust, chemicals, biological fluids, aerosols) and the impact that each regeneration cycle has on the mechanical-physical properties of the disposable FFP2. Exposures to chemicals, biological agents, or dust, can damage the filtering capacity and visually alter the mask appearance. It will therefore not be possible to apply the same number of regenerations for all types of use. Regarding the effects of the regeneration method on disposable masks, literature works [20, 21] reported the retaining of mechanical-physical properties (filtration and sealing and shape) for disposable FFP2s treated via dry heat processes or ozone. In this study, a maximum N_R=10 cycles have been selected considering that real-life conditions such as occasional dirt, accidental bruises cuts and accidental item loss can reduce the overall masks service life.

3.1.1 Case study 1 - Hospital company (H), Milan

The hospital company taken as reference oversees health care of citizens from Milan municipality and province. Of the 400 operators, 2,000 use a disposable FFP2 daily for 8 hours a day. During the hospital shift, disposable FFP2 masks can encounter infected bio-aerosols and can be contaminated with fluids or biological agents (blood, urine, medicines, infected saliva), but will not be subjected to dust clogging. The assumption that is made is therefore the one of biological contamination risk, which is eliminated through regeneration. It is therefore assumed regeneration for a maximum number of times equal to N_R=5.

3.1.2 Case study 2 - Multi-Utility (MU), Lombardy region

The company taken as reference carries out waste collection services in all its sites located in Lombardy (Milan, Pavia, Bergamo, and Brescia). The company is composed of 12,000 employees of which 3,000 use disposable FFP2 daily. These FFP2 used by waste-collection operators for 8 hours a day, encounter dust and atmospheric agents (sun, rain, wind). It is then assumed that for these masks there is a higher risk of filtering capacities degradation due to dirt and dust clogging. It is therefore assumed regeneration for a maximum number of times equal to N_R=3.

3.1.3 Case study 3 – Fire and Rescue Services (FRS), Provincial Command of Milan

The organization of the Fire and Rescue Service assists the citizens of Milan (and Italy) through rescue operations and in carrying out emergency missions. Of the 1,000 daily active operators, 100 use disposable FFP2 masks for 30 minutes per day. During the performance of their activities, the Fire and Rescue Service are not exposed to chemical or biological agents, for this reason it is possible to consider that the filtering properties of the disposable FFP2 in their equipment are not drastically influenced by the daily use. Additionally, these FFP2 are used for 1/16 of their service life (30 minutes of maximum use against an 8-hour work shift). It is therefore assumed that it is possible to regenerate the FFP2 of the Fire and Rescue Service for a maximum number of times equal to N_R=10.

In addition to the previous information, another parameter that influences regeneration efficiency is the maximum number of masks that can be simultaneously loaded into the regenerating technology for each operating cycle, called number of batches=N_b. Since each regeneration cycle is equivalent to a certain electricity consumption, a high Nb per machine leads to greater energy efficiency and therefore to less environmental pollution and more savings in economic terms.

Through the dataset showed in Table 1 and the specific equations presented at the beginning of this section, it is possible to calculate the savings deriving from the application of the regeneration method to each one of the user's case-study and compare them with the single use approach.

Table 1. Parameters related to disposable FFP2 regeneration for the three different case studies

User Case Study	H	MU	FRS
FFP2 (day) 	2000	3000	100
 [N_R]	5	3	10
 [N_B]	485	485	100

3.2 Regeneration versus single use

This paragraph displays the results of the application of equations presented in section 2 on data coming from Table 1 for each one of the three-user case-study. The outcomes of the equations are shown in terms of environmental, economic, and volumetric impact deriving from the application of the regeneration method to disposable FFP2 masks.

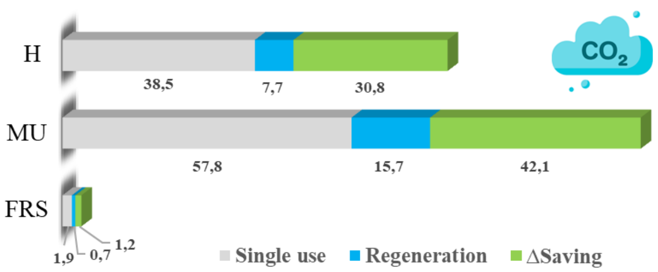

Figure 4. Environmental impact in case of regeneration versus single use of FFP2 disposable masks for the three different case studies

Figure 4 shows the amount of CO_2 equivalent yearly produced by the three different users selected for this study and taking into consideration the practice of single use versus reuse of disposable FFP2 made possible via regeneration. The N_R chosen varies from user to user, depending on the parameters presented in Table 1. Results for the MU user show that the annual contribution deriving from the single use approach of supplied disposable FFP2 amounts to 57.8 t of CO_2, dropping down to 15.7 t if regeneration with an $N_R = 3$ is implemented (therefore a disposable FFP2 will be used once and regenerated 3 times for a total of 4 total uses, saving the purchase and disposal of 4 masks). The same considerations apply to the remaining two users. The saving on the environmental impact (t of eq. CO_2 emissions) linked to the reuse of a disposable FFP2 are respectively 30.8 t for the hospital and 1.2 t for the FRS.

Figure 5 shows the economic impact, in terms of thousands of euros per year, deriving from the supply of disposable FFP2 masks by the three entities. In this case it is possible to note that the reuse of FFP2 through regeneration involves a lower cost in economic terms, compared to the repurchase linked to single use and disposal, even in the case of low N_R ($N_R = 3$ for MU and N_R=5 for H). As it is obvious, regenerating a disposable FFP2 means increasing the possible number of reuses which means that each time a mask is regenerated the purchase of a new one is avoided. As an example, from the results related to the H in Figure 3, it is possible to see how at a N_R=5 there is an expense of 4 times lower than the value linked to the single use practice. This translates specifically into 19,000 against 120,000 €, with a net saving of 101,000 €. Results for the remaining two users with savings of 138,400 and 5,300 € respectively for the MU and FRS.

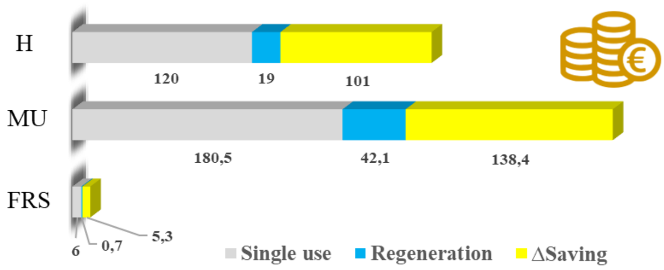

Figure 5. Economic impact: Regeneration versus single use of FFP2 for three case studies

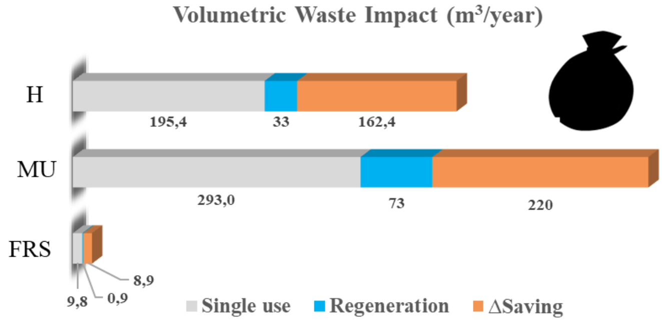

Figure 6. Volumetric waste impact: regeneration versus single use of disposable FFP2 for three different users

Figure 6 shows the impact in volumetric terms (m^3), related to the end life of a disposable FFP2. In this case, taking into consideration the FRS user, it can be noted that for $N_R = 10$, the volumetric waste produced is reduced by 1 order of magnitude, specifically from 9.8 to 0.9 m^3/y. The difference between single use and use with regeneration is also evident for the remaining entities where, for the MU, the volume of waste produced goes down from 293 to 73 m^3 (with N_R=3), and from 195.4 to 33 m^3 (N_R=5) in the H user case. As a conclusive note, it should be specified that the N_R selected for the calculation of the impacts presented in this study were chosen taken into consideration a robust and well-made mask, the BLS FFP2 O2 102, produced with high-quality materials and with starting filtration properties higher than 99% [22]. This mask mechanical-physical and protective capabilities remain almost unaltered as the cycles of reuse and bioburden abatement treatment increase (up to 10 regeneration cycles). The following section will sum up the general outcomes related to the application of the regeneration practice on disposable FFP2 and will represent the total and percentage savings comparison with for the three case-study users with aid of tables and illustrations.

3.3 CAPEX and OPEX related to the adoption of the FFP2 regenerating solution

The FFP2 mask regeneration system employs a single-unit apparatus to eliminate bioburden while preserving the mechanical properties of FFP2 masks, enabling their reuse. This approach offers simplicity in procurement and scalability, making it an attractive solution for public entities and businesses.

Cost Analysis. The acquisition cost of this apparatus ranges between 1,000 and 3,000 euros. Each operation cycle can regenerate up to 485 masks, consuming approximately 4 kW of energy. Considering the current Italian energy market (April 2024), the per-cycle regeneration cost translates to approximately 50 cents (12 cents per kWh). While no technological modifications have been evaluated, the simplicity of the underlying physical principle (low-ppm ozone rotary drying) facilitates scalability.

Comparative Cost Analysis. Compared to the daily purchase of disposable FFP2 masks, the cost of regeneration is significantly lower. As of April 13, 2024, the price of disposable FFP2 masks in Italy ranges from 10 to 50 cents per unit. Therefore, a single regeneration cycle, capable of regenerating up to 485 masks, effectively reduces the cost equivalent to purchasing 1 to 5 new masks.

Economic and Environmental Benefits. For organizations in sectors that require substantial PPE usage, such as healthcare institutions, the regeneration system offers significant economic savings. Additionally, each regenerated mask (up to 10 times) avoids disposal, thereby reducing the environmental impact associated with disposable masks.

Additionally, since regenerating a FFP2 removes its bioburden (and hence the possibility of cross-contamination and infection), it allows the Mask to be recycled, providing them a second life as new materials or components, as previously stated, and demonstrated through Figure 1.

On this topic studies from Crespo et al. and Idress et al. demonstrate the feasibility of recovering the component material of FFP2 and transform them into new objects via grinding, melting and injection molding steps (thermo-plastic recycling) [11] or producing agglomerates to become green concrete to be fed to the cement industry [23] even though no marketable feasibility evaluation of such practices has been investigated up to present time.

4. CONCLUSIONS

The shortage of disposable facemasks, occurred during the COVID-19 pandemic period, led to the search for new methods to reuse these protective devices which were continued to be adopted on a daily base even after the end of the pandemic, especially in hospitals and medical area. What remains interesting to evaluate from 2023 on is the effect of a method that allows the reuse of the same disposable mask several times reducing environmental and economic impacts for its user. To better understand the concept of sustainability behind the regenerative approach, this work shows the impacts related to the single use, end of life and repurchase of a disposable facemask and compares them with those deriving from the application of regeneration and therefore multiple re-use of the same protective device.

4.1 Visualization of the savings deriving from the application of the regeneration method on disposable FFP2 masks

Table 2 summarizes the impacts related to the use of regeneration applied to disposable FFP2 masks to the three different reference users identified in this study and shows these results in terms of total (ΔS_{total}) and percentage (S%) savings for the environmental, economic, and volumetric impact categories.

Table 2. Environmental, economic, and volumetric impacts related to the presence or absence of Regeneration on disposable FFP2 for the case studies

	t CO_2 eq.		Thousand €		m^3	
	ΔS	S%	ΔS	S%	ΔS	S%
H	30.9	80.1	101.4	84.2	162.8	83.3
MU	42.1	72.8	138.4	76.7	219.8	75
FRS	1.2	61.9	5.3	88.1	8.9	90.9

Considering the FRS case (100 daily users), it is possible to note how regeneration allows a total saving of 1.2 tons of CO_2, 5,300 € (+ 88.1% compared to single use and repurchase), and 8.9 m^3 of urban solid waste. The effect of regeneration is more evident for the MU user (3,000 daily users) where the maximum number of reuses is equal to N_R=3 (and therefore medium-low). In this case an annual saving of 42.1 tons CO_2, 138,400€ and 219.8 m^3 of volumetric waste are spared, with a total saving of 76.7% in economic terms and a 75% reduction in the volume of urban solid waste produced by the disposable masks. The cases presented in this work are intended to give an idea of the potential environmental and economic benefits that the regeneration approach (and therefore reuse of a disposable FFP2) could bring to users of different size and function (either national bodies or private entities). In addition, there is a further positive aspect to be addressed, which is the possibility, upon mask (EL) to apply a last (BA) to abate the biological load present on the masks, enabling potential access to recycling operations. This means a further lower environmental impact, because reusing the polymeric components of a mask to create new objects means avoiding the production of new blank material (which carries with it an environmental, economic, and waste footprint). As a last step, this study quantifies the savings showed in Table 3 for the MU case study in physical assets, to make its results more intuitive.

From Table 3 it is possible to note that the adoption of the regeneration practice, over a period of one year, allows the MU, to obtain an environmental impact reduction equal, in term of eq. CO_2, to almost 4 times the Milan-Rome air route travelled by plane with a passenger load of 100 people. While in economic terms, to buy the latest generation electric super car or finally, to avoid the production of a waste volume that would completely fill 10 trucks (with a capacity of 22 m^3) of the Milan municipal garbage collection service.

Table 3. Visual of the savings incoming from the adoption of the regenerative process for case study 2

Entity	Impact Category	Savings/Year
	t CO_2	4 x 
MU	Thousand €	1 x 
	m^3	10 x 

4.2 Future developments

From the visualization of the results presented in this study follows that the application of regeneration on disposable FFP2 masks results in a significant reduction of environmental and economic and volumetric impacts, for those entities willing to adopt it. What should be generally emphasized is that the number of regenerations applicable to the disposable FFP2 largely depends on the type of use and quality of the mask itself and that cannot be standardized; it is hence important to evaluate a suitable maximum N_R for each type of use on a case-by-case basis. Since in literature there are no statistical references to the rupture percentage in relation to a specific use of a disposable FFP2, this study has hypothesized N_R=10, 5, 3 which consider both mechanical-physical (clogging of filter fibres, loss of electrostatic charge) and as well visual factors (such as blood stains, biological fluids, and environmental elements). The maximum N_R value has hence been identified as 10. This value is a compromise between the actual number of reuses (before the mask gets dirty, is lost or accidentally broken by the user) and the real ability of the materials making up the mask to withstand further regeneration cycles (this assumption is made considering, as a process regeneration process, ventilated dry heat with ozone).

In conclusion, this study demonstrates, through a series of simplified mathematical equations, that it is possible to obtain, by applying a biological load abatement process (BA) to disposable FFP2 masks, a stream of advantages in environmental and economic terms, reducing the impact related to single use, disposal and repurchase.

The study evaluates three specific cases considering different reuse numbers (R_N=3 for MU, 5 for H and 10 for FRS).

In all three cases, this work shows that regeneration undoubtedly brings environmental and economic benefits to the investigated users, making it an interesting tool for both public and private entities.

4.3 Potential challenges and limitation to the regeneration method

Possible limitations to the wide-spread use of this regenerative method, thus to disposable mask reuse, are linked to the scalability of the selected regeneration process, and to the acceptance by the users.

The scalability of the regeneration process for its potential widespread adoption depends on two main factors, one of a technological and cost-based nature and the other of a regulatory nature. The first factor is based on the simplicity of both the technology used to regenerate the masks and the procedures to be applied within the various work environments in which they are used. The regulatory factor instead refers to any restrictions given by international or national regulations regarding the reuse of said masks. Both of these factors were considered during this study and summarized below.

In the case of future epidemics or pandemics, the scalability principle of the continuous regeneration method, from a technological standpoint, is based on the following key principles: low acquisition costs, small footprint, and short device decontamination times (in the case of the selected regeneration method, up to 485 FFP2 masks can be regenerated in 30 minutes, and in an affordable space since the regeneration device occupies a volume of about 1 m^3). However, the method requires a supporting Standard Operating Procedure (SOP), and the mask must be delivered and retrieved through a container equipped with an identifying barcode for the operator, who must always reuse their own mask. This necessitates a dedicated logistics system, which is not affected by different users, regional settings, or organizational structures. Therefore, the method is suitable to be adopted globally without evident difficulties in its implementation. The following figures report some of the steps that were tested at the Milano Fire House, such as the procedure of delivery of the FFP2 mask by the user and its subsequent return following the regeneration process.

In terms of regulatory framework, the UNI EN 149 standard, stemming from a standardization process conducted by the European Committee for Standardization (CEN), delineates the requirements, testing methods, markings, and usage information for respiratory protective face masks in accordance with European standards (i.e., FFP2 and FFP3 semi-facial masks). The standard allows for the potential reuse of FFP2 masks for multiple applications or work shifts, however without specifying the quantity or duration thereof. In this context, the standard pertains to the manufacturer's indications and the quality of the product, permitting the mask's reuse for consecutive shifts. The assessment of such reuse falls within the purview of the employer, contingent upon workplace conditions, duration of use, and shift length.

Building upon the aforementioned discussion, the UNI EN 149 standard sanctions multiplex use, potentially certifiable through tests conducted by accredited laboratories, which may corroborate findings from studies, including our own, identifying specific mask regeneration techniques without compromising their original properties. While peripheral to the primary focus of this study, it is nonetheless noteworthy that there are grounds for certifying the possibility of multiple applications of FFP2 or FFP3 face masks.

Furthermore, it is imperative to recognize that such certification must harmonize with any pertinent national regulations where applicable.

Concerning the second factor, public acceptance, at this stage we have only envisioned the re-use for first responders and huge agencies operators since at this high level it is easier to set-up in parallel with the re-generation process a common

SOP that will provide the same operator with its re-generated mask multiple times. This method is hence not intended towards citizens.

Regarding the acceptance of a regeneration method, we can consider two primary audiences: users and the general public. Concerning users, they encompass workers exposed to biological risks. Although the concept outlined in this study stems from the COVID pandemic, it remains evident that the selected worker categories—namely firefighters, hospital workers, and urban waste collectors—are routinely exposed to biological hazards. Thus, our study maintains relevance for these categories even outside pandemic contexts. However, the pandemic context has prioritized safety concerns over environmental issues, potentially facilitating the acceptance of our proposed plastic material regeneration procedure in workplaces. Therefore, we believe that environmental sensitivity in work environments may be more easily promoted during peacetime, thereby enhancing acceptance of the proposed regeneration procedure.

Potential obstacles to the acceptance of such a method by users are twofold, as analyzed in our study. The first concerns how an FFP2-type mask is perceived. Treating the mask as a personal item, our study proposes a procedure that assigns masks to individual workers during subsequent reuses, rather than redistributing regenerated masks to different colleagues. While this logistical approach adds complexity, it mitigates a significant barrier to user adoption, as illustrated in Figures 7 and 8.

Figure 7. SOP for FFP2 mask reuse

Figure 8. SOP for FFP2 mask reuse, operators giving back its mask to the regeneration operator (COVID-19 period)

The second potential obstacle pertains to the olfactory perception of a regenerated mask. In the identified regeneration process, ozone—a constituent element—leaves a faint smell in the regenerated product, associated with the notion of freshness and cleanliness.

Finally, regarding public acceptance, although this study focuses on FFP2 masks—essentially individual protective systems not typically used by the general public—we posit that the adoption of regeneration could be favourably supported due to its positive environmental impact.

4.4 Future research directions

During the COVID-19 pandemic, we witnessed a proliferation of methods for what we term here as the regeneration of biological risk filtration devices in Europe, characterized as FFP2 and FFP3 masks. Countless techniques were proposed to address the issue, which at the time was framed as a logistical challenge due to concerns about a shortage of such valuable protective systems. During this period, the biological laboratories of the CBRN unit of the Milan Fire Brigade developed a regeneration process based on a predetermined mixture of ventilated dry air at stable temperature and ozone.

The future steps of this work primarily involve publishing the outcomes of this method, only briefly described in this study, which instead focuses on the environmental and economic implications of employing such a process. Here, it is our intention to mention that our study includes a comparison of the identified regeneration method with other methods and technologies, as well as the optimization of the regeneration process in terms of efficiency and costs. For the purposes of this study, it is not pertinent to detail the results of these investigations. However, it is worth noting that the outcome of our experiments is highly positive and warrants further exploration to demonstrate its validity not only concerning its demonstrated resistance to SARS-CoV-2 and bacteria but also by extending it to additional classes of pathogens. It follows that such experiments would also bolster the certification of the method.

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