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Review of the valorization options for the proper disposal of face masks during the COVID-19 pandemic

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A B S T R A C T

The COVID-19 pandemic has affected not only human health and economies but also the environment due to the large volume of waste in the form of discarded personal protective equipment. The remarkable increase in the global usage of face masks, which mainly contain polypropylene, and improper waste management have led to a serious environmental challenge called microplastic pollution. Potential practices for waste management related to waste valorization of discarded face masks as the major type of waste during the COVID-19 pandemic are explored in this study. Recommendations based on governmental practices, situation of state facilities, and societal awareness and engagement applicable to emergency (including COVID-19 pandemic) and post-pandemic scenarios are offered while considering potential solutions and available waste management practices in different countries during emergency conditions. However, multicriteria decision making for a country must determine the optimal solution for waste management on the basis of all affecting factors. Awareness of scientific, governments, and communities worldwide will successfully eradicate this important environmental issue.

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1. Introduction

The use of personal protective equipment (PPE) has dramatically increased worldwide due to the COVID–19 pandemic. Regardless of the ability of countries to prepare and distribute vaccines eventually, reverting to an almost normal lifestyle will certainly take time. Face masks are the most commonly used PPE at the global scale, and their use is estimated to be 129 billion every month (Prata et al., 2020). Disposable face masks are made of plastic, in which the main component is polypropylene (PP), although polyethylene, polyurethane, polyacylonitrile, polystyrene, and polycarbonate are also utilized as materials (Akarsu et al., 2021; Fadare and Okoffo, 2020a). Many countries and the World Health Organization (WHO) (World Health Organization, 1999, 2020) have issued regulations and guidelines on the waste management of PPE and the disposal of plastic waste. On the one hand, the improper disposal of face masks not only will spread the disease but will also negatively affect the environment (De-la-Torre et al., 2021; Rakib et al., 2021). On the other hand, the adsorption of organic and inorganic nutrients by the plastic waste will provide a stable environment for pathogenic bacteria, contaminants and viruses to propagate further (Frère et al., 2018; Jedruchniewicz et al., 2021; Murphy et al., 2020; Torres et al., 2021). The nano- or microfibers of face masks are prepared using electrospinning technology (Dutton, 2009; Zafar et al., 2016). Moreover, disposable face masks are produced using polymeric materials, which are a voluminous source of microplastics in the environment (Ammendolia et al., 2021; Aragaw, 2020; Shen et al., 2021). The disintegration of face masks in the form of micro- and nanoplastic waste due to various environmental factors (e.g., temperature, humidity, and salinity) will deteriorate the health of living creatures and worsen the environmental situation (Hirt and Body-Malapel, 2020; Toussaint et al., 2019; Wang et al., 2021; Zhang et al., 2020).

The COVID-19 pandemic has raised the seriousness of improperly handling waste materials, especially plastic waste, in developing and low-income countries. A recent study revealed that around 0.15 to 0.39 million tons of plastic debris can pollute oceans within a year due to improper waste management (Chowdhury et al., 2021; Hasan et al., 2021). Waste can release various toxic materials, which are dangerous to all creatures (Saliu et al., 2021; Sullivan et al., 2021). Various environmental issues that originate from disposable face mask waste have been investigated to provide community awareness about this serious issue (Fadare and Okoffo, 2020b; Selvaranjan et al., 2021).

While developed countries have implemented green and sustainable waste management strategies and benefited from societal awareness and engagement, developing and low-income countries have continuously suffered from inadequate waste management strategies and poorly handled waste facilities, including landfills, and low levels of environmental knowledge and societal engagement (Nzediegwu and Chang, 2020; Sangkham, 2020). The pandemic-related waste issue will likely continue after COVID-19 given the forecasted annual growth of the virus since its outbreak (Singh et al., 2020) and the massive improper disposal of PPE. Thus, the waste problem calls for the extensive attention and direct involvement of scientists, industry players, citizens, and policymakers (Patricio Silva et al., 2020). In most countries, correct handling of PPE discarded by hospitals is implemented in accordance with the regulations and guidelines of WHO (World Health Organization, 1999, 2020); however, the main issue centers on the usage and disposal of PPE by ordinary citizens. Fig. 1 presents various types of disposable face masks, the global share of the face mask market, and the estimated quantity of masks to be used during a pandemic; these data are reliable indicators of single-use face mask disposal on the basis of the information from market research analysis from KBV Research and researchers’ estimation (Nzediegwu and Chang, 2020; Research, 2020; Tripathi et al., 2020).

The majority of face masks potentially exposed to COVID-19 contamination are in the form of household waste, but they are being handled as if they are uncontaminated municipal waste. Incidentally, the global valorization rate of plastic waste is low, and related governmental regulations and policies are lacking in low-income and developing countries. Thus, this study proposes options to tackle the aforementioned waste issue, considering that this problem can further lead to serious health and environmental concerns in the short term. In particular, this study aims to investigate the various available valorization methods for plastic waste, specifically discarded disposable face masks, to provide insights into the initiatives and facilities of countries and the environmental awareness and engagement of the society.

2. Disinfection technologies

Disinfection plays an important role in PPE waste disposal because it can mitigate the spread of various fatal diseases. A comparison of the commonly used disinfection methods is shown in Table 1.

Despite the research on the reuse of PPE with respect to different reprocessing methods (Price et al., 2020; Rowan and Laffey, 2021), the trust and acceptance of healthcare workers and the public pose as the main barrier to the proper management of PPE waste. Similarly, the possibility of being contaminated with COVID-19 and the reported decline in the effectiveness of protective filters have hindered most scientific technical committees from proposing timely recommendations.

Voudrias (2016) compared different disinfection technologies by analyzing a set of criteria (i.e., environmental, economic, technical, and social criteria) for waste management and concluded that steam disinfection is an optimal
technology for treating infectious medical waste (Table 2). PP, as the main plastic material of disposable face masks, can be effectively treated via steam disinfection, but accurate temperature and time span and full replacement of air with steam are needed to enhance this technique’s performance (Sastri, 2014). Nonetheless, the disinfection method can help deal with the face mask waste issue in developing and low-income countries. Developed mobile and on-site disinfection units for treatment of contaminated wastes, such as Sterilwave (Beritin, 2020) and Integrated Sterilizer & Shredder (Celitron, 2016), and temporary storage (resting) could reduce the problem of healthcare wastes (Das et al., 2021). Chemical techniques are mostly utilized as disinfection techniques prior to mechanical shredding for the pretreatment of COVID-19-related wastes (Selvaranjan et al., 2021).

The consideration of various practices adopted in different countries (Table 3) demonstrates that adopted strategies depend on the economic condition and government policy of a country. No universal management strategies exist for healthcare wastes from households. Fig. 2 presents few proposed waste management strategies during the COVID-19 pandemic.

Scientific reports have determined that viruses can survive between 48 h and 9 days depending on certain factors (i.e., material, concentration, temperature, and humidity), and the proper storage (resting) of discarded face masks can only kill the viruses after 10 days (Battegazzore et al., 2020). These recent scientific findings have opened new options to low-income countries for initiating various valorization procedures, such as inertization, without the need to implement further disinfection. However, before valorization, different disinfection methods, which can be optimized on the basis of the techniques’ availability and performance, should be considered. The selection of the optimal disinfection method generally depends on the health and waste regulation of the government and the available facilities in a country.

3. Face mask waste management (valorization)

Fig. 3 presents the proposed procedure for the management of waste, particularly discarded face masks into the environment and from household.

The disposal methods for nonbiodegradable plastic waste (Zhang et al., 2021) will be discussed in the next subsections. Different valorization options for face mask waste management can be utilized depending on the governmental regulations and the facility situation in a country. Recent studies on the valorization of face mask waste are listed in Table 4.

3.1. Chemical valorization

Incineration is a popular waste-to-energy technology. This method converts waste into heat, which is then used to generate electricity. However, with respect to other commonly used combustion processes, incineration produces
highly toxic pollutants, mainly polychlorinated dibenzo-para-dioxin and polychlorinated dibenzofuran (Panda et al., 2010). Therefore, the incineration of plastic waste is not recommended as a valorization method for discarded PPE. An alternative to incineration is pyrolysis, which is a common chemical valorization technique for plastic waste.

3.1.1. Pyrolysis (biofuel production)

Converting solid plastic waste into liquid fuel is an efficient and economical method of valorization (Juwono et al., 2019), and the chemical treatment of plastic waste seems to be one of the most promising techniques. This solid-to-liquid conversion method of valorization is environmentally friendly and regarded as an efficient alternative to landfills.
Martynis et al., 2019; Park et al., 2019; Suet al., 2021). Recently, researchers have produced syngas and C1-2 hydrocarbon liquid fuel, thus helping alleviate the current problem of inadequate waste management (Aragaw and Mekonnen, 2021; plastic waste (i.e., plastics from PPE in general and plastics from protective facemasks and clothes in particular) into the environment is minimal. Furthermore, pyrolysis is an effective alternative to the valorization method of converting the disinfection of contaminated PPE and facemasks. Pyrolysis requires a simple equipment design, and its impact on the environment is minimal. Moreover, pyrolysis is an effective alternative to the valorization method of converting plastic waste (i.e., plastics from PPE in general and plastics from protective face masks and clothes in particular) into liquid fuel, thus helping alleviate the current problem of inadequate waste management (Aragaw and Mekonnen, 2021; Martynis et al., 2019; Park et al., 2019; Su et al., 2021). Recently, researchers have produced syngas and C1-2 hydrocarbon from disposable masks by using CO2-assisted pyrolysis (Jung et al., 2021). This method is promising and contributes to the reduction of CO2 emission from other sources while producing value-added products. (Torres and De-la Torre, 2021) presented various options for face mask waste management.

3.1.2. Carbonization

Carbonization is an important method for converting polymer waste as the carbon source to different valuable carbon materials, which can be utilized in various applications, such as energy conversion and storage and environmental applications (Zhuo and Levendis, 2014). Carbonization is an energy-saving, emission friendly, controllable, and simple process that can produce various carbon-based materials, such as activated carbon, carbon fiber, carbon sphere, graphite, and carbon nanomaterials (Bazargan and McKay, 2012; Chen et al., 2020). Face mask waste mainly contains polypropylene, which is an interesting waste for carbonization (Hu and Lin, 2021; Joseph et al., 2021). Meanwhile, high temperatures or incineration. Pyrolysis is a thermochemical treatment technique involving the thermal cracking of large macromolecules of organic and synthetic plastic materials (Miandad et al., 2019). Several studies have focused on the pyrolysis process to recycle plastic waste because of its ability to produce liquid fuels and the subsequent application of this energy source in engines, turbines, boilers, and generators (Budsaereechai et al., 2019). Unlike the mechanical valorization of plastic materials involving waste sorting, pyrolysis does not require prior separation of different types of plastics. In pyrolysis, different plastic types are mixed and then converted into liquid fuel to generate energy for various industrial applications (Quesada et al., 2020). During the thermochemical decomposition, plastic materials are treated at high temperatures between 300 °C and 700 °C in the absence of oxygen. The high temperature requirement of pyrolysis can facilitate the disinfection of contaminated PPE and face masks. Pyrolysis requires a simple equipment design, and its impact on the environment is minimal. Furthermore, pyrolysis is an effective alternative to the valorization method of converting plastic waste (i.e., plastics from PPE in general and plastics from protective face masks and clothes in particular) into liquid fuel, thus helping alleviate the current problem of inadequate waste management (Aragaw and Mekonnen, 2021; Martynis et al., 2019; Park et al., 2019; Su et al., 2021). Recently, researchers have produced syngas and C1-2 hydrocarbon from disposable masks by using CO2-assisted pyrolysis (Jung et al., 2021). This method is promising and contributes to the reduction of CO2 emission from other sources while producing value-added products. (Torres and De-la Torre, 2021) presented various options for face mask waste management.

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Table 2
Comparison of treatment technologies on the basis of a set of assessment criteria (Voudrias, 2016).

| Criteria               | Subcriteria                                      | Rank                                                                 | Ref.                                                                 |
|------------------------|--------------------------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------|
| Environmental          | Greenhouse gas emissions                         | Incineration > steam disinfection ≈ microwave disinfection > reverse polymerization > chemical disinfection | (Zhao et al., 2009)                                                  |
|                        | Environmental impact of other air emissions      | Incineration > chemical disinfection > reverse polymerization > steam disinfection ≈ microwave disinfection | (Diaz et al., 2005; Edlich et al., 2006; Harm, 2001; Zhao et al., 2009) |
|                        | Environmental impact of liquid residues          | Chemical disinfection > incineration > steam disinfection > reverse polymerization > microwave disinfection | (Diaz et al., 2005; Harm, 2001; Zhao et al., 2009)                  |
|                        | Environmental impact of solid residues           | Incineration > chemical disinfection > steam disinfection ≈ microwave disinfection > reverse polymerization | (Harm, 2001)                                                        |
|                        | Energy consumption                               | Incineration > reverse polymerization > steam disinfection > chemical disinfection | (Zhao et al., 2009)                                                  |
|                        | Water consumption                                | Incineration > chemical disinfection > steam disinfection > reverse polymerization | (Zhao et al., 2009)                                                  |
|                        | Volume reduction                                 | Incineration > reverse polymerization ≈ steam disinfection > chemical disinfection | (Cross, 2011)                                                       |
|                        | Pathogen inactivation                            | Incineration > steam disinfection ≈ microwave disinfection ≈ reverse polymerization ≈ chemical disinfection | based on vendor information                                        |
| Economic               | Capital cost                                     | Reverse polymerization > incineration > chemical disinfection > steam disinfection | (Karagiannidis et al., 2010; Özkan, 2013; Tudor et al., 2009)       |
|                        | Operation and maintenance cost                   | Incineration > microwave disinfection > reverse polymerization > steam disinfection ≈ chemical disinfection | (Karagiannidis et al., 2010; Özkan, 2013; Tudor et al., 2009)       |
|                        | Disposal cost                                    | Incineration > steam disinfection ≈ microwave disinfection > reverse polymerization > chemical disinfection | (Commission, EC; Department for Environment, 2013)                  |
| Technical              | Treatment effectiveness                          | Incineration > steam disinfection ≈ microwave disinfection ≈ reverse polymerization ≈ chemical disinfection | based on vendor information                                        |
|                        | Automation                                       | Incineration ≈ steam disinfection ≈ microwave disinfection ≈ reverse polymerization ≈ chemical disinfection | (Harm, 2001)                                                        |
|                        | Need for skilled operators                       | Incineration > reverse polymerization > microwave disinfection > steam disinfection > chemical disinfection | (Cross, 2011)                                                       |
| Social                 | Technology acceptance                            | Steam disinfection > microwave disinfection ≈ reverse polymerization > chemical disinfection > incineration | (Harm, 2001)                                                        |
|                        | Cost acceptance                                  | Steam disinfection > chemical disinfection > microwave disinfection > reverse polymerization | (Karagiannidis et al., 2010; Özkan, 2013; Tudor et al., 2009)       |

involved in the carbonization process can act as a disinfectant and destroy viruses and other contaminants. The potential of carbonizing face mask waste in the utilization of supercapacitors (Hu and Lin, 2021; Zhu et al., 2021) and adsorbents (Anastopoulos and Pashalidis, 2021) has been recently investigated.

3.2. Physical valorization

3.2.1. Thermomechanical valorization

As a form of physical valorization, material extrusion has the potential to increase the re-use of recycled plastic waste (Awoyera and Adesina, 2020; Battegazzore et al., 2020; Tulashie et al., 2020). Battegazzore et al. (2020) proposed a solution to the problem of face mask valorization in the pretext of environmental protection and sustainable development. First, the different parts of a disposable face mask, such as the mask cloth, ear loop, and metallic nose parts, were separated. Regardless of the brand, PP was determined as the main polymer of the face masks. Then, attenuated total
Table 3
Different countries’ existing practices for healthcare waste management, treatment, and disposal during the COVID-19 pandemic (ERIA, 2020; Tsukiji et al., 2020; Sangkham, 2020).

| Country      | Existing Practices for Healthcare Wast Management                                                                 | COVID-19 Waste Treatment and Disposal                                                                 | References                                                                                                                                 |
|--------------|----------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|
| Thailand     | • Providing special red bins labeled “For used face masks only” in highly visible areas                               | Incineration, autoclave, and sanitary landfill                                                       | (Department, 2020; Health, 2020; Thampanishvong and Wibulpolprasert, 2020)                                                             |
|              | • Governors advise households to separate health waste in different bags if no red bins are available nearby and to label the bags. |                                                                                        |                                                                                                                                           |
|              | • Designating specific storage areas                                                                                |                                                                                        |                                                                                                                                           |
|              | • Sending waste from community healthcare facilities to district healthcare facilities once a week                  |                                                                                        |                                                                                                                                           |
|              | • Temperature-controlled storage available at the district level                                                    |                                                                                        |                                                                                                                                           |
|              | • Transporting by licensed waste management service providers (WMSPs) (requires temperature-controlled vehicles)      |                                                                                        |                                                                                                                                           |
|              | • Treating waste within 48 h after transportation                                                                   |                                                                                        |                                                                                                                                           |
|              | • Disinfecting vehicles and bins daily with NaClO                                                                    |                                                                                        |                                                                                                                                           |
| China        | • Collection of used masks in special trash cans (If unavailable, residents disinfect used face masks and wrap them in plastic bags before disposal to prevent air exposure.) | Temporary incinerator installation and municipal solid waste incinerator to coprocess medical waste in a rotary kiln. Hazardous waste is thoroughly incinerated in high-temperature flue gas and slag residue after 60 min of high-temperature (850 °C) incineration. | (Rongmeng and Jianguo, 2020; Kang et al., 2021; Ma et al., 2020; Wang, 2020; Yang et al., 2021) |
| India        | • Used face masks from quarantined homes or other households are kept in a paper bag for 72 h before disposal as general waste. |                                                                                        |                                                                                                                                           |
|              | • Face masks' straps are cut before disposal to prevent reuse.                                                        |                                                                                        |                                                                                                                                           |
|              | • Governors advise nonquarantined homes and residents to dispose used masks by disinfecting them with an ordinary bleach solution (5%) or sodium hypo-chlorite solution (1%). |                                                                                        |                                                                                                                                           |
|              | • Masks are wrapped and kept in a closed bin before provision to sanitary workers.                                   |                                                                                        |                                                                                                                                           |
|              | • Used masks in COVID-19 isolation wards, laboratories, and test centers are discarded and collected in separate “yellow color-coded plastic bags” labeled “COVID-19 waste.” |                                                                                        |                                                                                                                                           |
|              | • Disinfecting inner and outer surfaces of containers, trolleys, and bins with 1% NaClO solution daily               |                                                                                        |                                                                                                                                           |
|              | • Deputing dedicated sanitation workers for biomedical and general solid waste collection and timely transfer to temporary storage |                                                                                        |                                                                                                                                           |
|              | • Using vehicles with GPS, barcoding systems for containers with HCW for waste tracking, and labeling vehicles with “Biohazard” sign |                                                                                        |                                                                                                                                           |
| South Africa | • Minimizing the volume of HCW at source                                                                           | Incineration by licensed companies, use of common biomedical waste treatment facilities (CBWTFs), and disposal via deep burial only in rural or remote areas without CBTWF facilities | (Bandela, 2020)                                                                                                                        |
|              | • Removing 3/4 full sealed box sets and storing at the central storage area prior to collection for treatment and disposal |                                                                                                      |                                                                                                                                           |
|              | • Securing space with the sign of “Suspected COVID-19”                                                              | Large volume of yellow color-coded (incinerable) COVID-19 waste beyond the capacity of existing CBWTFs and BMW incinerators necessitates permitting the usage of HW incinerators at existing treatment, storage, and disposal facilities (TSDFs) or captive industrial incinerators if any exist in the state/union territory. |                                                                                                                                               |
|              | • Storage on-site in the following manner: securing sufficient capacity, preventing access to these areas by unauthorized persons, marking with warning signs on, or adjacent to, the exterior of entry doors, gates, or lids, securing by using locks on entry doors, gates, or receptacle lids, and preventing odor |                                                                                                      |                                                                                                                                           |
|              | • Using plastic bags with a capacity of 60 liters or more and at least 80 µm in thickness                            |                                                                                                      |                                                                                                                                           |
|              | • Ensuring the time of the collection of a consignment by a transporter from the relevant generator’s premises         |                                                                                                      |                                                                                                                                           |
### Table 3 (continued)

| Country   | Existing Practices for Healthcare Waste Management                                                                 | COVID-19 Waste Treatment and Disposal                                                                 | References                                                                 |
|-----------|---------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Singapore | ● Face masks and associated wastes, such as tissues, with potential exposure to COVID-19 contamination are managed like ordinary uncontaminated municipal waste.  
● Face mask disposal is advised in residential and public areas. | Mostly incineration                                                                                   | (ISWA, 2020)                                                              |
| South Korea | ● Used masks from households are disposed in garbage bags labeled “Waste for incineration” and “Waste bag for landfill” through a volume-based waste free (VBWM) system.  
● The recyclable waste is separated from the bags in the VBWM system for transportation to recycling facilities.  
● Waste from infected can be stored for 7 days and should be delivered and incinerated within 2 days.  
● Vehicles for delivering medical waste are regularly sterilized. | Incineration or landfills without recycling                                                              | (Rhee, 2020; UNESCAP, 2020)                                              |
| Malaysia  | ● Separation of clinical waste from generated waste  
● Labeling of clinical waste and disposal into proper containers and bags in accordance with color-coded containers or plastic bags  
● Collection by licensed contractors for disposal and treatment at 12 incineration facilities nationwide  
● Equipping cold rooms in large healthcare facilities  
● Collecting daily or 3 times a week depending on the quantity  
● Transportation is done only by a special lorry licensed to transport hazardous waste, which belongs to concession companies. | Mostly incineration                                                                                   | (Bavani, 2020; Agamuthu and Barasarathi, 2020)                               |
| Taiwan    | ● Infectious waste is collected and coded as C-type waste.  
● Governors consider discarded masks as general waste, which should be disposed in regular garbage bins to prevent virus contamination.  
● Used masks are discarded in a lidded trash can.  
● Wearing face masks in public is mandatory, and improper disposal of masks incurs fines.  
● City governments encourage citizens to record and report evidence of mask littering acts to authorities for the cash reward of 30% of the fines issued to the offenders. | Mostly incineration                                                                                   | (Lee, 2020; News, 2020; Tsai, 2021)                                        |
| Bangladesh| ● Use of color-coded bins (red: sharp waste, yellow: infectious/pathological waste, and black: nonhazardous waste)  
● Storing bins on premises. (They are regularly collected by covered vehicles for transportation to treatment sites.) | Incineration                                                                                          | (Ferronato and Torretta, 2019; Rahman et al., 2020)                        |
| Indonesia | ● Identification of the classification and communication (labels and symbols) means  
● Designating COVID-19 infectious waste bins  
● Conducting internal sterilization and disinfection before bags are tied  
● Labeling bags with “Danger, do not open”  
● Disinfecting bags before collection  
● Scheduling regular waste transportation by cleaning services on weekdays | Mostly incineration, disinfecting at source, transporting to disposal sites, and open burning (if no incinerator is available) or hazardous waste landfill | (Salim et al., 2020; TEMPO.CO, 2021)                                        |

Reflectance (ATR) analysis was performed to determine the typical absorption of PP materials. Their findings showed that the PP materials were entirely recyclable. Moreover, in accordance with the IR and ATR spectra, the ear loops were composed of polyurethane-, polyethylene terephthalate-, or PP-based materials. As for the valorization strategy, the researchers found that the polymers could be recycled individually or as a mixture. Subsequently, an economic evaluation was conducted to determine the most sustainable solution to the problem of face mask disposal. The recycled thermoplastic polymers were directly fed into an extruder, and the melting mixture was used to produce low-cost thin films. On this basis, recycled materials with relatively good performance could be prepared. This proposed solution entailed a simple and cost-effective method and could be applied to the valorization of discarded PPE and face masks.
| Country | Existing Practices for Healthcare Waste Management | COVID-19 Waste Treatment and Disposal | References |
|---------|---------------------------------------------------|-------------------------------------|------------|
| Mexico  | - The same protocol as that for other infectious waste in accordance with the Mexican Standard #087  
- Use of hermetic containers and polyethylene bags in accordance with the type of healthcare wastes  
- Use of bags with translucent red polyethylene of minimum caliber 200 and translucent yellow color of minimum 300-gauge, waterproof feature, a heavy metal content of not more than one parts per million, and chlorine-free property  
- Filling to 80% of the capacity of bags and closing and transporting them to temporary storage sites  
- Marking with the universal risk symbol and biological legends  
- Designating the temporary storage of biological-infectious-dangerous waste  
- Storing biological-infectious-hazardous waste separated from patient areas and medicine warehouse (The storage area must be accessible for collection and transport, without risks of flood and entry of animals and with signs alluding to their dangerousness and access only to responsible personnel.)  
- Noncompact hazardous-biological-infectious waste during collection and transportation  
- Use of collection vehicles with closed box and hermetic vehicles operated with cooling systems to keep residues at a maximum temperature of 4 °C and with mechanized loading and unloading systems  
- Hazardous-biological-infectious waste must not be mixed with any other type of municipal or industrial waste during transportation. | Incineration or confinement in an emergency cell in a landfill and earth covered every day and treatment and disposal as normal hazardous healthcare waste (autoclave, incinerator, radio wave, etc.) | (Tsukiji et al., 2020; Melissa Gómez and Virginia Gabriela, 2021) |
| Japan   | - Separating and storing infectious, noninfectious, and general wastes and sharp objects from other infectious wastes with proper containers  
- Sealing easy-to-use and durable containers  
- Transporting by using a designated cart to avoid scattering and spilling wastes within facilities  
- Use of short storage periods  
- Access of storage rooms by authorized persons only  
- Applying clear labeling on infectious waste containers at storage rooms | Incineration, melting, steam sterilization (autoclave), dry sterilization, and disinfection followed by shredding and disposal to sanitary landfills | (Center, 2012; Tsukiji et al., 2020) |
| Nepal   | - Designating waste storage in health facilities  
- Use of specific trolleys for transportation within hospitals  
- Use of specific vehicles for transportation from healthcare facilities to WMSPs | Mostly burning, small-scale incineration, or dumping in backyards and municipal landfills | (Tsukiji et al., 2020; Sharma et al., 2020) |
| Philippines | - Waste generated from regular housekeeping and office work is considered general waste and can be handled by municipal waste management services.  
- Special registered transporters and TSDFs for handling healthcare waste and disposing of it  
- Each vehicle used for transporting the waste has the following special markings: name and ID of transport, placard, waste class, and waste number.  
- The registered transporter is required to submit a compliance and completion report of transportation, attested by a representative from the healthcare and TSD department. | Steam sterilization (autoclave) prior to disposal in a landfill and pyrolysis | (EJN, 2020; GOV.PH, 2020) |

3.2.2. Filters (wastewater treatment)  
Plastic waste has been used to prepare ceramic filters in wastewater treatment (Kinoshita et al., 2013; Yasui et al., 2016, 2019). Similarly, PP fibers have been used as a filtering medium to improve the performance of filtration in various applications (Alsalhy et al., 2017; Nakamura et al., 2019). Sokolovic et al. (2019) investigated the possibility of employing recycled PP fibers in filter beds. The recycled PP fibers in the bed coalesced were used to separate the oil droplets from oil–water mixtures. The experimented PP fibers were obtained from recycled shopping bags and PP fiber waste materials.
in the carpet industry. Their results showed that the bed coalesces could successfully separate the oil and water from the mixture. At present, large amounts of PP-based face masks are discarded daily to the environment. The valorization of these waste materials via wastewatertreatment seems to be a profitable endeavor.

3.2.3. Thickening agents

Polymers, including PP, exhibit swelling and gel-forming behavior in organic and mineral media, and this characteristic allows the polymers to function as thickening agents (Martín-Alfonso et al., 2009). Recycled PP is used as a potential thickener agent of lubricating greases. Martín-Alfonso et al. (2013, 2014) investigated different concentrations of recycled PPs as a component of mineral oil for the gel-like dispersion of lubricating grease. Overall, the valorization of PPs can considerably improve industrial applications from the economic and environmental aspects.

3.2.4. Building materials

According to WHO (World Health Organization, 1999), inertization or stabilization, in which waste materials are mixed with cement and other substances, is an inexpensive disinfection method. The low cost is partly attributed to the method’s simple equipment design. Utilizing fibers as construction materials to reinforce and increase the tensile strength of structures is an old concept emanating from the Neolithic age (Costa et al., 2019). The incorporation of fibers obtained from plastic waste into concrete has attracted the attention of many researchers (Bahij et al., 2020; Sharma and Bansal, 2016). The effects of PP-based fibers on concrete performance have also been investigated (Ahmed and Lim, 2021; Camille et al., 2020; Mohammadhosseini et al., 2020b). For instance, adding 0.1% to 2% (by volume) of fibers can help prepare lightweight structures with high tensile strength, crack resistance, durability, and good freeze/thaw protection quality (Banthia and Gupta, 2006; Hanumesh et al., 2018; Mohammadhosseini et al., 2020a; Wu et al., 2020). The application of PP fibers to asphalt/bitumen for road construction and lightweight concrete has presented promising results (del Rey Castillo et al., 2020; Tapkin et al., 2011; Williams-Wynn and Naido, 2020). Saberian et al. (2021) utilized single-use face mask waste to prepare pavement base/sub-base with improved ductility, flexibility, and compressive strength. The researchers prepared sustainable bricks utilizing 52% mask waste, 45% paper waste, and 3% binder, which could be used as a replacement for masonry bricks (Adlakha, 2020). The addition of 0.2% by volume of shredded face mask waste can improve strength properties of concrete (Kilmartin-Lynch et al., 2021).

The findings from past studies provide another option for handling discarded PPE, especially face masks with PP fibers. The utilization of these waste materials to prepare concrete not only addresses the economic aspect of inertization or stabilization but also ensures the production of high-performance concrete. However, as part of the safety procedure, possibly contaminated PPE should be disinfected before it is utilized as a building material.
4. Recommendations

The following are recommended for enhanced management and valorization of discarded face mask waste while considering various governmental practices, facilities, and societal awareness:

- The scientific community must present the various economic and environmental advantages of waste valorization to authorized governments in consideration of the society, environment, and economy for multi-criteria policy-making decisions.
- The governments should establish a working infrastructure for safe waste collection, effective waste segregation, transportation, and valorization of discarded PPE. The valorization techniques could be selected on the basis of the availability of a facility in place to avoid existing practices of open incineration and landfill.
- Storing the waste in proper storage and resting them for at least 72 h before disposal and disinfection could minimize the spread of various infections (Bandela, 2020; Organization, 2020).
- The governments and nongovernmental organizations, especially in low-income and developing countries, must inform all citizens about the danger of infection spread and micro- and nanoplastic pollution, which directly affect living creatures' well-being, and teach them proper disposal and disinfection methods. Public education is an efficient way of improving waste management which emphasizes the importance of source segregation behavior. Waste segregation at source considerably controls the quality and volume of plastic wastes left in the environment and plastic wastes deposited in landfills which is therefore resulting in a dramatic reduction of micro- and nanoplastic formation (Fredrick et al., 2018; Phan Hoang and Kato, 2016; Salequzzaman and Stocker, 2001).
- Contrary to expectations, raising awareness among the public about the potential benefits of recycling has not convinced people to participate in waste management activities, therefore, additional incentives must be considered to promote citizens’ waste disposal attitude for proper waste management (Bolaane, 2006).
- Additional disinfection systems and waste valorization facilities must be provided to overcome this issue.
- For low-income countries affected by emergency situations, such as COVID-19, a good option for face mask valorization could be stabilization (building material preparation), carbonization and fuel production methods.

These recommendations are generally applicable to emergency and postpandemic scenarios and must be modified when applied to normal situations.

5. Conclusion

The large volume of face masks produced and discarded during the COVID-19 pandemic has continuously contributed to environmental pollution. Specifically, the problem of micro- and nanoplastic disintegration has become an urgent concern. This waste problem calls for the extensive attention and direct involvement of scientists, industry players, citizens, and policymakers. The utilization of the incineration method for face masks and other PPE from medical centers and quarantined houses in many countries is not recommended because it releases toxic chemicals. This study hence offers perspectives in handling the waste issue on the basis of various methods for the valorization of plastic materials. The optimal solution to a multidimensional problem should consider factors related to governmental regulations, economy, safety, environment, and society, and available facilities (technologies) require multi-criteria decision making.

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.

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