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"Gheorghe Asachi" Technical University of Iasi, Romania

PERSONAL PROTECTIVE EQUIPMENT (PPE) DURING THE COVID-19 CRISIS: A REVIEW OF CURRENT KNOWLEDGE AND FUTURE DIRECTIONS

Emanuela-Adina Nicula[1], Remus Creţan[2], Alexandru-Sabin Nicula[1,3,4*]

[1]Romanian Academy, "Costin C. Kiriţescu" National Institute for Economic Research, Mountain Economy Center, Petreni Street 49, 725700, Vatra Dornei, Romania
[2]West University of Timişoara, Department of Geography, Vasile Pârvan Avenue 4, 300223, Timişoara, Romania
[3]Babeş-Bolyai University, Faculty of Geography, Centre for Research on Settlements and Urbanism, Clinicilor Street 5-7, 400006, Cluj-Napoca, Romania
[4]Romanian Academy, School of Advanced Studies of the Romanian Academy, Doctoral School of Economic Sciences, "Costin C. Kiriţescu" National Institute for Economic Research, Institute for Economic Forecasting, 13 Septembrie Street 13, 050711, Bucharest, Romania

Abstract

The COVID-19 pandemic significantly altered everyday life, making Personal Protective Equipment (PPE) a mandatory "social norm" worldwide. While PPE serves a critical protective function, it also has a controversial dark side related to environmental pollution. The release of contaminated plastic into the environment threatens the achievement of fundamental Sustainable Development Goals. This study is based on a comprehensive bibliographic analysis of existing literature on PPE, with a focus on face masks as a primary component. The aim of our research is to highlight the significant environmental impact of increased usage and improper disposal of PPE, leading to plastic pollution. In addition to consolidating existing knowledge on PPE, this paper explores the magnitude of the issue and reviews potential solutions, such as the development of biodegradable PPE, the use of cloth masks, effective waste management practices, and recycling and reusing methods. These steps are crucial in preparing for future health crises.

Key words: Covid-19 pandemic, environmental waste, face masks, Personal Protective Equipment (PPE), plastic pollution

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1. Introduction

Today's reality worldwide is governed by two major crises: one concerning health, due to Covid-19, and one concerning the environment, attributed to climate change, both being intensively debated and investigated in order to develop sustainable strategies to overcome them. During the times "ruled" by COVID-19 (the pandemic was declared on 11 March 2020 by the World Health Organization) (Murray et al., 2020), masks and related waste were a ubiquitous sight, ranging from urban agglomerations (Van Fan et al., 2021) to oceans (Abdullah and Aal, 2021), beaches (Ardusso et al., 2021), and mountain areas, as a result of rapacious consumption (Ammendolia et al., 2021). The increased use of face masks constitutes a real threat to the environment as no administration or authority had been prepared for such a massive quantity of plastic-containing materials to be continuously discarded without proper and sustainable management. It is important to highlight that the harmful and undesirable environmental impact of Personal Protective Equipment is translated into: "macro/meso/micro/nano plastic pollution" (Dey et

* Author to whom all correspondence should be addressed: e-mail: sabin.nicula@gmail.com; Phone: +40 749 980 159

al., 2023), contamination and alteration of terrestrial and aquatic ecosystems (Cubas et al., 2023; Ortega et al., 2023; Pizzaro-Ortega et al., 2022), microbiome changes, water and soil degradation, solid waste accumulation (Iddrisu et al., 2024; Khan et al., 2023; Sangkham 2020; Soo et al., 2022), and contribution to Greenhouse Gases (GHG) emissions.

Plastic PPE opened a literal Pandora's box (Chawla et al., 2020), scientists around the world speaking of plastic catastrophes (Shammi and Tareq, 2020) or a "plastic plague" (Shetty et al., 2020), which can only worsen the current and unresolved worldwide plastic contamination.

The starting point of our endeavour was the recommendation made by the World Health Organization (WHO) to wear masks as a crucial step to curb the spread of the pandemic and save lives (WHO, 2021a), with the distinction that medical masks should be worn by frontline health workers in clinical settings and people with Covid-19 suggestive symptoms (Greenhalgh et al., 2020), while non-medical fabric masks should be worn by the public at large.

At the time of this paper's conceptualisation, respectively close to the end of 2023, three years after the Covid-19 outbreak, the world still battles the ongoing pandemic situation, new cases being reported worldwide every day. Most recent data indicates that 231 countries and territories around the world are still affected by the virus, the total cases reaching 702,756,923, of which 673,661,508 being recovered individuals and 6,979,015 fatalities (Worldometer, 2024), with the mention that a share of 67% of the world population has gone through a complete initial protocol of vaccination (Our World in Data, 2024).

The general population started using large amounts single-use face masks on a regular basis, thus leading to a new type of waste. Governments lacked sustainable strategies for such refuse and, consequently, a new phenomenon emerged: public littering of used face masks (Ammendolia et al., 2021; Mejjad et al., 2021; Prata et al., 2021; Roberts et al., 2021; Roberts et al., 2022). Fadare and Okoffo (2020) suggest that this behaviour can contribute to the accumulation of microfiber in the environment, with direct effects on microplastic contamination and pollution, some authors researching the topic even coining a new name for our era - The Plasticene (Canning-Clode et al., 2020; Corcoran et al., 2014; Haram et al., 2019; Reed, 2015).

This paper aims to review primary literature on PPE, face masks mainly, based on the fact that their increased use and improper discarding may contribute to the dispersion and accumulation of significant amounts of (micro-) plastic in the environment, endangering its wellbeing and severely impacting the ongoing global efforts to reduce plastic pollution, hindering the advances made in achieving fundamental Sustainable Development Goals (SDG) such as: SDG 3 (Good Health and Well-Being) SDG 6 (Clean Water and Sanitation), SDG 8 (Decent Work and Economic Growth), SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action).

The study contributes to the extant corpus of knowledge pertaining to COVID-19 at both international (Chakraborty and Maity, 2020; Chintalapudi et al., 2020; Jupîneanț et al., 2023; Shetty et al., 2020;) and Romanian (Crețan, 2021; Crețan and Light, 2020; Dascălu, 2020; Doiciar and Crețan, 2021) levels, while also enhancing the scholarly discourse surrounding PPE research. This approach is important because there was identified a need for deeper comprehension about the pollution generated by simply throwing away and improperly managing these items when it comes to stakeholders and the general populace. These aspects are more relevant than ever, considering the fact that scholars anticipate an increase in face masks and related PPE items by 40% per month until 2025 (Dey et al., 2023; Ilyas et al., 2020). The research could also contribute to the development of more effective communication and educational strategies (Ilovan et al., 2018; Nicula et al., 2017) and can be a starting point to change these behaviours.

Even if there has been an extensive global use of face masks, the environmental implications remain poorly understood still and there is a limited number of research focusing on the topic and on assessing the life cycle of these items. In conclusion, the study can pave the way for future research, innovation, and policy-making efforts aimed at enhancing the effectiveness, sustainability, and compliance of PPE usage, filling in an existent literature gap.

2. Theoretical background

2.1. Single-use face masks–the most common PPE engaged in the COVID-19 battle

Starting back in 2020, an unprecedented year during which a dangerous virus surfaced (JHCRC, 2021; WHO, 2021b), a novel type of coronavirus, dubbed SARS-CoV-2 (Severe Acute Respiratory Syndrome Coronavirus 2) (Binda et al., 2021; Rothan and Byrareddy, 2020), was responsible for the Coronavirus disease known as COVID-19.

Chakraborty and Maity (2020, p.2) state that: "the COVID-19 pandemic is considered as the most crucial global health calamity of the century and the greatest challenge humankind has faced since the Second World War".

In the new paradigm created by the pandemic advent, Personal Protective Equipment (PPE) represent "a current hot topic" (Cook, 2020, p.920) and a "critical subject" (Kalantary et al., 2020), a must have for all, both for frontline healthcare staff and the general population, as well as the best strategy to prevent the spread of COVID-19 (Higginson et al., 2020). Scholars indicate various definitions for PPE, respectively: "an equipment worn to minimize the exposure to hazards that cause serious workplace injuries and illnesses" (Chawla et al., 2020); "the protective clothing […] designed to protect the

wearer's body from infection and injury" (Allison et al., 2020, p.5), and "the most reliable and affordable defence against infection and the transmission of the virus" (Vanapalli et al., 2021). PPE usually includes surgical face masks, gloves, gowns, aprons, goggles, protective eyewear, face shields (Haque et al., 2021; Higginson et al., 2020; Kalantary et al., 2020; Shammi and Tareq, 2020; Singh et al., 2020).

Considering the scope of the pandemic, PPE rapidly became the most readily available weapon worldwide to fight this battle. Many countries adopted restrictive precautionary measures for fighting and against the spread of COVID-19 (Silva et al., 2021), the most widespread and direct being the mass wearing of face masks (Chintalapudi et al., 2020; Lin et al., 2020; Mitze et al., 2020; Rhee, 2020; Wang et al., 2020) on a daily basis, as a mandatory condition. By May 2020, data indicated that 88% of the world's population (approximately 6.7 billion people) resided in countries that mandated the wearing of face masks in public areas (Akarsu et al., 2021).

Such materials basically became a part of everyday routine, the habit becoming omnipresent worldwide (Feng et al., 2020; Matusiak et al., 2020). On the other hand, Ghosh et al., (2020) indicate that the use of face masks as means of protection has had a long history, dating back to the Roman Empire as well as the Middle Ages: miners covered their faces with animal bladders, sailors used wet pieces of cloth material wrapped around their faces, knights used visors as armour for their safety and so on.

According to Allison et al., (2020) a medical mask is an "unfitted (i.e. loose-fitting) mask worn by an infected person, healthcare worker, or member of the public to reduce the transfer of potentially infectious body fluids between individuals".

Due to the highly contagious nature of the virus and the ensuing lockdown directives (Haque, et al., 2021), millions of face masks have been manufactured. They were later used and discarded across the globe, Prata et al., (2020); Silva et al., (2021) indicated a monthly estimate use of 129 billion face masks worldwide, while Benson et al., (2021) calculated that approximately 3.4 billion single-use facemasks are being disposed of per day worldwide.

Single-use face masks contain mixed plastics (Vanapalli et al., 2021) and consist of multiple polymer layers (Monella, 2020), such as: polypropylene, polyurethane, polyacrylonitrile, polystyrene, polycarbonate, polyethylene, or polyester (Aragaw, 2020; Potluri and Needham, 2005 cited in Fadare and Okoffo, 2020). Most face masks are comprised of three layers: inner (containing soft fibres), middle (known as the melt-blown filter) and the outer layer (most of the times coloured and containing water-resistant nonwoven fibres) (Ardusso et al., 2021). Because of these common plastic components, especially polypropylene (a type of microplastic), face masks and other types of PPE are extremely difficult to recycle and take a long time to naturally decay (they generally have a 450 year life span) thus making them genuine ecological ticking time bombs likely to turn into a disaster for biodiversity (Visram, 2020).

2.2. Plastic pollution and single-use face masks

Plastic pollution is spread across the world (De-la-Torre et al., 2021a; Malizia and Monmany-Garzia, 2019) and has been a huge environmental concern even before the COVID-19 pandemic due to its long and short-term consequences to terrestrial and aquatic ecosystems (Borrelle et al., 2020; Chowdhury et al., 2020; Compa et al., 2019, Costa et al., 2023; da Costa, 2021; Dioses-Salinas et al., 2020; Egessa et al., 2020; Harris et al., 2021; Häder et al., 2020; Kannan et al., 2023; Lau et al., 2020; Mehran et al., 2021; Vlachogianni et al., 2020; Weideman et al., 2020). The pandemic has exacerbated this problem through increased plastic demand and consumption and the follow-up waste (Klemeš et al., 2020; Van Fan et al., 2021).

As previously mentioned, face masks are known to be included in the single-use plastics (SUPs) product category. After being discarded, masks become waste, but are not classified and managed as hazardous waste (Cociș et al., 2012; Vac et al., 2012) since their primary source of origin are households and the general population. Also overlooked is the fact that they contain plastic that needs to be handled properly. An example is presented by Parashar and Hait (2021), in Wuhan, where roughly 200 kg of face masks were found in 200 public waste bins.

This new type of waste (COVID-19 litter) (Hiemstra et al., 2021) is located in a grey area between general waste and medical waste (Yeh, 2020). Unfortunately, because of the uncertainty created and the lack of implemented mandatory laws, there have been many documented cases of littering worldwide (De-la-Torre and Aragaw, 2021; De-la-Torre et al., 2021b; Ryan et al., 2020; Silva et al., 2021).

A WWF report indicates that 1% of improperly managed face masks would result in approx. 10 million face masks/per month accumulated in the environment.

Considering that each mask weights about 4 grams, this would lead to the dispersion of more than 40 thousand kilograms of plastic in nature, as stipulated by the same report (Shetty et al., 2020, Silva et al., 2020).

Dey et al., (2023) state that the life of single-use face masks is influenced by the materials they are made from and the environmental conditions they encounter, Chamas et al., (2020) indicating that terrestrial environments favour degradation compared to aquatic ones because of temperature variation, water absorption. We basically have a front seat to an environmental disaster waiting to happen. Our dependency on plastics, coupled with a reluctance to recycle will leave a long-lasting footprint for future generations (Reed, 2015).

3. Methods

In order to achieve a broad review, accurate information was gathered regarding the research topic. A detailed screening was also conducted, followed by the extraction of original articles, review articles, short communications, letters to editor, cover stories from Web of Science Clarivate Analytics and Scopus search engines. The main keywords for the search were "Sars-CoV-2" OR "Coronavirus" OR "COVID-19" in conjunction with "Personal Protective Equipment" OR "PPE" OR "face mask*" OR "environment" OR "plastic pollution" OR "waste". The outcomes were limited to the period comprised between 2020 and 2021 at first, as most articles tackling face masks (the most common PPE) as a possible source of environmental plastic pollution associated with the COVID-19 pandemic were published in the aforementioned years, but the most relevant ones written in 2022-2024 were also consulted later. Where necessary, the most representative references cited in the retrieved documents were consulted. Searched by title, a total of 872,443 scientific documents were found, namely 107,409 (2020), 165,618 (2021), 146,576 (2022), 97,528 (2023) and 4932 (2024). The temporal analysis of the data set initially reveals an escalation in editorial activity between 2020 and 2021, likely in response to the critical imperative to develop and optimize Personal Protective Equipment (PPE) amidst the global public health emergency posed by the COVID-19 pandemic, followed by a progressive and substantial reduction in the volume of specialized publications from 2022 to 2024. This trend could be attributed to a combination of factors, including the mitigation of the crisis's acuity due to vaccination efforts and the attainment of herd immunity, as well as a potential saturation of the scholarly literature in this specific field, thus prompting a redirection of research interests towards new challenges and paradigms in public health. A selection was then made taking into account titles and abstracts.

We acknowledge the crucial role that the selection process plays in shaping the scope and validity of our review results. This criterion was established to ensure a rigorous and transparent selection process, enabling the identification of the most relevant studies while minimizing the risk of bias. By clearly stating this parameter, we aim to provide a reproducible and objective framework for our study selection, thus enhancing the reliability and applicability of our review findings. The inclusion criteria were made by taking into consideration four components: the type of scientific document (review articles were prioritized); the highly cited papers; the hot papers and the newest ones. The selected references (129) that were summarized have been tabulated (Table 1A in Appedix). A graphical representation of bibliographic analysis was also conducted, based on publication year (Fig. 1a)) and journal reviewed (Fig. 1b).

We can say that most reviewed and cited articles are from 2020 (61), the emblematic pandemic year and from 2021 (35). The abundance of articles on PPE during this time was a direct response to the critical role of PPE in controlling the pandemic. The scientific community mobilized to address the immediate need for effective protection, tackle global shortages, understand the virus's transmission, inform guidelines and best practices, drive innovation in PPE, minimizing the environmental impact etc. This body of work represents a concerted effort to mitigate the impact of the pandemic and conserve public and environmental health.

Figure 1 shows also some articles (from the period 1990-2018) that were included because they approach topics related to plastic PPE and provide insights that helped shape this study (e.g. technical textile for protection, professional homemade masks, cloth masks performance and efficacy, plastic pollution, environmental impact of plastic, hazardous waste). In terms of journals, Figure 1 shows that most of reviewed articles were published in Science of the Total Environment, which promotes scientific research into the environment and its relationship with humankind.

It is important to mention that no record of interest towards this research subject was found, dating from before to the current pandemic. Additionally, official statements, technical guidelines, press releases of international organizations, such as the World Health Organization, John Hopkins Coronavirus Resource Center (JHCRC, 2021), were consulted for the official and trustworthy information provided. Data interpretation was based on selecting major debates on two lines of study - single-use face masks and plastic pollution, followed by discussions on the findings and implications and limitations.

4. Results and discussion

4.1. Single-use face masks as a source of plastic in the environment

Plastic is the most widespread material of the modern era, found everywhere around us, being indispensable and ubiquitous (Alvarez, 2018; Ziani et al., 2023) due to its affordability and availability (Anderson et al., 2021), versatility, durability and flexibility (Malizia and Monmany-Garzia, 2019; Silva et al., 2020).

During the COVID-19 pandemic, plastic based products have been of paramount importance as life-saving protective gears, but their known negative environmental implications seem to have been overlooked or even cast aside, at least for the moment. Despite this, researchers started focusing on the investigation of the after-use environmental impact of single–use face masks as a potential source of plastic contamination (Haque et al., 2021; Haque and Fan, 2022; Hiloidhari and Bandyopadhyay, 2023; Singh et al., 2020; Tabatabaei et. al., 2021).

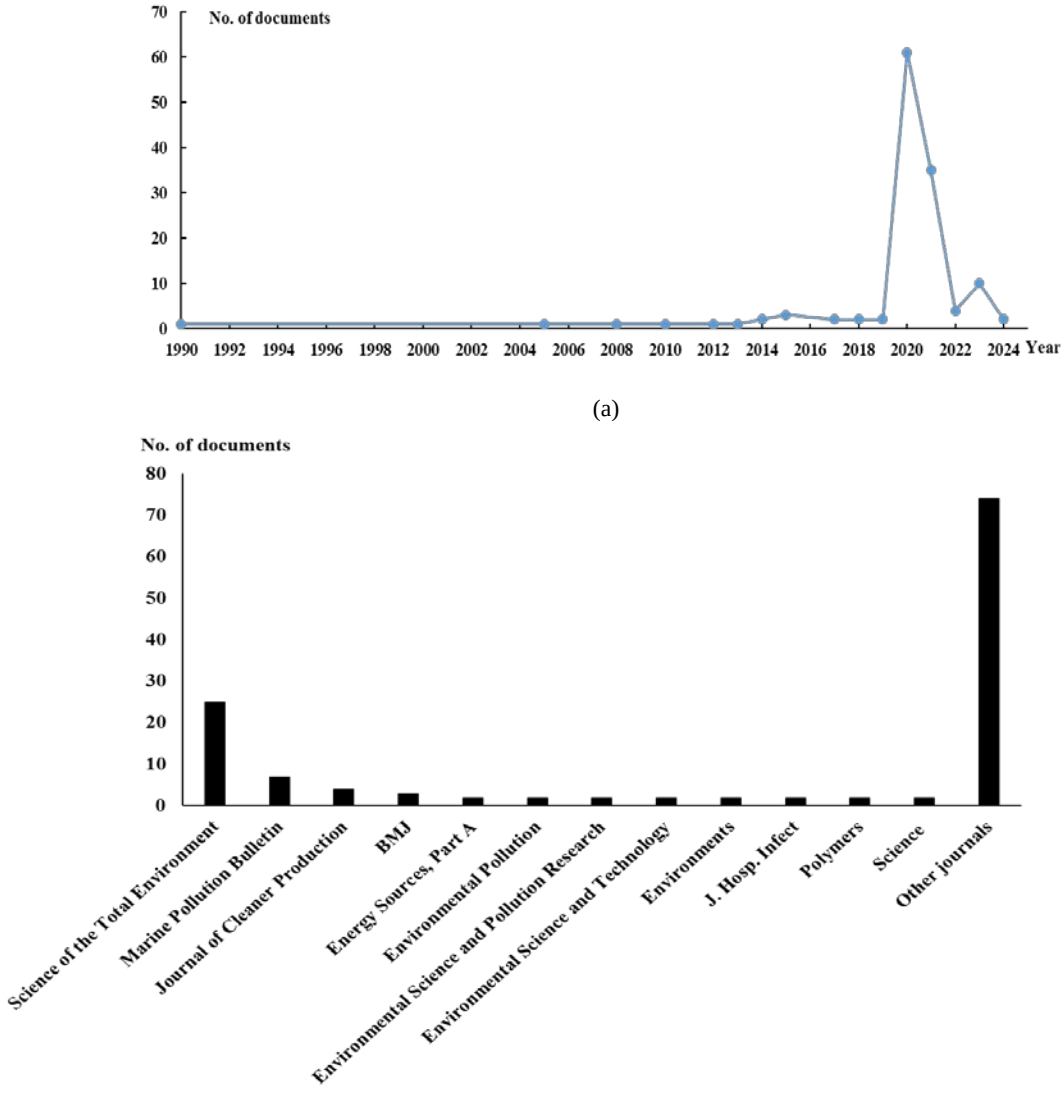

Fig. 1. Temporal (a) and thematic analysis of published journals (b)
Data source: Web of Science Clarivate, 2024

Based on an accumulation survey, conducted to establish the amount of PPE improperly disposed of, Ammendiola et al., (2021) discovered that, from the total PPE debris documented in the metropolitan area of Toronto, Canada, 31% were face masks (97% were intended for single-use) and labelled them as newly identified sources of plastic contamination. Similarly, Fadare and Okoffo (2020) indicated that disposable face mask waste could be a new source of microplastic fibres, as they degrade/fragment into particles smaller than 5 mm, known as microplastics, under environmental conditions.

They also highlight that the plastic and microplastic components of masks have adverse effects on aquatic lives, with direct implications on human health, and may significantly contribute to climate change (Nistor et al., 2018). Last but not least, the indecorously discarded face masks can act as disease vectors, as plastic particles have the ability to propagate various pathogens. Haque et al. (2021) made several projections based on current pandemic trends, respectively wearing face masks, and concluded that humanity faces a new type of plastic waste problem that is likely to cause severe microplastic pollution in both terrestrial and aquatic environments.

This unprecedented increase in the amount of single-use face masks found almost everywhere (roads, medical facilities, parking lots, beaches, landfills, gutters, and shopping carts, etc.,), induced Benson et al. (2021) to focus their research on the assessment of the environmental footprint of plastic waste generated during COVID-19 pandemic as they studied the potential impact related to plastic pollution. In order to achieve said result, they calculated the daily as well as the monthly quantities of face masks generated by each country (with an average of 1 mask/capita/day) and the related plastic waste, with the aid of self-devised model equation. Regional estimates are shown in Table 1.

Table 1. Estimated daily amount of discarded face masks and generated plastic waste (Benson et al., 2021)

Region	*Average face mask / capita/day*	*Estimated daily facemask discarded*	*Estimated plastic waste generated (tons)*	*Estimated plastic waste generated per day (tons)*
Asia	1	1,875,181,681	348,079,108	953,641
Europe	1	445,022,934	56,072,702	153,623
Africa	1	411,814,854	100,544,861	275,465
South America	1	380,414,703	49,046,434	134,373
North America	1	244,335,150	27,665,223	75,795
Oceania	1	21,682,379	3,200,836	8,769
Total		**3,378,451,702**	**584,609,165**	**1,601,666**

They also devised a classification of pandemic plastic products in macro- and mesoplastics, specifying that such materials can disrupt the environment through poor waste management or inadequate discharge. In complete consonance with Benson et al., (2021); Boyle (2020) and Chaudhuri (2020), strongly believe that significant amounts of used face masks are a contributing factor to the vast amount of plastic pollution and will potentially worsen the already existing plastic crisis. An analogous study was devised by Allison et al. (2020) by estimating the daily quantity of plastic resulted from wearing single-use face masks in the United Kingdom. They highlighted that if every person used one single-use mask each day for a year (an optimistic scenario), the result would be 66,000 tons of contaminated plastic waste, the resulting impact on climate change being ten times higher than the usage of reusable masks. They also state that the lack of existing systems for the general public along with a mandatory face mask wearing policy will eventually lead to thousands of tons of landfilled contaminated waste.Based on similar calculations, Akarsu et al., (2021) indicated that approximately 50 million contaminated face masks have been generated daily in Turkey, which translates to 73,000 tons of contaminated waste per year. Aragaw et al. (2020) argued that microplastic pollution caused by face masks should be a worldwide focus in order to fill in the huge knowledge gaps on the matter. The research conducted revealed that once littered, face masks end up in rivers and from there into large bodies of water such as seas and oceans, being an emerging source of microplastic fibre contamination.

Focusing on the environmental burdens that single-use face masks are carrying, Prata et al. (2021) indicate that this type of PPE is exacerbating the plastic contamination problem, from the production process (release of greenhouse gases) to the disposal, while environmental issues are strongly related to the type of mask used and people's behaviour. In a previous study, Prata et al. (2020) argue that littered face mask residue will most certainly become a frequent sight, present in the environment for decades to come and possibly disturbing the ecological balance.

Nowakowski et al. (2020) conducted a study on the disposal of PPE (face masks and gloves) during the COVID-19 pandemic in Poland, through telephone surveys and online questionnaires. Respondents identified that the resulted PPE waste represents a threat to the environment, causing, among other things, plastic pollution, a fact also stated by Anderson et al. (2021).

The increased use of PPE, as a possible cause for secondary environmental catastrophes, was also investigated by Shammi and Tareq (2020). The case study was Bangladesh and they concluded that disposable masks (as plastic polymers) will contribute to microplastic pollution and will irreversibly damage the health of the ecosystem.

Also regarding (micro-) plastic pollution, Abbasi et al., (2020) expressed their concerns regarding the considerable use of face masks. Thusly, they computed the number of face masks that are likely to be used in each of the countries of the Arabian Peninsula, taking into consideration varying levels of acceptance rate and average number of daily uses. Their research also concluded that (micro-) plastic fractions will accumulate in terrestrial and marine environments. The formula used to calculate the daily mask usage (DMU) was (Eq, 1) (Abbasi et al., 2020):

$$DMU = P * \gamma * \delta * \beta \quad (1)$$

where: (P) represents the total population, percentage of urban population (γ), acceptance rate (δ) for the usage of masks, and the average daily number of masks (β) used per person. They deduced that (micro) plastic contamination in the Arabian Peninsula must become a top priority in the current COVID-19 pandemic.

Other scholars reported that the coastal areas of overpopulated cities, such as Lima, Peru, are cluttered with PPE, mostly masks, their inadequate disposal on beaches or surfing and fishing sites representing a source of microplastics (De-la-Torre et al., 2021b).

As indicated in the previously reviewed literature, the increased usage of single use face masks during the Covid-19 pandemic created mask waste which, if inadequately managed, can raise environmental concerns (Hartanto and Mayasari, 2021; Nzediegwu and Chang, 2020). This new surge of litter has also transformed into a serious threat to animal life, Hiemstra et al., (2021) presenting the first overview of cases of face masks used by birds as

nesting material (2 reported cases in Netherlands), cases of ingestion (5 reported cases in Brazil, Netherlands, USA, UK,), entanglement (10 reported cases in Canada, France, Italy, Netherlands, USA, UK), carrying (3 reported cases in the UK), chewing (1 reported case in Malaysia) and hiding (1 reported case in France). Nature is sick and tired of our plastic, therefore single-use disposable masks as PPE need to be completely overhauled in order to reduce their environmental impact.

4.2. Cloth masks - a green and clean alternative to single-use face masks

Taking in consideration that the plastic components of disposable face-masks are extremely dangerous for the environment, eco-friendly alternatives, such as reusable masks for the general public, have been recommended by various scholars, Prata et al., (2021) highlighting that a correct use and maintenance of reusable masks appears to have three major advantages: reduced waste, by 85%; lower climate impact (3.5 times lower); reduced cost (3.7 times cheaper).

In their analysis, Greenhalgh et al., (2020) also indicate that cloth masks should be used as a substitute for disposable masks, in order to prevent shortages for healthcare workers on one hand and protect the public on the other. Javid et al. (2020) agree with the former, but at the same time raise the question whether the protection role and benefits of disposable masks can be extrapolated to cloth masks, as sound evidence is still thin. However, the existing data suggest that reusable cloth masks are 15% less effective in retaining pathogens than single use-surgical ones (Javid et al., 2020). Dharmaraj et al. (2021) emphasized that three-layered cloth masks, made of 70% cotton and 30% polyester, exhibited nearly 40-60% filtration efficiency.

Other researchers focused on environmentally friendly non-medical masks, respectively Hartanto and Mayasari (2021) as they used an analytic hierarchy process (AHP, developed by Saaty, 1990) to determine suitable materials for manufacturing, taking into consideration the following parameters: breathability, comfortability, filtration efficiency and environmental impact index. Their findings showed that the best materials for eco-friendly masks, out of a total of 26 alternatives, were Quilt, Cotton 600 TPI and Quilting cotton, as they fully comply with WHO standards and requirements.

Other research on the performance of fabrics and materials for making cloth face masks includes: Aydin et al., (2020); Chua et al., (2020); Clase et al., (2020); Davies et al., (2013); Jang and Kim (2015); Jung et al., (2014); Konda et al., (2020); MacIntyre et al., (2015); Mueller et al., (2020); Rengasamy et al., (2010); Rogak et al., (2020); Shakya et al., (2017); Tcharkhtchi et al., (2021); Teesing et al., (2020); van der Sande et al., (2008), Wilson et al., (2020); Zhao et al., (2020).

The non-traditional materials widely recommended for public use in the form of homemade facial masks are: cotton fabrics (100 % cotton T-shirt), natural silk, chiffon, tea towel, vacuum cleaner bag, pillowcase, antimicrobial pillowcase, cotton mix, linen, scarf, non-woven sterile wraps, dried baby wipes, since they are washable and reusable. Furthermore, they help mitigate the detrimental environmental effects of widespread use of disposable and non-biodegradable face masks and can provide significant protection against the transmission of aerosol particles and pathogens.

5. Implications and limitations

5.1. Managerial implications

In light of the comprehensive review conducted on the usage, efficacy and impacts of PPE during and post COVID-19 pandemic, it becomes paramount for managerial entities and policy makers to heed a multifaceted approach, rooted in both immediate actions and strategic foresight.

Plastic being ubiquitous and scholars sounding the alarm on plastic pollution as the next global pandemic (Fadare and Okoffo, 2020), all efforts must be concentrated on curbing the persistent proliferation of plastic waste, in order to sustain the planetary boundaries that keep Earth stable (Rockström and Gaffney, 2021).

Solving the problem of single-use face mask plastic pollution requires transdisciplinary approaches and the involvement of all interested parties (scientists, policymakers, stakeholders, service providers, waste managers), from local to national level (Nistor and Nicula, 2021). It is critical to raise awareness and educate the citizens to not jeopardize the health and security of the environment by consuming large amounts of disposable masks and create future unwanted consequences in the shape of plastic contamination (Abbasi et al., 2020; Ammendolia et al., 2021) and appeal instead to reusable alternatives. The idea that the general public must be taught about adequate use and disposal of single-use plastic masks is also endorsed by the research of Anderson et al., (2021), highlighting that the key to any pandemic situation is to combine each individual's active and responsible participation with law enforcement in order to avoid for plastic to transform from "protector with high utility to polluter" (Parashar and Hait, 2021).

Protocols must be created, green and sustainable solutions must be enforced, significant efforts are mandatory to reach a better and sustainable solid waste management for this plastic-containing PPE (De-la-Torre et al., 2021b), to implement cutting-edge recycling and repurposing methods (Torres and De-la-Torre, 2021) and restrain the current plastic pandemic (Parashar and Hait, 2021).

Another proposed solution is to rethink and redesign conventional face masks by using biodegradable materials such as hemp, starch, rice husk as well as the advocating towards reusable

masks, as they are harmless to terrestrial and marine ecosystems, thus reducing the amounts of generated mask waste (De-la-Torre et al., 2021b; Dharmaraj et al., 2021).

In order to mitigate the impact of generated PPE waste, Saberian et al., (2021) suggest an innovative procedure to recycle used surgical face masks by shredding and mixing them with other waste materials for pavements base/sub-base layers in civil constructions, reducing the construction costs and environmental consequences. More advanced solutions were put forward by Hu and Lin (2021) such as the transformation of polypropylene plastic into cathodes for super capacitors. Battegazzore et al. (2020) proposed various analyses (morphological, chemical, physical, thermal) on face masks and then introducing, validating and developing different recycling methods.

In retrospect, innovation in PPE technology must be prioritized to develop more effective, reusable, and sustainable solutions, thereby reducing dependence on single-use items. This includes the adoption of new materials and designs that offer higher levels of protection, comfort, and environmental sustainability. Education and training programs for healthcare workers and the public on proper PPE use are essential to maximize its effectiveness and minimize wastage. Lastly, fostering collaboration among governments, industry, and research institutions is crucial for sharing knowledge, coordinating responses, and driving advancements in PPE technology. By addressing these recommendations, we can enhance the global preparedness for current and future health crises, ensuring that PPE serves as a cornerstone of infection control strategies.

5.2. Limitations of study and future directions

While this review provides comprehensive insights into the usage, disposal and impact of PPE during the COVID-19 crisis, it is not without limitations. One significant limitation is the study's reliance on published literature and guidelines available up to the point of writing, which may not capture the most recent advancements or emerging challenges in PPE technology and practices. Future research should consider longitudinal studies to understand the long-term effectiveness and impacts of PPE usage, including new developments in materials and design that could offer improved protection and sustainability.

Another limitation is the focus primarily on healthcare settings, which overlooks the experiences and challenges of PPE usage in non-healthcare environments such as retail, education, and public transportation. Future studies could explore PPE practices across these sectors to develop more holistic and adaptable PPE guidelines.

Moreover, the environmental impact of increased PPE usage is a critical concern that warrants further investigation. Future research should explore innovative solutions for reducing the environmental footprint of PPE, including the development and commercialization of biodegradable and recyclable PPE materials.

Lastly, there is a need for more in-depth studies on the socio-economic barriers to accessing quality PPE, especially in low-resource settings. Future research could identify effective strategies for improving PPE accessibility and affordability, ensuring equitable protection for all populations against COVID-19 and future pandemics.

6. Conclusions

The COVID-19 pandemic changed the status quo and mandated governments across the globe to enforce the use of face masks for their citizens, as the recommendations made by the WHO were mostly poorly interpreted. It has become clear that the COVID-19 pandemic made people turn in great numbers towards the use of this type of PPE, sources of plastic pollution and peril towards the security and health of all environments. This fact has led to the intensification of the littering phenomenon due to the improper disposal of mask waste and lack of adequate management options. In this respect, this study indicates that single-use disposable face masks should be given a careful consideration regarding (micro-) plastic pollution, the matter being one of great concern and providing fertile ground for more detailed future research to fully understand the dimensions of the problem and find viable solutions.

The general conclusion is the necessity of acknowledging that the COVID-19 pandemic increased our plastic dependency, especially through the use of protective face masks. However, it is imperative to maintain a healthy balance between our behaviour and environmental sustainability. Plastic can be a friend and ally if we apply the elements of circular economy (reduction, recycle, recovery), but also our worst enemy and polluter if mismanaged. It is time to rethink our interaction with our planet and understand the COVID-19 pandemic as an opportunity to identify and strengthen all critical weak points (the everlasting plastic issue and its management, waste that is on the verge of environmental asphyxiation) as well as to environmentally educate ourselves in order to prevent future turning points.

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Appendix

Table 1A. Tabular literature summaries

Author	***Type of source***	***Major topic***
Ardusso et al., (2021); Alvarez (2018); Benson et al., (2021); Borrelle et al., (2020); Chamas et al., (2023); Chowdhury et al., (2020); Compa et al., (2019); da Costa (2021); De-la-Torre et al., (2021a), Dioses-Salinas et al., (2021); Egessa et al., (2020); Häder et al., (2020); Haram et al., (2020); Harris et al., (2021); Lau et al., (2020); Malizia and Monmany-Garzia (2019); Monella (2020); Reed (2015); Silva et al., (2020); Silva et al., (2021); Pizzaro-Ortega et al., (2023); Vlachogianni et al., (2021); Weideman et al., (2020); Ziani et al., (2023).	Research	Plastic/Microplastic pollution/contamination; Covid-19; Plastic waste
Abbasi et al., (2020); Akarsu et al., (2021); Allison et al., (2020); Aragaw (2020); Battegazzore et al., (2020); Boyle (2020); Chua et al., (2020); Cook (2020); Costa et al., (2023); Cubas et al., (2023); Dey et al., (2023); Dharmaraj et al., (2021); Fadare and Okoffo (2020); Feng et al., (2020); Ghosh et al., (2020); Greenhalgh et al., (2020); Yeh (2020); Hartanto and Mayasari (2021); Hu and Lin (2021); Javid et al., (2020); Jung et al., (2014); Matusiak et al., (2020); Mejjad et al., (2021); Mitze et al., (2020); Murray et al., (2020); Prata et al., (2021); Saberian et al., (2021); Soo et al., (2022); Tcharkhtchi et al., (2021); Teesing et al., (2020); Torres and De-la-Torre (2021); Van der Sande et al., (2008); Visram (2020); Wang et al., (2020).	Research; Discussion; Stories	Face masks; Single-use face masks; Pollution; Environmental issues
Abdullah and Aal (2021); Ammendolia et al., (2021); Binda et al., (2021); Chawla et al., (2020); De-la-Torre and Aragaw (2021); De-la-Torre et al., (2021b); Higginson et al., (2020); Hiloidhari and Bandyopadhyay (2023); Kalantary et al., (2020); Khan et al., (2023); Iddrisu et al., (2023); Ilyas et al., (2023); Nowakowski et al., (2020); Ortega et al., (2023); Rhee (2020); Roberts et al., (2021); Roberts et al., (2022); Sangkham (2020); Shammi and Tareq (2020); Singh et al., (2020).	Research	Personal Protective Equipment (PPE); Environmental impact; Plastic pollution; Waste; Litter
Clase et al., (2020); Davies et al., (2013); Jang and Kim (2015); Konda et al., (2020); MacIntyre et al., (2015); Mueller et al., (2020); Potluri and Needham (2005); Rengasamy et al., (2010);	Research	Cloth masks; Homemade masks; Pandemic, Textiles for protection; Non-traditional masks
Author	***Type of source***	***Major topic***

Shakya et al., (2017); Wilson et al., (2020); Zhao et al., (2020); Anderson et al., (2021); Aydin et al., (2020); Canning-Clode et al., (2020); Chakraborty and Maity (2020); Chaudhuri (2020); Chintalapudi et al., (2020); Cociș et al., (2012); Corcoran et al., (2014); Crețan and Light (2020); Crețan (2021); Dascălu (2021);	Research Discussion	COVID-19 pandemic; Plastic pollution; Plastic waste management; PPE and pandemic related topics
Doiciar and Crețan (2021); Haque et al., (2021); Haque and Fan (2022); Hiemstra et al., (2021); Ilovan et al., (2018); Jupîneanț et al., (2023); Kannan et al., (2023); Klemeš et al., (2020); Lin et al., (2020); Mehran et al., (2021); Nicula et al., (2017); Nistor et al., (2018); Nistor and Nicula (2021); Parashar and Hait (2021); Prata et al., (2020); Rockström and Gaffney (2021); Rogak et al., (2020); Rothan and Byrareddy (2020); Ryan, et al., (2020); Shetty et al., (2020); Tabatabaei et al., (2021); Van Fan et al., (2021); Vanapalli et al., (2021); WHO (2021).		