



Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.



Review

Plastics in the time of COVID-19 pandemic: Protector or polluter?

Neha Parashar, Subrata Hait *

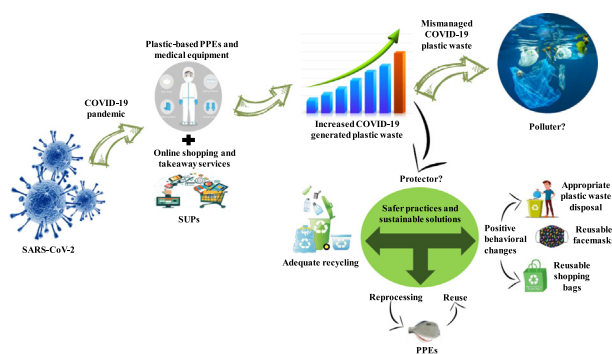
Department of Civil and Environmental Engineering, Indian Institute of Technology Patna, Bihar 801 106, India



HIGHLIGHTS

- COVID-19 pandemic has reemphasized the indispensable role of plastics in our daily life.
- Usage of PPEs and packing materials amid COVID-19 is causing plastic pandemic worldwide.
- Provisional reversal or stay on SUPs ban during COVID-19 may change consumers' behavior.
- Effective decontamination for reprocessing of PPEs reduces plastic waste generation.
- Automated waste management and product innovation may lead to environmental sustainability.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:

Received 21 September 2020

Received in revised form 30 November 2020

Accepted 1 December 2020

Available online 10 December 2020

Editor: Damia Barcelo

Keywords:

COVID-19

Personal protective equipment (PPEs)

Single-use plastics (SUPs)

Sustainable plastic waste management

Circular economy

PPEs decontamination

ABSTRACT

The COVID-19 pandemic has reemphasized the indispensable role of plastics in our daily life. Plastics in terms of personal protective equipment (PPEs) and other single-use medical equipment along with packaging solutions owing to their inherent properties have emerged as a life-savior for protecting the health and safety of the front-line health workers and the common citizens during the pandemic. However, plastics have been deemed as evil polluter due to their indiscriminate littering and mismanagement amid increased plastic usage and waste generation during this unprecedented crisis. This article reviews and assesses to dwell upon whether plastics in the time of pandemic are acting as protector of the public health or polluter of the environment. Considering the utilities and limitations of plastic along with its management or mismanagement, and the fate, an equitable appraisal suggests that the consumers' irresponsible behavior, and attitude and poor awareness, and the stress on waste management infrastructure in terms of collection, operation, and financial constraints as the major drivers, leading to mismanagement, turn plastic into an evil polluter of the environment. Plastic can be a protector if managed properly and complemented by the circular economy strategies in terms of reduction, recycle and recovery, and thereby preventing leakage into the environment. To safeguard the supply chain of PPEs, several decontamination techniques have been adopted worldwide ensuring their effective reprocessing to prioritize the circular economy within the system. Policy guidelines encouraging to adopt safer practices and sustainable technical solutions along with consumers' education for awareness creation are the need of the hour for preventing plastic to turn from protector with high utility to polluter.

© 2020 Elsevier B.V. All rights reserved.

* Corresponding author.

E-mail address: shait@iitp.ac.in (S. Hait).

Contents

1. Introduction 2

2. Review methodology. 3

3. Impacts of COVID-19 pandemic on global plastic production and usage 3

 3.1. Demand and supply of PPEs during the pandemic 3

 3.2. Impact of takeaway services and e-commerce shopping on plastic usage during the pandemic 4

 3.3. Impact of reversal of single-use plastics (SUPs) bans on plastic production during the pandemic 4

4. Plastic waste generation, management and fate during COVID-19 pandemic 5

 4.1. Plastic waste generation during the pandemic 5

 4.2. Global practices for plastic waste management during the pandemic 6

 4.2.1. Challenges associated with plastic waste treatment and disposal practices during the pandemic 7

 4.2.2. Potential technological solutions to manage plastic waste during the pandemic and beyond 10

 4.3. Plastics: protecting health or damaging the environment during COVID-19 pandemic?. 12

5. Future perspectives 12

6. Conclusions 13

CRedit authorship contribution statement. 13

Declaration of competing interest. 13

References 13

1. Introduction

With the coronavirus disease 2019 (COVID-19), a pandemic of global concern caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the entire world has come to a halt witnessing a lifestyle that is becoming the new normal. SARS-CoV-2 is known to be easily transmissible from one person to another (sustaining the median incubation period of approximately 5.1 days), infecting on an average of 2.4–3.3 people from just one confirmed case (Lauer et al., 2020; Ortiz-Prado et al., 2020). The COVID-19 crisis has reemphasized the indispensable role of plastic in our daily life. Plastics have contributed immensely to the healthcare sector and public health safety during the pandemic. In addition to the imposition of nationwide lockdown, social distancing, restriction on traveling and public gathering, frequent usage of hand sanitizers along with wearing of mostly plastic-based personal protective equipment (PPEs), viz. face masks, gloves for common citizens to protective medical suits, aprons, gowns, face shields, surgical masks, and other PPEs for frontline health workers as precautionary measures have been adopted to avoid virus contamination to fight the spread of COVID-19 (Kahlert and Bening, 2020). Plastics integrate excellent strength to weight ratio and durability with versatility. Owing to these properties, plastics are irreplaceable in the healthcare sector with major applications in single-use medical tools and equipment and packaging along with use in some surgical operation and transplant (Chen et al., 2020). Further, plastics have evolved as the perfect material for packaging purposes as they are lightweight, flexible, and highly durable. Packaging applications account for the most extensive use of plastics worldwide. Consumers' behavioral changes coupled with the dependency on online shopping and takeaway services for home delivery of essential items during the pandemic have led to a considerably increased demand for plastic-based packaging items, including single-use plastics (SUPs), against the backdrop of prevailing bans or restrictions in many countries (Grashuis et al., 2020; Laato et al., 2020; Tenenbaum, 2020; Wang et al., 2020a). A surge in the plastic demand during the pandemic is, therefore, primarily due to the manufacturing of PPEs and packaging materials (ADB, 2020). The majority of PPEs are made up of polymers like polyurethane (PU), polypropylene (PP), polycarbonate (PC), low-density polyethylene (LDPE), polyvinyl chloride (PVC), while the plastics used in packaging materials mainly consist of high-density polyethylene (HDPE), low-density polyethylene (LDPE), polystyrene (PS), polyethylene terephthalate (PET), etc. Among these, PS and LDPE are rarely recycled plastics, PET and HDPE are widely recycled, while PVC and PP are often not recycled (Klemeš et al., 2020). The usage and recyclability of the plastics used for PPEs and packaging materials during the pandemic are depicted in Fig. 1.

Plastics bring prosperity to mankind, but also limitations and problems as their prime advantage turns out to be the main problem. Being cheaper than conventional materials, plastics allow single-use in innumerable applications with disposability is considered as a major advantage by the users prioritizing hygiene, albeit plastic is reported to be no better alternative than other materials with respect to the persistence of the novel coronavirus (van Doremalen et al., 2020). This has led to an increase in the use and disposal of plastic-based items for both medical and non-medical applications during the pandemic. Hazardous COVID-19 biomedical waste (BMW) containing infected plastic-based PPEs and other disposable items from the impacted sources like COVID-19 hospitals, quarantined facilities, containment zones, along with similar non-infected items from non-impacted sources are generated (UNEP, 2020). Therefore, the COVID-19 BMW generation can be directly linked to the unprecedented use of mostly plastic-based PPEs and other disposables warranted since the novel coronavirus outbreak. The growing usage of SUPs and plastic-based packaging materials coupled with the increasing demand for medical products and packaging amid the pandemic has significantly spiked the plastic waste generation worldwide (Jribi et al., 2020; WEF, 2020; WHO-UNICEF, 2020). Thus, the pandemic has presented a major environmental challenge in terms of plastic waste management. Waste management facilities are generally designed for steady-state operations with moderate variations in waste volume and composition under normal circumstances. However, the pandemic-induced change in waste generation and composition dynamics is highly likely to impact the normal operation of the existing facilities. Further, the reduction in plastic recycling due to plummeting oil and petroleum prices in view of reduced transportation activities in the time of pandemic-induced lockdowns has turned plastic waste management a huge challenge (BIR, 2020; Eco-Business, 2020; Kaufman and Chasan, 2020). During this unprecedented uncertainty, the consumption of different PPEs and packaging materials, including SUPs, is on the threshold of creating a plastic pandemic across the globe unless effectively managed (Fadare and Okoffo, 2020; Hale and Song, 2020). Mismanagement and littering of plastic waste may not only pose a risk of virus transmission but also create pollution in terrestrial and marine ecosystems (Mol and Caldas, 2020).

The general perception of the society to consider plastic as an evil polluter has been further built up based on the media reports and newsletters highlighting the worsened environmental situation due to the mismanaged plastic waste during the COVID-19 pandemic. Contrary to this general viewpoint, the irresponsible and negligent attitude of the consumers in sheer mismanagement and the underutilization of the resource are the major catalysts contributing and aggravating plastic

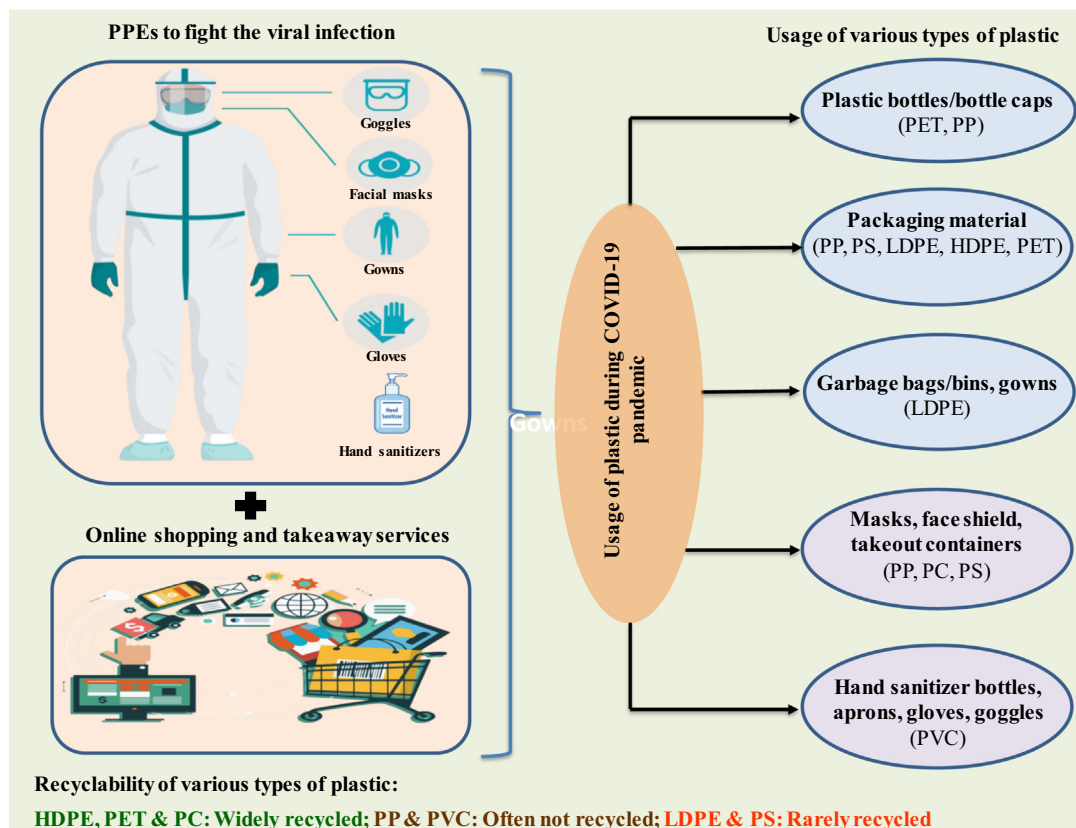


Fig. 1. Usage and the recyclability of various types of plastics during the COVID-19 pandemic.

pollution (Aragaw, 2020; Borg, 2020). Notably, PPEs and other plastic-based medical equipment have emerged as a life-savior for protecting the health and safety of the frontline health workers and the common citizens in the time of the pandemic. However, an equitable appraisal is needed comparing all pros and cons of plastics, their management or mismanagement, and fate in the environment during the COVID-19 pandemic. In this context, the article reviews and assesses to dwell upon whether plastics in the time of pandemic are acting as protector of the public health or polluter of the environment. For the purpose of the review and the assessment, the pandemic-induced repercussions on global plastic production and usage emerging out of PPEs demand and supply, online shopping and takeaway services as well as provisional reversal or stay of SUPs bans is highlighted. Further, the impacts of the pandemic on the global plastic waste generation and associated critical issues and challenges of plastic waste management system are analyzed. The article also adds up to the current literature presenting various guidelines and advisories issued by several international agencies and countries for plastic waste management in view of the pandemic. Moreover, the fate of plastic in the hour of the pandemic to dissect plausible short- and long-term ecological repercussions is discussed. The article also presents an assessment of different decontamination methods to reprocess and reuse PPEs to safeguard the shortage of their supply chain in commensurate with the increased demand across the globe. At last, future implications concerning innovative technical solutions and safer practices together with robust policies are presented to support legislative bodies and policymakers to deal with the current challenges of plastic waste management during the pandemic and beyond.

2. Review methodology

To present the basic outline of the review, a document search was conducted using the Scopus database, Google Scholar, and Google by

searching for different keywords, such as 'plastic consumption during COVID-19 pandemic', 'impact of COVID-19 on plastic waste generation', 'plastic waste management during COVID-19 pandemic', 'COVID-19 waste management', and 'reprocessing and reuse of PPEs during COVID-19 pandemic'. Data were retrieved from the mentioned sources including documents like journal articles, data papers, short survey reports, editorial notes, news articles, and organizational documents/reports. To set the authenticity of the data/information gathered, documents including journal papers, newsletters, and organizational documents were only considered for the purpose of the review. The initial search collectively fetched around 1500 journal papers from the Scopus database and the Google scholar, while around 50 organizational documents/reports and 78 news articles were extracted from the Google. To stick with the informative dataset relevant to the topic of the review article, manual screening of documents based on the summary (in case of news articles and organizational reports) and abstracts (in case of journal papers) were performed excluding the articles, which were not found exclusive to the concerned review topic. Finally, a total of 96 documents (including 59 Journal papers, 23 organizational documents/reports, and 14 news articles) related to the topic were considered and referred for the purpose of the review.

3. Impacts of COVID-19 pandemic on global plastic production and usage

3.1. Demand and supply of PPEs during the pandemic

The human-to-human nature of transmission of coronavirus necessitates the mandatory usage of plastic-based PPEs by the common citizens in addition to the frontline health workers to protect from the viral infection. Henceforth, the COVID-19 pandemic has resulted in skyrocket demand for essential PPE kits, which showed a tremendous increase in plastic manufacturing and distribution across the globe

(Prata et al., 2020). To deal with the viral infection in the current pandemic, the WHO has projected a monthly demand of 89 million of facial masks, 76 million of gloves, 30 million of gowns, and 1.6 million of goggles along with 2.9 million of hand sanitizers as a part of safety measures for frontline health workers (WHO, 2020b). Further, the WHO has estimated a monthly increase of 40% in the supply chain of different medical safety products worldwide during the pandemic. Similarly, the CAGR for the production of PPEs is projected to show around 20% spike from 2020 to 2025 (WEF, 2020). The demand and usage of various PPEs during the COVID-19 period so far in selected countries across the globe have been summarized in Table 1.

The monthly consumption of facial masks and medical gloves has been reported to be around 129 billion and 65 billion, respectively, for 7.8 billion populations across the globe (Kalina and Tilley, 2020). According to the World Economic Forum (WEF), the daily usage of medical kits has reached a staggering level even in the areas with relatively low confirmed COVID-19 cases in the UK. For instance, around 39,500 facials masks, 11,500 medical gloves, 1500 gowns, and 4200 filtering facepiece respiratory masks (FFP₃) have been used in the UK during February 2020 (WEF, 2020). Further, the estimated demand in the UK ranges in between 10 and 16 million PPEs per day despite the current supply of 14 million PPEs per day by the government (BBC, 2020). The Freedonia Group, a leading market research firm based in the US, has estimated an increased growth rate of around 312% in the present demand of face shields during the pandemic (BBC, 2020; LA Times, 2020). At the same time, the demand for medical gloves is expected to increase by 12.5% in 2020 in countries like China with such a high population as per the estimate (BBC, 2020; LA Times, 2020). Alone in China, the production of face masks soared up to 116 million in February 2020, which was 12 times greater than the previous month, i.e., January 2020 (Wang et al., 2020b). Given the total population of China is more than 1.4 billion, the gap between the rising demand and associated supply has been reported to be substantial during the pandemic (BBC, 2020; LA Times, 2020). This trend is of no exception in other countries,

where the increase in the number of coronavirus cases has propelled the upsurge in demand for PPEs along with rising safety awareness.

3.2. Impact of takeaway services and e-commerce shopping on plastic usage during the pandemic

Total lockdowns imposed in the time of pandemic in many countries across the globe have led people to rely on online shopping and takeaway services for procuring essentials, including food items and groceries. The dependency on e-commerce shopping and takeaway services for home delivery of essential items has resulted in the increased demand for SUP carry bags and other types of plastic for packaging purposes. The pandemic has also induced a novel form of consumer demand and behavioral changes like panic buying, stockpiling of food items and groceries among the masses and thereby resulted in a surge in plastic-based packaging items in many countries (Grashuis et al., 2020; Laato et al., 2020; Wang et al., 2020a). The percentage growth in online shopping and takeaway services for some selected countries during the pandemic has been shown in Fig. 2. The consumers' behavioral changes as dictated by hygienic concerns, panic buying, and stockpiling have led to a considerable surge in requirement for plastic-based packing materials (Jribi et al., 2020). This growing trend of online shopping and takeaway services further exaggerates the increased demand for plastic production and usage, which have been estimated to proliferate with a sales growth rate of 14% in the US and 40% in Spain (WEF, 2020). The estimated growth of plastic packaging is projected to surge from USD 909.2 billion as of 2019 to 1012.6 billion by 2021 with the annual growth rate of 5.5% corresponding to the impact of the COVID-19 pandemic on plastic products consumption (Business Insider, 2020).

3.3. Impact of reversal of single-use plastics (SUPs) bans on plastic production during the pandemic

The more worrisome issue that emerged out of this pandemic is reversing the momentum of a long battle to reduce the production and usage of SUPs (Shetty et al., 2020). Amidst the concerns of cross-contamination by reusing the plastic bags and containers as propagated and supported by the plastic manufacturers, many countries like the US, the UK, Canada, Portugal have temporarily revoked or deferred the SUP bans in the time of the COVID-19 pandemic. Earlier this year, the US was planning to ban on the use of straws, takeaway containers, and mandating the citizens to carry their own reusable bags as an effort to combat the pollution caused by the SUPs. But due to the outbreak of novel coronavirus, such movements are halted amid worries about the coronavirus clinging to reusable bags and other cutleries (Klemeš et al., 2020). For instance, a proposed state-wide ban on plastic bags in New York is put on hold as of May 2020. More recently, the states like California and Oregon have suspended the ban on plastic bags, while Connecticut, Delaware, Hawaii, New Jersey, New Mexico, Oregon, Washington, etc. have put a pause or postponed bans on the SUP products (USA Today, 2020). On the other hand, Massachusetts and New Hampshire have strongly discouraged the use of reusable plastic bags by reintroducing SUP products in anticipation of coronavirus transmission (World Bank, 2020). Despite the imposed ban on disposable plastic bags earlier this year (January 2020) to slash the plastic waste generation in Thailand, the country is now witnessing a 30% growth in its SUP production (TEI, 2020). Further, the European Plastics Converters (EuPC), a trade association, has called up the EU legislative agencies to roll back the imposed ban on a set of SUP items in the member states of the European Union due to COVID-19 pandemic (Financial Times, 2020).

Moreover, the drastic decrease in the cost of plastic manufacturing due to plummeting oil and petroleum prices owing to reduced transportation activities in the time of pandemic-induced lockdowns is yet another factor contributing to the abrupt increased manufacturing and supply of plastic products in proportion with the demand (Eco-

Table 1
Demand and usage of plastic-based PPEs during COVID-19 pandemic in various countries.

Country	Demand and usage of plastic-based PPEs during COVID-19	References
China	<ul style="list-style-type: none"> Plastic manufacturers are producing 116 million surgical masks per day Around 14.8 million facial masks have been produced as of February 2020 	ADB, 2020; BBC, 2020; LA Times, 2020; WEF, 2020
India	<ul style="list-style-type: none"> Around 25 lakhs PPEs are required per day in the fight against COVID-19 	Tol, 2020
Thailand	<ul style="list-style-type: none"> Around 62% more plastic consumption in April 2020 as compared to the amount consumed in the last 12 months About 1.5–2 million masks used daily nationwide 	TEI, 2020
Bangladesh	<ul style="list-style-type: none"> Around 455 million surgical masks and 1216 million gloves have been used during the first month of COVID-19 pandemic 	ESDO, 2020
UK	<ul style="list-style-type: none"> Per day demand of plastic medical kits ranges between 7.5 and 12 million in the fight against COVID-19 National Health Service Hospital (NHS), UK uses more than 55 thousand masks, aprons, and gowns per day 	BBC, 2020
France	<ul style="list-style-type: none"> Around 40 million surgical masks are used weekly 	BoF, 2020
Japan	<ul style="list-style-type: none"> About 600 million facial masks produced per day as of April 2020 	METI, 2020
Italy	<ul style="list-style-type: none"> Monthly demand for facial masks and medical gloves has been increased to 1 billion and 0.5 billion, respectively in the fight against COVID-19 	IMF, 2020

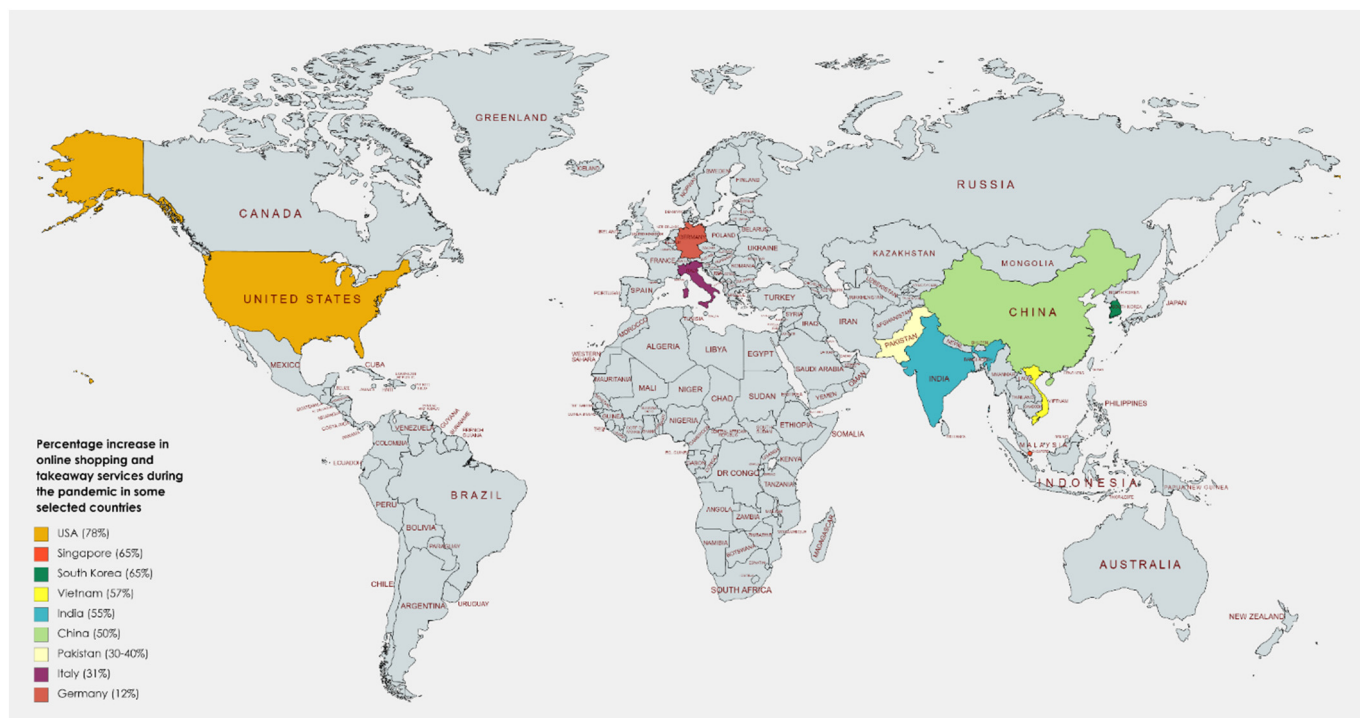


Fig. 2. Percentage increase in online shopping and takeaway services during the pandemic in some selected countries. Data sourced from Bhatti et al. (2020), Mu-Hyun (2020), and Today Online (2020). Created with mapchart.net©.

Business, 2020). This has led manufacturing industries to choose between plastic recycling and plastic production, and the latter has emerged as an economically viable option over the former in the current situation. As a result, the manufacturing industries are returning back to produce new virgin plastic, further adding up to the unsustainable plastic growth rate and mismanaged plastic waste generation with a decreased rate of plastic recycling. For example, a significant reduction in demand in the range of 30–40% for recycled plastics in the South-East Asian countries has been reported due to plummeting oil prices during the pandemic (BIR, 2020). Further, more and more subtle changes in plastic product consumption like swapping the reusable bags with SUP bags as a precautionary measure, disposable wipes usage for disinfection, and carrying hand sanitizer bottles most of the time are some of the extreme reactions exaggerating the plastic production (Kalina and Tilley, 2020). Therefore, the increased usage of SUPs in the time of pandemic has ensued in a substantial surge in plastic production. A more severe threat is now apparent worldwide as the developing countries were struggling hard to manage their plastic trash even before the COVID-19 pandemic. Revoking or postponement of bans on SUPs and unprecedented usage of PPEs have posed stiffer challenges in terms of effective waste management amid increased plastic waste generation during the pandemic.

4. Plastic waste generation, management and fate during COVID-19 pandemic

4.1. Plastic waste generation during the pandemic

The pandemic has brought about a change in waste generation and composition dynamics and thereby posed a stiff challenge for the local authorities, service providers, policymakers, and regulatory agencies. The unprecedented usage of mostly plastic-based PPEs by the frontline health workers and common citizens has resulted in the increased plastic waste generation globally (Patrício Silva et al., 2020). Further, the disposal of many plastic-based parts of the coronavirus testing kits employing reverse transcription polymerase chain reaction (RT-PCR) after single use

for hygienic concerns has given rise to the plastic waste generation. Moreover, the increased usage of SUPs and plastic-based packaging materials for e-commerce shopping and takeaway services amid the pandemic has spiked the plastic waste generation further (Jribi et al., 2020; WEF, 2020). Additionally, plastic packaging waste is increasingly getting generated due to the growing global demand for medical products and packaging in the time of pandemic (WHO-UNICEF, 2020). During the pandemic, the BMW stream mostly comprises of infected plastic-based PPEs and other disposable items from the impacted sources as well as similar non-infected items from non-impacted sources are generated (UNEP, 2020; Yang et al., 2021). The COVID-19 BMW generation with a greater proportion of plastics has been directly linked to the excessive use of mostly plastic-based PPEs, and other disposables necessitated since the novel coronavirus outbreak (Klemeš et al., 2020; Sharma et al., 2020). The average daily generation of biomedical waste containing plastic waste in selected Asian countries or their prominent cities during the pandemic is presented in Fig. 3.

As per the report released by the Ministry of Ecology and Environment, China, about 240 t of medical waste with a greater proportion of plastics was generated daily in Wuhan during the outbreak as compared to 40 t per day (tpd) before the pandemic (Klemeš et al., 2020; WEF, 2020). The assumption that medical waste containing plastics is only generated at the hospitals and health treatment facilities can sometimes be misleading in the pandemic scenario. For instance, approximately 200 kg of discarded masks were found over 200 public dustbins in Wuhan, China (SUEZ, 2020). Further, the entire Hubei Province in China showed a sharp increase of 370% in medical waste generation, containing a substantial portion of plastics, with a cumulative generation of 207 kt in China during the outbreak (Klemeš et al., 2020). Following this trend, Frost & Sullivan, a consulting firm based in the USA, predicted that the country might produce as much medical waste containing plastic waste in just two months of duration during the pandemic as much produced in one entire year (WEF, 2020). In Bangladesh, a total of 14,500 t of hazardous plastic waste, with about 3076 t in Dhaka alone, comprising of facial masks, hand gloves, and single-use polybags, were generated during the first month of the COVID-19 outbreak (ESDO, 2020). Further, about



Fig. 3. Average daily generation of biomedical waste containing plastic waste in selected Asian countries or their prominent cities during COVID-19 pandemic. Data sourced from ADB (2020); CPCB (2020b); ESDO (2020); Rhee (2020); WEF (2020). Created with mapchart.net©.

1216 million hand gloves amounting to an estimated quantity of 3039 t of disposable plastic waste generation was also reported. At the same time, around 250 t of medical waste containing plastic-made surgical masks and gloves, and 1.1 t of SUP waste from hospitals and pathological testing laboratories, respectively, were reported to be generated. In South Korea, about 295 t of infectious medical waste containing plastics sourcing from hospitals (61%), isolation centers (34%), and the community treatment facilities (5%) in the one-month period during February–March 2020 in the time of pandemic has been reported to be generated (Rhee, 2020). Further, Indonesia reported an average increase of 30% in biomedical waste generation during the early months of the COVID-19 outbreak from around 10,903 t in January 2020 to 14,606 t in April 2020 (UNEP-IGES, 2020). Similarly, the Philippines, Vietnam, and Kuala Lumpur in Malaysia reported around 16,800, 9600, and 9240 t of medical waste, respectively, with a greater proportion of plastics during the first two months of the coronavirus outbreak (ADB, 2020). In India, about 2907 hospitals, 20,707 quarantine centers, 1539 sample collection centers, and 264 testing laboratories are involved in the generation of COVID-19 BMW (CPCB, 2020b). It has been reported that around 22 kg of plastic waste is generated for every 1000 tests for coronavirus employing the RT-PCR technique. At this rate, about 14.5 tpd of plastic waste is generated from the testing alone in India. In addition to about 609 tpd of normal biomedical waste, a total of around 101 tpd of COVID-19 biomedical waste containing plastic waste is generated in India (CPCB, 2020b). The state-

wise average daily generation of COVID-19 biomedical waste containing plastic waste in India is shown in Fig. 4.

Increased usage of SUPs and plastic-based packaging materials for on-line shopping and takeaway services amid the pandemic-induced lockdowns in many countries has surged the plastic waste generation further. In Thailand, the plastic waste generation is reported to be increased to 6300 tpd from 1500 tpd amid the pandemic owing to the soaring rate of home deliveries and takeaway services (TEI, 2020). A study by the National University of Singapore (NUS) highlighted that an additional amount of about 1334 t of plastic waste was generated from takeaway and home delivery services in Singapore during the two months of lockdown (April–May 2020) (Today Online, 2020). These dramatic changes in the volume and composition of plastic waste in the time of pandemic have warranted special attention to sustainable practices and resilient infrastructures for effective plastic waste management.

4.2. Global practices for plastic waste management during the pandemic

Plastic waste management globally has already been inadequate considering the waste generation in the pre-pandemic situation. Waste management infrastructures are generally designed for steady-state operations with average waste flowrate and composition with moderate variations under normal circumstances. However, the pandemic-induced dramatic change in waste generation and

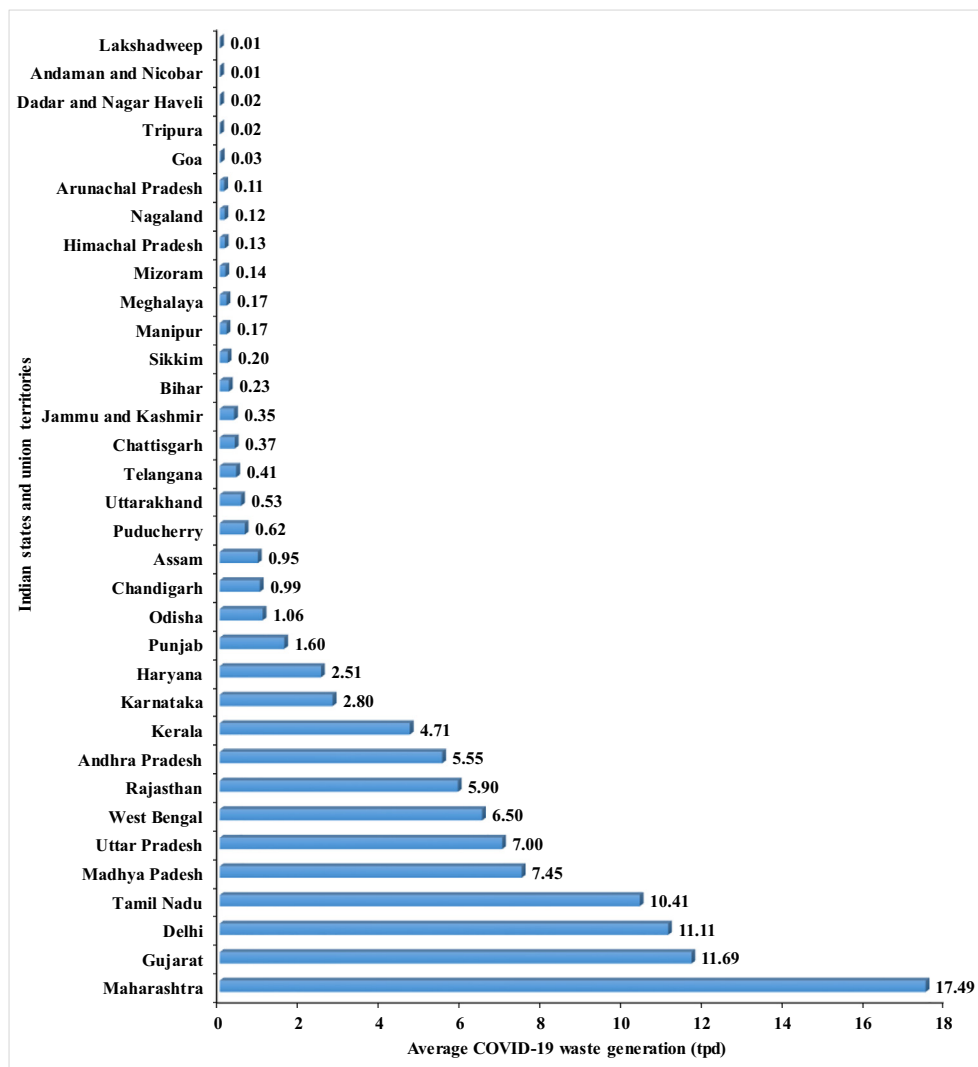


Fig. 4. Average daily generation of COVID-19 biomedical waste containing plastic waste in India. Data sourced from CPCB (2020b).

composition dynamics is highly likely to overburden the existing infrastructures and thereby disrupt the normal operation. Efficient management of plastic waste and biomedical waste containing mostly plastic waste during the pandemic poses a considerable challenge for different components of the system, viz. source identification, segregation, collection and transportation, and treatment and disposal in addition to the hygiene, safety, and associated training aspects of personnel and workers involved. In this context, various international organizations such as the WHO, UNICEF, UN-Habitat, UNEP, European Commission, Asian Development Bank (ADB), and country's apex pollution monitoring bodies and health organizations like Occupational Safety and Health Administration (OSHA), USA, Ministry of Ecology and Environment (MEE), China, National System for Environmental Protection (SNPA), Italy, Central Pollution Control Board (CPCB), India, Ministry of Health and Population (MHP), Nepal, Ministry of Health and Indigenous Medical Services, Sri Lanka have recently issued specific guidelines and advisories to manage COVID-19 BMW containing plastic waste as summarized in Table 2. Most of these guidelines and advisories are mainly concerned with hygiene routines, use of PPEs, and segregation, collection, storage, transportation and, proper treatment and disposal of potentially contaminated waste as an emergent response to the steep increase in waste generation during the pandemic (Penteado and de Castro, 2021; Yang et al., 2021). In addition to the prevailing BMW management rules in various countries, these guidelines and

advisories are contingent to minimize adverse impacts of waste generated on health and the environment during the pandemic. Based on these guidelines, global practices and approaches, the fate and management of plastic waste, including those contained in BMW during the COVID-19 pandemic, are conceptualized and summarily depicted in Fig. 5. Despite guidelines and advisories are laid down, it has been reported that some Asian nations do not follow proper procedures for waste handling leading to the piling up of infectious COVID-19 generated plastic waste within the general community. For instance, developing countries like Cambodia, the Philippines, Thailand, India, Malaysia, Indonesia, Bangladesh, Vietnam, and Palestine have been reported to dump their infectious BMW in open landfills. This is another instance where inappropriate management of infected PPEs and medical waste may increase the chances of the spread of viral infection in the environment (Sangkhom, 2020). Thus, one of the numerous issues that will inevitably occur is infectious plastic waste, if not handled appropriately, might be the underlying driver of extreme illnesses and environmental issues during and post-pandemic period.

4.2.1. Challenges associated with plastic waste treatment and disposal practices during the pandemic

From the treatment and disposal perspectives, mechanical recycling, incineration, and landfilling are the most widely employed methods for plastic waste management worldwide. Given the unprecedented surge

Table 2
Guidelines issued by various organizations for the management of COVID-19 waste containing plastic waste.

Organization	Country/region	Guidelines/recommendations	References
World Health Organization (WHO) and UNICEF (WHO-UNICEF)	Worldwide	<ul style="list-style-type: none"> • Single-use masks and gloves must be discarded after each use. • Health-care waste including used PPEs (gloves, masks, goggles, fluid-resistant apron) must be collected in clearly marked lined containers and sharp safe boxes, and stored, preferably on-site prior to treatment and safe disposal. • Waste produced at home during quarantine needs to be packed in strong black bags and sealed properly prior to collection by the municipal entities. • Health-care waste should preferably be treated by autoclaving or high temperature burn incinerators. 	WHO-UNICEF, 2020
Asian Development Bank (ADB)	Worldwide	<ul style="list-style-type: none"> • Infected COVID-19 solid waste (including PPEs) must be double bagged before treatment/disposal. • COVID-19 infected domestic/medical waste (plastics included) should not be recycled and must undergo incineration or sanitary landfilling. 	ADB, 2020
United Nations-Habitat (UN-Habitat)	Worldwide	<ul style="list-style-type: none"> • Potentially infectious waste including used PPEs should be placed in colored double bags tied with string or adhesive tape. • If potentially infectious waste cannot be separated from other wastes, entire waste is to be placed in double bags and sealed. In such cases, entire waste is to be considered as residual waste not meant for material recovery. • Increased frequency of waste collection at regular interval from COVID-19 sources, especially hospitals. • On-site temporary storage for 72 h before disposal followed by thermal treatment of infectious waste. Sanitary landfilling is to be done in cases where thermal treatment is not possible. • Material recycling in multi-material recovery plants can be adopted after storing the materials for an appropriate time followed by sterilization. 	UN-Habitat, 2020
Union Nations Environment Programme (UNEP)	Worldwide	<ul style="list-style-type: none"> • Effective management of biomedical and health-care waste by separate collection, transportation, storage, treatment and disposal with personnel protection and hygiene. • Medical waste including contaminated PPEs mixed with garbage from domestic sources should be collected by the municipalities and waste management operators, treated as hazardous waste and disposed of separately. 	UNEP, 2020
European Commission	Member States across the European Union (EU)	<ul style="list-style-type: none"> • COVID-19 health-care waste from healthcare facilities, laboratories and other contaminated zones should be treated and managed in accordance to the EU law on waste, especially Directive 2008/98/EC on waste and articles 17, 23, 24, and 25 thereof relating hazardous waste and the European Centre for Diseases prevention and Control (ECDC) advisories. • Medical waste including used plastics containing highly and low infectious substances should be treated as category A (UN 2814/UN 2900) and category B (UN 3291), respectively. Waste generated from non-impacted settings must be disposed of with the residual waste. • Treatment of medical waste containing used plastics by incineration followed by safe disposal. Separate and safe storage of medical waste in sealed and disinfected containers in secured areas if treatment facility is temporarily unavailable. • PPEs used by COVID-19 infected patients and those used by health workers must initially collected in separate bags and not mixed together and then both the bags must be collected in one general double layered bag for appropriate disposal. 	European Commission, 2020
Ministry of Ecology and Environment (MEE)	China	<ul style="list-style-type: none"> • Collection and disposal of infectious plastic medical waste generated during the pandemic must be the priority for medical waste disposal units. • Treatment facilities like incineration for domestic and hazardous plastic waste generated must take place in accordance with the competent medical health authorities. • COVID-19 waste management practices (storage, transportation, and disposal) must not compromise the personal health hygiene. 	MEE, 2020
Occupational Safety and Health Administration (OSHA)	USA	<ul style="list-style-type: none"> • Waste management system must not pay special attention to suspected COVID-19 contaminated plastic waste over the PPEs used by frontline health workers to combat the infection. • COVID-19 contaminated municipal solid waste must be treated like other non-contaminated municipal solid waste undergoing strict administrative actions. • Use of PPEs and safe work practices must be adopted by workers to prevent the exposure to infection. 	OSHA, 2020
Central Pollution Control Board (CPCB)	India	<ul style="list-style-type: none"> • Double layered plastic bags must be used to collect the waste from COVID-19 isolation wards and ICUs. • CBWTF operators should be timely informed about the generation of biomedical waste (including face masks, gloves) from quarantine centers for their timely collection and treatment. • Plastic BMW must be handed over to urban local bodies (ULBs) waste collector and should finally reach to CBWTF. • CBWTF operators must ensure health hygiene while handling COVID-19 infected waste (wearing layered masks, nitrile gloves, gumboots, safety goggles and water-proof aprons/gloves). • COVID-19 plastic waste (goggles, hazmat suits, nitrile gloves) should be disinfected/shredded/recycled. • Used masks, head caps, shoe covers must be incinerated. 	CPCB, 2020a
National System for Environmental Protection (SNPA)	Italy	<ul style="list-style-type: none"> • COVID-19 plastic waste generation has been classified under COVID-19 impacted and COVID-19 non-impacted sources. • Impacted COVID-19 plastic waste must be collected in double layered bags with no need to separate the waste on source collection and they should be treated as 	SNPA, 2020

Table 2 (continued)

Organization	Country/region	Guidelines/recommendations	References
Ministry of Health and Population (MHP)	Nepal	<ul style="list-style-type: none"> residual waste. Non-impacted COVID-19 plastic waste must be collected employing separate collection system and treated as residual waste to be delivered via sealed bags. PPEs must be worn by workers handling the COVID-19 waste. Auxiliary staff and health workers will undergo appropriate training to dispose the plastic-based PPEs. Protective gears including facial masks, gloves, face shields, aprons/gowns must be used to avoid infection at different levels of the health care system. 	MHP, 2020
Ministry of Health and Indigenous Medical Services	Sri Lanka	<ul style="list-style-type: none"> Infectious waste generated from the impacted and non-impacted sources is advised to be segregated at the source itself using colored-coded containers. On transportation of the solid waste including infectious plastic waste to the treatment facilities, leakage or spillage must be checked to avoid contamination. All the contaminated waste including plastic-based PPEs shall be incinerated or autoclaved following proper safety protocol. 	Ministry of Health and Indigenous Medical Services, 2020

in waste generation, plastic recycling across the globe has seen a sharp decline in the time of the pandemic. For instance, many states in the US are either suspending or downsizing the municipality-run recycling programs out of a total of around 9000 such facilities owing to the fund crunch at the local level during the pandemic. Peoria, Illinois has already suspended recycling programs, whereas Omaha, New Orleans, and Lexington in Virginia are contemplating massive downsizing (Scientific American, 2020; SWANA, 2020). The disruption in the recycling program is even further magnified in countries like Brazil, Guatemala, Haiti, India, Indonesia, Kenya in the developing world due to severe fund crunch. Further, the informal recycling sector, prevalent in the developing world, is bearing the brunt of the pandemic owing to the poor collection and lack of market demand for recycled plastics (Prata et al., 2020; Scientific American, 2020; Sharma et al., 2020; Urban and Nakada, 2021). Many plastic recycling techniques are susceptible to impurities in the form of inorganics, additives, dirt, and polymer cross-contamination (Klemeš et al., 2020). Unlike the efficient recycling of single-stream plastics like PET with the least impurities, it is very

difficult and unrewarding to recycle mixed plastic streams, SUPs, multi-layer plastics, composites, and degraded plastic materials (Peng et al., 2020). Moreover, restricted physical collaboration owing to social distancing and employee safety in the work environment, along with staff shortage, are also limiting the plastic recycling programs across the globe to realize their full potential during the pandemic (BIR, 2020). Considerable reduction in the plastic recycling rate amid the unsustainable plastic production rate and increased waste generation in the time of pandemic may lead to mismanagement and leakage into the terrestrial and aquatic ecosystems.

Incineration as a thermal treatment is another widely used method for the management of plastic waste and BMW. Incineration of plastic waste, regardless of segregation and impurities, in the temperature range of 800–1000 °C for safer destruction with the provision of waste heat recovery can be a reasonable choice considering its lower labor prerequisite with lesser chances of contamination (Klemeš et al., 2020; White, 2020). Based on the volume of the waste, incineration is an ideal alternative for waste generation >10 tpd, whereas other

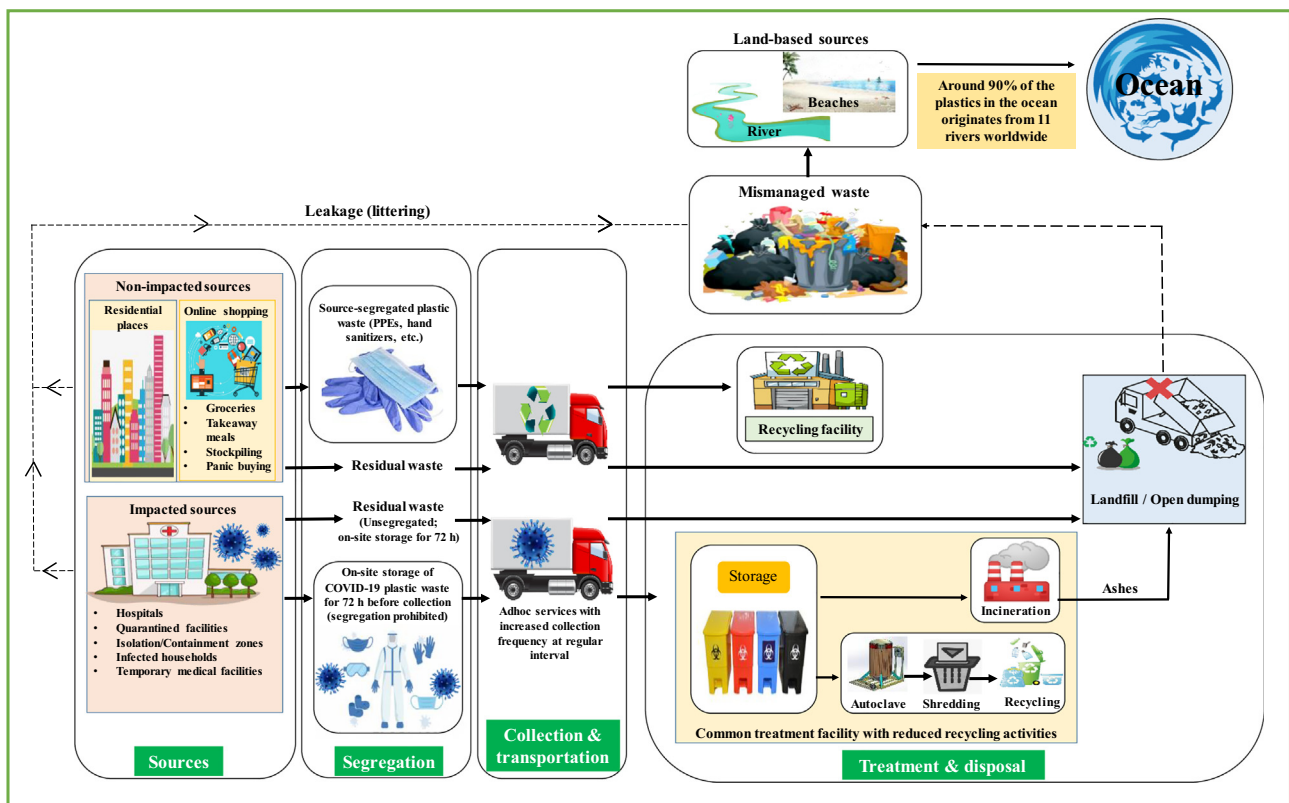


Fig. 5. Fate and management of plastic waste during COVID-19 pandemic.

thermal techniques like autoclaving, microwave irradiation are preferred for waste generation of <10 tpd (Patrício Silva et al., 2021). However, the major challenge during the pandemic lies in the breaching of existing incineration capacity by a wider margin with the increased plastic waste generation. For example, the peak medical waste generation of 240 tpd in Wuhan, China has breached the existing incineration capacity of 49 tpd during the coronavirus outbreak (Klemeš et al., 2020). Further, the emission of hazardous gases like dioxins and furans from the incinerators without adequate air pollution control always remains a concern (Wang et al., 2020b).

Landfilling is a commonly preferred method for the disposal of plastic waste, mainly in developing countries, despite being the least preferred option in the waste management hierarchy. However, unscientific landfilling and indiscriminate dumping of waste are prevalent in many parts of the developing world barring few megacities equipped with sanitary landfilling facilities. This could result in the landfills and dumpsites exhausting their capacity, severe space crunch, leakage, and mismanagement of plastic waste, leaching of toxic chemicals, etc. (Vanapalli et al., 2020). Prioritization of landfilling could lead to littering and open burning of a significant quantity of plastic waste and thereby resulting in an increased environmental footprint (ACR+, 2020). For instance, significantly increased instances of unscientific landfilling and open burning of plastic waste in many Indian cities during the pandemic have been reported (Corburn et al., 2020). A considerable drop in the recycling activities and the exhaustion of existing incineration capacity in many countries during the pandemic suggest the prospective leakage and mismanagement of a significant amount of plastic waste either in landfills or the natural environment causing long-term environmental repercussions (UNEP, 2020). There are several plausible routes of mismanagement and leakage of plastic waste from the sources and the disposal sites in the existing waste management framework as depicted in Fig. 5.

Increased production and consumption of plastic-based PPEs create havoc when inappropriately discarded and littered, contributing to mismanaged plastic waste finding its way into the oceans, ultimately via land-based waterways (Fadare and Okoffo, 2020; Hellewell et al., 2020; Kalina and Tilley, 2020). The problem has been further exacerbated due to recent flooding in many South Asian countries like Bangladesh, Nepal, Bhutan, and India (Inter Press Service, 2020; The Third Interpole, 2020). At the onset of the COVID-19 pandemic, OceansAsia, a Hong Kong-based organization, reported an astonishing cluster of medical wastes including PPEs is being accumulated at the beaches in Soko Islands based in Hong Kong (Kalina and Tilley, 2020). Studies have also highlighted the leakage of plastic waste, especially SUPs into the ocean as a result of littering and mismanagement during the pandemic (Kulkarni and Anantharama, 2020; Scientific American, 2020; UNEP, 2020). Further, the environmental factors like UV radiation, wind velocity, sunlight, and other physical and mechanical processes result in the fragmentation of littered plastic particles into the smaller plastic debris like micro- or nano-plastics contaminating terrestrial and aquatic ecosystems (Patrício Silva et al., 2020). In light of the current pandemic, adding to the existing vast challenge of plastic pollution, the recent abrupt increase in the consumption of SUPs (especially facemasks) has aggravated the problem leading to the potential release of microplastics contaminating the waterways. Recent studies have also highlighted that the polymeric constituents of surgical masks and packaging material consumed during the pandemic may act as a potential source of microplastic pollution globally if continued to dispose of inappropriately though the possible long-term impacts are still unknown (Aragaw, 2020; Fadare and Okoffo, 2020). For instance, the inappropriate disposal of even 1% of facial masks would be equivalent to monthly 10 million masks polluting the environment and amounting to an indispensable dispersion of about 40,000 kg plastic into the environment considering the weight of each facial mask to be approximately 4 g (Patrício Silva et al., 2020). Thus, the indiscriminate littering, unscientific landfilling, and the leakage of plastic waste during

the pandemic may further cause microplastic pollution, posing a serious impact on the aquatic species. The size and appearance of used PPEs and their fragmented debris may lead to their false identification and ingestion by such marine species like sea turtles and fishes as food and influencing the food chain as the long-term impacts (Fadare and Okoffo, 2020; Prata et al., 2020).

4.2.2. Potential technological solutions to manage plastic waste during the pandemic and beyond

With the limited available options and overwhelming burden on the efficacy of existing waste management infrastructures, integration of new approaches and technological solutions for plastic waste collection, segregation, and subsequent treatment including decontamination of PPE kits could be beneficial in addressing the key challenges during and post-pandemic period. In addition to the capacity enhancement of the existing waste management system, it is expected that the new approaches and technological solutions can be contingent to deal with the surge in plastic waste generation. The WHO guidelines suggest mandatory incineration of PPEs and other infectious waste including plastic waste in the temperature range of 900–1200 °C (WHO-UNICEF, 2020). However, the design capacity of the incinerators needs a thorough overhaul to deal with the pandemic-induced surge in plastic waste generation and composition dynamics. Further, the incinerators need to be augmented with advanced air pollution control equipment to minimize secondary pollution. Incineration technique augmented with advanced air pollution control mechanisms is most prevalent in Europe, with countries like Denmark, Finland, Poland, and Sweden continue to incinerate more than 50% of the municipal solid waste and plastic waste supplementing the market energy demand (Istrate et al., 2020; Mollica and Balestieri, 2020). In Spain, cement plants are permitted to co-incinerate waste if the need arises (ACR+, 2020). Incineration integrated with stringent air pollution control can be a short-term, convenient option to deal with the increased generation of plastic waste and BMW in the time of the pandemic. However, the long-term solution lies in adopting the recycling paradigm following the waste management hierarchy.

The scarcity of protective medical kits during the current crisis in response to the exceeding demand has challenged the supply chain of PPEs significantly in many regions across the globe. Innovative technological solutions and advanced disinfection practices to boost the supply chain of PPEs considering the increased global demand are the need of the hour. Decontamination of used PPEs, FFRs, surgical and procedure masks can be posited as a potential temporary solution to ease the shortage of plastic-based medical safety gears owing to their reuse without having major impacts on the filtering and fit testing efficiency providing satisfactory safety performance (Su-Velez et al., 2020). Selection of different decontamination methods depending on the influential factors such as the amount and type of COVID-19 generated plastic waste, transportation, operational maintenance, and cost economics has been outlined elsewhere (Ilyas et al., 2020; Wang et al., 2020b; Zorko et al., 2020). Potential disinfection solutions involving chemical sanitization, and some high-heat treatment options are considered to be ecologically viable too (Rubio-Romero et al., 2020; Wang et al., 2020b).

Physical and chemical decontamination methods like scientific sterilization of infected BMW, microwave/radio wave disinfection, and steam disinfection/autoclaving are likely to help in reducing the viral transmission risk from the infected COVID-19 plastic waste (Belhadi et al., 2020; Rowan and Laffey, 2020). A brief summary of some selected studies on the decontamination methods for reprocessing and reuse of pathogen-infected plastic-based PPEs has been presented in Table 3.

Ultraviolet germicidal irradiation (UVGI), ethylene oxide, and vaporous hydrogen peroxide (VHP) have been found to effectively disinfect the used medical safety kits (Polkinghorne and Branley, 2020). Mechanical crushing of used PPEs into smaller fractions followed by chemical disinfection has been reported to efficiently deactivate infectious

Table 3
Summary of studies on the decontamination methods for reprocessing and reuse of pathogen-infected PPEs.

Country	Medical kits examined	Decontamination methods	Protocol adopted	Effects/impacts	Advantages	References
India	<ul style="list-style-type: none"> Respirators PPEs 	Physical-irradiation and heat treatment	Warm ultraviolet hybrid model (WUVH) based on ultraviolet irradiation and heat treatment applied	99.99% reduction of infectious coronavirus achieved within 16 min of the decontamination cycle	<ul style="list-style-type: none"> Degrade other pathogens as well Customized to be used at 3 different modes, for example, standalone warm heat, standalone UV radiation and, hybrid model Sanitization speed in achieving efficacy increased leading to damage of viral DNA and membrane 	Banerjee et al., 2020
Belgium	<ul style="list-style-type: none"> Surgical masks FFRs 	Physical-irradiation, chemical, and heat treatment	UGVI, VHP, and dry heat treatment applied	All the 3 methods successfully reduced the infectious load by more than three orders of magnitude	<ul style="list-style-type: none"> The first investigation of stable decontamination with the use of 3 different techniques Time-efficient and user friendly 	Ludwig-Begall et al., 2020
USA	<ul style="list-style-type: none"> N95 respirators Surgical masks Procedure masks 	UV irradiation, chemical, and heat treatment	Isopropanol (IPA)-soaking/spraying, UVGI and heat treatment (dry and moist steam) carried out	<ul style="list-style-type: none"> IPA successfully benefited the disinfection of N95 respirators UVGI sustained filtration efficiency of all every kit examined Better compatibility of filtering and fit testing efficiency achieved by dry heat treatment 	<ul style="list-style-type: none"> Time-efficient and user friendly Commercial available 	Ou et al., 2020
USA	PPEs	Chemical treatment	Self-decontamination of SAR-CoV-2 contaminated fabrics made up of dimethyl terephthalate (DMT) & mono-ethylene glycol (MEG) using disinfectant - Duritex (natural biopolymer) were performed	Reduced 99.99% of infectious viral load	<ul style="list-style-type: none"> Potentially useful for disinfection of clinical PPEs On comparing with other disinfection methods, the decontamination starts before the doffing of the PPEs 	Campos et al., 2020
USA	N95 respirators	Chemical and heat treatment	Low-temperature sterilization applied with 59% VHP	Successful decontamination of N95 respirators	<ul style="list-style-type: none"> Filtration and mask fit efficiency were not hampered even after high concentration chemical treatment 	Jatta et al., 2020
China	<ul style="list-style-type: none"> N95 respirators Surgical masks 	Dry heat treatment	Dry heat pasteurization applied for 1 h at the temperature 70 °C	<ul style="list-style-type: none"> At 60–70 °C, dry heat treatment successfully killed micro-organisms N95 respirators & surgical masks showed no changes in shape and composition Filtering efficiency of N95 respirators and surgical masks were maintained as 98% and 97% respectively 	<ul style="list-style-type: none"> Time-efficient and user friendly Easily operated at homes and clinical centers 	Xiang et al., 2020
Germany	FFRs	Moist heat treatment	Microwave generated heat evaluated for water absorption and filtration efficiency during FFRs disinfection	99.9% disinfection efficiency observed in inactivating bacteriophage as surrogate pathogen.	<ul style="list-style-type: none"> Cost effective and commercially available Can be performed at household and healthcare facilities 	Fisher et al., 2011
USA	N95 respirators	Dry and moist heat treatment, chemical treatment, and UV irradiation	<ul style="list-style-type: none"> Hot air (oven) – 75 °C, 30 min/cycle UV light (254 nm, 30 min/cycle) Hot steam (10 min/cycle) 	All 3 methods maintained the filtration efficiency around 95%	<ul style="list-style-type: none"> No mechanical deformation Commercially available Can be performed at household and healthcare facilities 	Liao et al., 2020

pathogens. Chemical disinfectants like sodium hypochlorite, calcium hypochlorite, chlorine dioxide, sodium peroxide, bleach, etc. could be the viable option considering their characteristics like odorless, tasteless, colorless, non-corrosiveness, and readily water-soluble with no reported hazardous by-product upon treatment (Wang et al., 2020b). Similarly, electromagnetic radiation-based microwave or radio wave disinfection technology can be used for effective sterilization of the contaminated plastic waste. This technology has been reported to be relatively faster, energy-efficient, high yield output, and minimal environmental consequences with no release of toxic particles or residue upon disinfection (Belhadi et al., 2020). Another on-site treatment method involving autoclaving equipped with high heat energy (temperature between 93 and 177 °C) and saturated water steam is known to efficiently decontaminate medical plastic waste (Ilyas et al., 2020;

Su-Velez et al., 2020). The steam generated in the process exhibits latent heat causing denaturation and coagulation of microorganisms leading to their inactivation with no significant release of harmful gases. The majority of these techniques utilize equipment and disinfectants, which are readily available in clinical centers or hospitals and could be considered for reprocessing of used PPEs and sanitization of facemasks. Besides, some of these techniques can be performed at the household level broadening the practice of decontamination across a wide range of healthcare settings (Polkinghorne and Branley, 2020). Considering the increased demand and shortcomings in the key supply chain of PPEs among different developed and developing countries, these decontamination methods might be useful in reprocessing of some selective used plastic protective gears like eye goggles, face shields, facemasks, and thereby reducing the plastic waste generation during the pandemic

(WHO, 2020a, 2020b). Besides, strategic planning to safeguard the supply chain of PPEs during the pandemic by ensuring adequate manufacturing, easy access, proper monitoring, and protection to curtail the shortage in the demand of medical safety kits would likely to benefit the healthcare system and environmental sustainability in the long run (Barcelò, 2020).

4.3. Plastics: protecting health or damaging the environment during COVID-19 pandemic?

The general notion of plastics as evil polluter has become more intense due to their mismanagement amid increased plastic usage and waste generation during the COVID-19 pandemic. However, it is necessary to acknowledge that we are witnessing and surviving in a new normal where the current situation is not the same as it is used to be during the pre-pandemic situation. Plastics cover a whole group of complex polymers and co-polymers, substrates, and laminates that have been used to secure and safeguard human wellbeing since the novel coronavirus outbreak in terms of PPEs and single-use medical equipment, and packaging for e-commerce utilities. Major applications of plastic in the healthcare sector include protective gear, medical tools and equipment, and packaging owing to its flexibility and durability. Further, a certain class of plastics is not only the most advantageous and proficient for packaging and carrying goods, but they are additionally the most ecologically viable option too. They are lightweight, low-volume, durable, inexpensive, and high-quality material having good insulating properties that play a significant role across environmental, social, and economic dimensions of environmental sustainability (Klemeš et al., 2020). Several studies have acknowledged that the flexibility and strength of certain polymers like films and foils have reduced the total packaging weight, which otherwise would have been increased by four-fold, leading to increased plastic waste up to 60% (Klemeš et al., 2020; Kulkarni and Anantharama, 2020; Vanapalli et al., 2020). Therefore, it would not exaggerate to infer that the world's major health crisis has eased by our dependency on plastic-based safety kits and packaging solutions in the present scenario. Though the usage and consumption of plastics have ensured the improved quality of life and public health protection during this unprecedented uncertainty, it is important to maintain a balance between public health protection and environmental sustainability. Considering the pros and cons of plastic in the time of the pandemic, an equitable appraisal suggests that the consumers' irresponsible behavior, and attitude and poor awareness, and the stress on waste management infrastructure in terms of collection, operation, and financial constraints as the major factors, leading to mismanagement, turn plastic into an evil polluter of the environment. Plastic can be a protector if managed properly and complemented by the circular economy strategies in terms of reduction, recycle and recovery, and thereby preventing leakage into the environment. To curb the ongoing plastic pandemic and beyond, sustainable solutions and safer practices include scientific decontamination of PPEs for reprocessing and reuse boosting the circular economy, plastic reduction policies, product redesign and innovation, and automation in plastic waste management to overcome the challenges of protecting public health without damaging the environment. Policy guidelines encouraging to adopt sustainable waste management practices and consumers' education for awareness creation are the need of the hour for preventing plastic to turn from protector with high utility to polluter.

5. Future perspectives

Lack of efficient planning and important policy interventions exaggerated the leakage and mismanagement of plastic waste into the environment leading to another threat during the prevailing pandemic. Though the preliminary statistics on the amount of plastic waste generated during the COVID-19 is staggering, it will take time to understand how precisely such additional plastic waste is going to impact the

environment. However, repercussions of COVID-19 generated plastic waste could be used as a landmark to be prepared with emergency measures and long-term waste management options helping us to build a better and safer future. Robust policies and sustainable approaches and initiatives are the need of the hour today to deal with the prevailing issues and challenges the world is facing related to plastic waste management amid increased waste generation during the pandemic. Advancements in the technological aspects along with sustainable approaches are required from corporate sectors, scientific community, and governments across the globe to address the sustainability challenges triggered during the pandemic. Responsive recovery plans and strategies espoused by regulating agencies worldwide must consider the deep roots influencing environmental stresses taking into account the pandemic multiple extents and global mobility. Sustainability measures taken today to combat the plastic pollution triggered by the COVID-19 crisis serve as an opportunity to materialize the much-awaited transformative changes towards a pollution-free society. Some of the approaches or solutions might need an immediate action call, while others will be of significant requirement in the longer run by categorizing core challenges needed attention in the short, medium, or long-term. Some of the recommendations to overhaul the existing plastic waste management paradigm inducing appropriate actions needed from policymakers, research communities, manufacturing industries along with public participation are as follows:

- Handling the COVID-19 generated plastic waste with structured waste management procedures is of utmost importance today. Therefore, the government, stakeholders, and policymakers must recognize the sustainability imparted by efficient waste management services and undergo necessary transition/amendment protocols for effective implementation at all the stages to ensure prevention, segregation, and suitable plastic waste treatment helping the nature to cope up from this pandemic.
- Following the local, national or international advisories and guidelines, color-coded bags should be used by the individual households to collect and dispose of used PPEs to avoid any littering and mismanagement. Further, color-coded bins must be deployed at the community level to ensure proper collection and disposal of such used PPEs. Moreover, the deployment of mobile treatment facilities to manage infectious plastic waste on-site must be considered.
- Robust policies must be devised to encourage plastic packaging materials with uniform compositions rather than mixed or multi-layer materials for improved recyclability. Further, plastic packaging materials need to be resin coded to enhance the recyclability of SUPs. At the same time, research efforts are warranted to develop sustainable techniques like chemical recycling to manage mixed plastic waste into valuable products such as fuels and chemicals to ensure circularity.
- Healthcare centers and scientific institutions must consider different decontamination methods to reprocess and reuse PPEs, particularly FFRs, without compromising the functional efficiency. UV irradiation, dry and moist heat treatment along with commercially available chemicals like ethylene oxide and VHP could be used as an alternate solution for effective decontamination of FFRs. Such decontamination methods will ensure the supply chain of plastic-based safety kits and reduce plastic waste generation, thereby encouraging sustainable approaches like reduce and reuse.
- To meet the demand of PPEs amid the pandemic, research and product innovation in developing eco-friendly and reusable PPE kits should be encouraged. Manufacturing industries must focus on the usage of biodegradable or compostable plastic materials like bio-plastics and compostable bags made from biomass with higher degradability and recyclability. Further, suitable associated infrastructure must be created to manage such bio-plastics waste.
- The use of reusable cloth facemasks must be promoted instead of the plastic-based commercially available facemasks to cut down the growth of plastic waste. If the cloth-based or similar fabric made

masks can provide the same level of protection, then initiatives should be put on the forefront to opt for reusable face coverings to reduce plastic pollution amid the pandemic.

- Positive lifestyle changes in our day-to-day life activities may act as a potential driver to minimize plastic waste generation during and after the pandemic. Reconsidering our choices on how to shop and order essentials online may lead to optimal resource consumption. For instance, avoiding packed food from restaurants and emphasizing more on locally grown eatables, using reusable shopping bags with its proper disinfection, choosing soap dispenser bottles or refillable hand washes/hand sanitizer over disposable bottles are some of the eco-friendly behaviors that we can adopt in an attempt to safeguard our environment while fighting the battle to prevent plastic pollution.
- Waste management infrastructures and services emerging from this pandemic to become resilient need creativity. Innovativeness and creativity will be the new normal in waste management by embracing new technology and out-of-box thinking. Restricted physical collaboration owing to social distancing and employee safety in the work environment, automation, and robotics with the deployment of artificial intelligence (AI), machine learning (ML), and internet of things (IoT) will play a key role in plastic waste segregation and recycling. Recently, several waste management enterprises have been reported to be working on artificial intelligence (AI) to effectively deal with waste generated during and aftermath of COVID-19. Further, many advanced techniques like thermal imaging, hyperspectral imaging, laser-induced breakdown spectroscopy (LIBS) are being researched upon for automated classification and segregation of plastics from mixed waste for recycling (Gundupalli et al., 2017a, 2017b; Junjuri and Gundawar, 2020).
- Following the sterilization by steam- or heat-based techniques, mechanical recycling of the plastic waste with automation must be promoted to contribute towards the circular economy. To achieve this, policy guidelines need to be formulated to incentivize mechanical recycling activities during and post-pandemic situations.
- Automated waste treatment techniques like pyrolysis, gasification, hydrothermal carbonization and other thermal conversion technologies could be employed to convert COVID-19 BMW with a greater proportion of plastics into energy and valuable by-products. Such technologies for plastic waste management should be encouraged to maximize the safety of human health and the environment altogether.
- Information, education, and communication (IEC) campaigns must be initiated to create mass awareness by educating the citizens to take up the responsibility for appropriate plastic waste disposal (particularly, facemasks and other SUPs) as well as to understand the environmental consequences posed by indiscriminate littering and mismanagement of plastic waste. Further, the environmental impact of plastic pollution menace must be included in the curricula at school, college, and university levels to create awareness among the next generation.

6. Conclusions

The COVID-19 crisis has highlighted the essentiality of plastic as a protector in the healthcare sector and public health safety owing to its intrinsic properties. However, the general perception about plastic as an evil polluter has been further strengthened due to its mismanagement and underutilization of resource value considering the pandemic-induced surge in plastic usage and waste generation. An equitable appraisal by comparing the functionalities and shortcomings of plastic suggests that the consumers' attitude and behavioral aspect of poor social awareness and the inadequacies of the existing waste management system as the key drivers make plastic an environmental polluter. It is important to acknowledge that plastic could be a protector rather than a polluter if the circular economy approaches are properly integrated. To prioritize the circular economy, continued progress

must be made in reprocessing and reusing the PPEs, especially FFRs by adopting efficient decontamination methods to keep the supply chain intact. Further, research and product innovation in developing eco-friendly and reusable PPE kits and carry bags made of bio-plastics with higher recyclability should be encouraged. Existing waste management systems and infrastructures should be automated with the deployment of AI, ML, and IoTs for plastic waste segregation and recycling. Mechanical recycling following the sterilization of infectious plastic waste must be incentivized with policy formulation to contribute towards the circular economy. Chemical recycling to manage mixed plastic waste into valuable products such as fuels and chemicals would certainly help in achieving circularity. IEC campaign and educational curricula are needed as a long-term plan to improve consumers' behavioral attitude and social awareness to tackle the plastic pollution menace. Safer practices and sustainable technical solutions supported by the robust policies for transitioning towards the circular economy paradigm coupled with consumers' education for awareness creation are crucial to restrict plastic to become a polluter from protector with high functionality.

CRedit authorship contribution statement

Neha Parashar: Investigation, Resources, Data curation, Visualization, Writing - original draft. **Subrata Hait:** Conceptualization, Methodology, Supervision, Visualization, Writing - review & editing.

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 manuscript.

References

- ACR+, 2020. Municipal waste management and COVID-19. Association of cities and regions for sustainable resource management (ACR+) <https://www.acrplus.org/en/municipalwaste-management-covid-19>. (Accessed 9 November 2020).
- ADB, 2020. Managing infectious waste during the COVID-19 pandemic. Asian Development Bank (ADB) <https://www.adb.org/sites/default/files/publication/578771/managing-medical-waste-covid19.pdf>. (Accessed 9 October 2020).
- Aragaw, T.A., 2020. Surgical face masks as a potential source for microplastic pollution in the COVID-19 scenario. *Mar. Pollut. Bull.* 159, 111517.
- Banerjee, R., Roy, P., Das, S., Paul, M.K., 2020. A hybrid model integrating warm heat and ultraviolet germicidal irradiation might efficiently disinfect respirators and personal protective equipment. *Am. J. Infect. Control* 000, 1–10. <https://doi.org/10.1016/j.ajic.2020.07.022>.
- Barcelò, D., 2020. An environmental and health perspective for COVID-19 outbreak: meteorology and air quality influence, sewage epidemiology indicator, hospitals disinfection, drug therapies and recommendations. *J. Environ. Chem. Eng.* 8, 104006. <https://doi.org/10.1016/j.jece.2020.104006>.
- BBC, 2020. COVID-19: How Long Does the Coronavirus Last on Surfaces. British Broadcasting Corporation (BBC) <https://www.bbc.com/future/article/20200317-covid-19-how-long-does-the-coronavirus-last-on-surfaces/>. (Accessed 21 August 2020).
- Belhadi, A., Kamble, S.S., Khan, S.A.R., Touriki, F.E., Kumar, M.D., 2020. Infectious waste management strategy during COVID-19 pandemic in Africa: an integrated decision-making framework for selecting sustainable technologies. *Environ. Manag.* <https://doi.org/10.1007/s00267-020-01375-5>.
- Bhatti, A., Akram, H., Basit, H.M., Khan, A.U., Naqvi, Raza, S.M., Bilal, M., 2020. E-commerce trends during COVID-19 Pandemic. *Int. J. Futur. Gener. Commun. Netw.* 13, 1449–1452.
- BIR, 2020. Covid-19 Update: Fragmented Picture for Under-Pressure Recycling Industry. Bureau of International Recycling (BIR) <https://www.eco-business.org/news-press/covid-19-infocenter/item/covid-19-update-fragmented-picture-for-under-pressure-recycling-industry/>. (Accessed 28 August 2020).
- BoF, 2020. LVMH to Supply France With 40 million Surgical Masks to Tackle Shortage. Business of Fashion (BoF) <https://www.businessoffashion.com/articles/news-analysis/lvmh-to-supply-france-with-40-million-surgical-masks-to-tackle-shortage/>. (Accessed 9 November 2020).
- Borg, K., 2020. How to Break Up With Plastics Using Behavioural Science. InnerSelf <https://innerself.com/content/social/environment/22067-how-to-break-up-with-plastics-using-behavioural-science.html>. (Accessed 15 September 2020).
- Business Insider, 2020. COVID-19 impact on packaging market by material type, application and region-global forecast to 2021. <https://markets.businessinsider.com/news/stocks/covid-19-impact-on-packaging-market-by-material-type-application-and-region-global-forecast-to-2021-1029187123>. (Accessed 20 September 2020).

- Campos, R.K., Saada, N., Rossi, S.L., Weaver, S.C., 2020. Thermally bonded disinfectant for self-decontamination of fabric against SARS-CoV-2. *J. Hosp. Infect.* <https://doi.org/10.1016/j.jhin.2020.09.008>.
- Chen, W.Q., Ciacchi, L., Sun, N.N., Yoshioka, T., 2020. Sustainable cycles and management of plastics: a brief review of RCR publications in 2019 and early 2020. *Resour. Conserv. Recycl.* 159. <https://doi.org/10.1016/j.resconrec.2020.104822>.
- Corburn, J., Vlahov, D., Mberu, B., Riley, L., Caiiffa, W.T., Rashid, S.F., Ko, A., Patel, S., Jukur, S., Martínez-Herrera, E., Jayasinghe, S., Agarwal, S., Nguendo-Yongsi, B., Weru, J., Ouma, S., Edmundo, K., Oni, T., Ayad, H., 2020. Slum health: arresting COVID-19 and improving well-being in urban informal settlements. *J. Urban Health* 88, S200. <https://doi.org/10.1007/s11524-020-00438-6>.
- CPCB, 2020a. Guidelines for Handling, Treatment and Disposal of Waste Generated During Treatment/Diagnosis/Quarantine of COVID-19 Patients. 3rd revision. Central Pollution Control Board (CPCB) https://cpbc.nic.in/uploads/Projects/Bio-Medical-Waste/BMW-GUIDELINES-COVID_1.pdf. (Accessed 13 September 2020).
- CPCB, 2020b. Consolidated Status Report on Scientific Disposal of Bio-Medical Waste Arising Out of Covid-19 Treatment – Compliance of BMW Rules, 2016 Before Hon'ble National Green Tribunal, Principle Bench. Central Pollution Control Board (CPCB), New Delhi https://greentribunal.gov.in/sites/default/files/news_updates/Status%20Report%20in%20A.%20No.%2072%20of%202020.pdf. (Accessed 11 September 2020).
- Eco-Business, 2020. Coronavirus-induced oil price plunge is hurting the circular economy for plastic. <https://www.eco-business.com/news/coronavirus-induced-oil-price-plunge-is-hurting-the-circular-economy-for-plastic/>. (Accessed 11 July 2020).
- ESDO, 2020. ESDO's Online Press Briefing on Covid-19 Pandemic Outbreak 14,500 Tons of Hazardous Plastic Waste in a Month. Environment and Social Development Organization (ESDO) <https://esdo.org/esdos-online-press-briefing-on-hazardous-plastic-waste-generation-in-a-month-during-covid-19-pandemic/>. (Accessed 17 September 2020).
- European Commission, 2020. Waste management in the context of the coronavirus crisis. https://ec.europa.eu/info/sites/info/files/waste_management_guidance_dg-env.pdf. (Accessed 12 September 2020).
- Fadare, O.O., Okoffo, E.D., 2020. Covid-19 face masks: a potential source of microplastic fibers in the environment. *Sci. Total Environ.* 737, 140279. <https://doi.org/10.1016/j.scitotenv.2020.140279>.
- Financial Times, 2020. Plastic straws and stirrers ban delayed because of coronavirus. <https://www.ft.com/content/8182d6db-f903-49a1-9e68-43341ad932ce>. (Accessed 14 September 2020).
- Fisher, E.M., Williams, J.L., Shaffer, R.E., 2011. Evaluation of microwave steam bags for the decontamination of filtering facepiece respirators. *PLoS One* 6. <https://doi.org/10.1371/journal.pone.0018585>.
- Grashuis, J., Skevas, T., Segovia, M.S., 2020. Grocery shopping preferences during the COVID-19 pandemic. *Sustain.* 12. <https://doi.org/10.3390/su12135369>.
- Gundupalli, S.P., Hait, S., Thakur, A., 2017a. A review on automated sorting of source-separated municipal solid waste for recycling. *Waste Manag.* 60, 56–74. <https://doi.org/10.1016/j.wasman.2016.09.015>.
- Gundupalli, S.P., Hait, S., Thakur, A., 2017b. Multi-material classification of dry recyclables from municipal solid waste based on thermal imaging. *Waste Manag.* 70, 13–21. <https://doi.org/10.1016/j.wasman.2017.09.019>.
- Hale, R.C., Song, B., 2020. Single-use plastics and COVID-19: scientific evidence and environmental regulations. *Environ. Sci. Technol.* 54, 7034–7036. <https://doi.org/10.1021/acs.est.0c02269>.
- Hellewell, J., Abbott, S., Gimma, A., Bosse, N.I., Jarvis, C.I., Russell, T.W., Munday, J.D., Kucharski, A.J., Edmunds, W.J., 2020. Feasibility of controlling COVID-19 outbreaks by isolation of cases and contacts. *Lancet Glob. Health* 8, e488–e496. [https://doi.org/10.1016/S2214-109X\(20\)30074-7](https://doi.org/10.1016/S2214-109X(20)30074-7).
- Ilyas, S., Srivastava, R.R., Kim, H., 2020. Disinfection technology and strategies for COVID-19 hospital and bio-medical waste management. *Sci. Total Environ.* 749, 141652. <https://doi.org/10.1016/j.scitotenv.2020.141652>.
- IMF, 2020. Italy, Europe and the Global Recovery in 2021. International Monetary Fund (IMF) <https://www.imf.org/en/News/Articles/2020/06/13/sp061320-Italy-Europe-and-the-Global-Recovery-in-2021>. (Accessed 9 September 2020).
- Inter Press Service, 2020. The COVID-19 plastic pandemic. <http://www.ipnews.net/2020/08/covid-19-plastic-pandemic/>. (Accessed 30 August 2020).
- Istrate, I.-R., Iribarren, D., Galvez-Martos, J.-L., Dufour, J., 2020. Review of life-cycle environmental consequences of waste-to-energy solutions on the municipal solid wastemanagement system. *Resour. Conserv. Recycl.* 157, 104778. <https://doi.org/10.1016/j.resconrec.2020.104778>.
- Jatta, M., Kiefer, C., Patolia, H., Pan, J., Harb, C., Marr, L.C., Baffoe-Bonnie, A., 2020. N95 reprocessing by low temperature sterilization with 59% vaporized hydrogen peroxide during the 2020 COVID-19 pandemic. *Am. J. Infect. Control* 000, 0–6. doi:<https://doi.org/10.1016/j.ajic.2020.06.194>.
- Jribi, S., Ben, H., Doggui, D., Debbabi, H., 2020. COVID-19 virus outbreak lockdown: what impacts on household food wastage? *Environ. Develop. Sustain.* 22 (5), 3939–3955.
- Junjuri, R., Gundawar, M.K., 2020. A low-cost LIBS detection system combined with chemometrics for rapid identification of plastic waste. *Waste Manag.* 117, 48–57. <https://doi.org/10.1016/j.wasman.2020.07.046>.
- Kahlert, S., Bening, C.R., 2020. Plastics recycling after the global pandemic: resurgence or regression? *Resour. Conserv. Recycl.* 160, 104948. <https://doi.org/10.1016/j.resconrec.2020.104948>.
- Kalina, M., Tilley, E., 2020. "This is our next problem": cleaning up from the COVID-19 response. *Waste Manag.* 108, 202–205. <https://doi.org/10.1016/j.wasman.2020.05.006>.
- Kaufman, L., Chasan, E., 2020. Cities wonder whether recycling counts as essential during the virus. *Bloomberg Green*. <https://www.bloomberg.com/news/articles/2020-03-27/cities-wonder-whether-recycling-counts-as-essential-during-the-virus>. (Accessed 30 August 2020).
- Klemeš, J.J., Fan, Y.V., Tan, R.R., Jiang, P., 2020. Minimising the present and future plastic waste, energy and environmental footprints related to COVID-19. *Renew. Sust. Energy. Rev.* 127, 109883. <https://doi.org/10.1016/j.rser.2020.109883>.
- Kulkarni, B.N., Anantharam, V., 2020. Repercussions of COVID-19 pandemic on municipal solid waste management: challenges and opportunities. *Sci. Total Environ.* 743, 140693. <https://doi.org/10.1016/j.scitotenv.2020.140693>.
- LA Times, 2020. The COVID-19 Pandemic Is Unleashing a Tidal Wave of Plastic Waste. *Los Angeles Times (LA Times)* <https://www.latimes.com/world-nation/story/2020-06-13/coronavirus-pandemic-plastic-waste-recycling>. (Accessed 9 August 2020).
- Laato, S., Islam, A.K.M.N., Farooq, A., Dhir, A., 2020. Unusual purchasing behavior during the early stages of the COVID-19 pandemic: the stimulus-organism-response approach. *J. Retail. Consum. Serv.* 57, 102224. <https://doi.org/10.1016/j.jretconser.2020.102224>.
- Lauer, S.A., Grantz, K.H., Bi, Q., Jones, F.K., Zheng, Q., Meredith, H.R., Azman, A.S., Reich, N.G., Lessler, J., 2020. The incubation period of coronavirus disease 2019 (COVID-19) from publicly reported confirmed cases: estimation and application. *Ann. Intern. Med.* 172, 577–582. <https://doi.org/10.7326/M20-0504>.
- Liao, L., Xiao, W., Zhao, M., Yu, X., Wang, H., Wang, Q., Chu, S., Cui, Y., 2020. Can N95 respirators be reused after disinfection? How many times? *ACS Nano* 14, 6348–6356. <https://doi.org/10.1021/acsnano.0c03597>.
- Ludwig-Begall, L.F., Wielick, C., Dams, L., Nauwynck, H., Demeuldre, P.F., Napp, A., Laperre, J., Haubruge, E., Thiry, E., 2020. The use of germicidal ultraviolet light, vaporized hydrogen peroxide and dry heat to decontaminate face masks and filtering respirators contaminated with a SARS-CoV-2 surrogate virus. *J. Hosp. Infect.* 106, 577–584. <https://doi.org/10.1016/j.jhin.2020.08.025>.
- MEE, 2020. Management and Technical Guidelines for Emergency Disposal of Medical Wastes Induced by the Novel Coronavirus Pneumonia Epidemic (Trail). Ministry of Ecology and Environment, China http://www.gov.cn/xinwen/2020-01/29/content_5472997.htm. (Accessed 20 August 2020).
- METI, 2020. METI to Convey Information on Menu of Support Measures for Businesses Affected by Novel Coronavirus Disease Utilizing LINE Application. Ministry of Economy, Trade and Industry (METI), Government of Japan https://www.meti.go.jp/english/press/2020/0416_001.html. (Accessed 13 July 2020).
- MHP, 2020. Health Sector Emergency Response Plan COVID-19 Pandemic. Ministry of Health and Population, Nepal https://www.who.int/docs/default-source/nepal-documents/novel-coronavirus/health-sector-emergency-response-plan-covid-19-endorsed-may-2020.pdf?sfvrsn=e831f44_2. (Accessed 17 September 2020).
- Ministry of Health and Indigenous Medical Services, 2020. Sri Lanka preparedness & response plan COVID-19. http://www.health.gov.lk/moh_final/english/public/elfinder/files/news/2020/FinalSPRP.pdf. (Accessed 2 September 2020).
- Mol, M.P.G., Caldas, S., 2020. Can the human coronavirus epidemic also spread through solid waste? *Waste Manag. Res.* 38, 485–486. <https://doi.org/10.1177/0734242X20918312>.
- Mollica, G.J.C., Balestieri, J.A.P., 2020. Is it worth generating energy with garbage? Defining a carbon tax to encourage waste-to-energy cycles. *Appl. Therm. Eng.* 173, 115195. <https://doi.org/10.1016/j.applthermaleng.2020.115195>.
- Mu-Hyun, C., 2020. Korea sees steep rise in online shopping during COVID-19 pandemic. *ZD Net*. <https://www.zdnet.com/article/korea-sees-steep-rise-in-online-shopping-during-covid-19-pandemic/>. (Accessed 28 August 2020).
- Ortiz-Prado, E., Simbaña-Rivera, K., Gómez-Barrero, L., Rubio-Neira, M., Guaman, L.P., Kyriakidis, N.C., Muslin, C., Jaramillo, A.M.G., Barba-Ostria, C., Cevallos-Robalino, D., Sanches-SanMiguel, H., Unigarro, L., Zalakeviciute, R., Gadian, N., López-Cortés, A., 2020. Clinical, molecular, and epidemiological characterization of the SARS-CoV-2 virus and the Coronavirus Disease 2019 (COVID-19), a comprehensive literature review. *Diagn. Microbiol. Infect. Dis.* 98. <https://doi.org/10.1016/j.diagmicrobio.2020.115094>.
- OSHA, 2020. Occupational Safety and Health Administration, United States. <https://www.osha.gov/SLTC/covid-19/controlprevention.html#solidwaste>. (Accessed 14 September 2020).
- Ou, Q., Pei, C., Chan Kim, S., Abell, E., Pui, D.Y.H., 2020. Evaluation of decontamination methods for commercial and alternative respirator and mask materials – view from filtration aspect. *J. Aerosol Sci.* 150, 105609. <https://doi.org/10.1016/j.jaerosci.2020.105609>.
- Patrício Silva, A.L., Prata, J.C., Walker, T.R., Campos, D., Duarte, A.C., Soares, A.M.V.M., Barceló, D., Rocha-Santos, T., 2020. Rethinking and optimising plastic waste management under COVID-19 pandemic: policy solutions based on redesign and reduction of single-use plastics and personal protective equipment. *Sci. Total Environ.* 742, 140565. <https://doi.org/10.1016/j.scitotenv.2020.140565>.
- Patrício Silva, A.L., Prata, J.C., Walker, T.R., Duarte, A.C., Ouyang, W., Barceló, D., Rocha-Santos, T., 2021. Increased plastic pollution due to Covid-19 pandemic: challenges and recommendations. *Chem. Eng. J.* 126683. <https://doi.org/10.1016/j.cej.2020.126683>.
- Peng, J., Wu, X., Wang, R., Li, C., Zhang, Q., Wei, D., 2020. Medical waste management practice during the 2019–2020 novel coronavirus pandemic: experience in a general hospital. *Am. J. Infect. Control* S0196-6553 (20), 30351–30355. <https://doi.org/10.1016/j.ajic.2020.05.035>.
- Penteado, C.S.G., de Castro, M.A.S., 2021. Covid-19 effects on municipal solid waste management: what can effectively be done in the Brazilian scenario? *Resour. Conserv. Recycl.* 164, 105152. <https://doi.org/10.1016/j.resconrec.2020.105152>.
- Polkinghorne, A., Branley, J., 2020. Evidence for decontamination of single-use filtering facepiece respirators. *J. Hosp. Infect.* 105, 663–669. <https://doi.org/10.1016/j.jhin.2020.05.032>.
- Prata, J.C., Silva, A.L.P., Walker, T.R., Duarte, A.C., Rocha-Santos, T., 2020. COVID-19 pandemic repercussions on the use and management of plastics. *Environ. Sci. Technol.* 54, 7766–7765. <https://doi.org/10.1021/acs.est.0c02178>.

- Rhee, S.W., 2020. Management of used personal protective equipment and wastes related to COVID-19 in South Korea. *Waste Manag. Res.* <https://doi.org/10.1177/0734242X20933343>.
- Rowan, N.J., Laffey, J.G., 2020. Challenges and solutions for addressing critical shortage of supply chain for personal and protective equipment (PPE) arising from Coronavirus disease (COVID19) pandemic – case study from the Republic of Ireland. *Sci. Total Environ.* 725, 138532. <https://doi.org/10.1016/j.scitotenv.2020.138532>.
- Rubio-Romero, J.C., Pardo-Ferreira, M. del C., Torrecilla-García, J.A., Calero-Castro, S., 2020. Disposable masks: disinfection and sterilization for reuse, and non-certified manufacturing, in the face of shortages during the COVID-19 pandemic. *Saf. Sci.* 129, 104830. <https://doi.org/10.1016/j.ssci.2020.104830>.
- Sangkham, S., 2020. Face mask and medical waste disposal during the novel COVID-19 pandemic in Asia. *Case Stud. Chem. Environ. Eng.* 2, 100052. <https://doi.org/10.1016/j.cscee.2020.100052>.
- Scientific American, 2020. COVID-19 Has worsened the ocean plastic pollution problem. <https://www.scientificamerican.com/article/covid-19-has-worsened-the-ocean-plastic-pollution-problem/#click=https://t.co/J1qlJfSaT>. (Accessed 29 August 2020).
- Sharma, H.B., Vanapalli, K.R., Cheela, V.S., Ranjan, V.P., Jaglan, A.K., Dubey, B., Goel, S., Bhattacharya, J., 2020. Challenges, opportunities, and innovations for effective solid waste management during and post COVID-19 pandemic. *Resour. Conserv. Recycl.* 162, 105052. <https://doi.org/10.1016/j.resconrec.2020.105052>.
- Shetty, S.S., Wollenberg, B., Merchant, Y., Shabadi, N., 2020. Discarded Covid 19 gear: a looming threat. *Oral Oncol.*, 104868 <https://doi.org/10.1016/j.oraloncology.2020.104868>.
- SNPA, 2020. Prime Indicazioni Generali Per La Gestione Rifiuti – Emergenza Covid-19. National System for Environmental Protection, Italy <https://www.snpambiente.it/2020/03/24/emergenza-covid-19-indicazioni-snpa-sulla-gestione-dei-rifiuti/>. (Accessed 28 August 2020).
- SUEZ, 2020. COVID-19: SUEZ mobilised to treat infectious biomedical waste. <https://www.suez.com/en/news/covid-19-suez-mobilised-to-treat-infectious-biomedical-waste>. (Accessed 25 August 2020).
- Su-Velez, B.M., Maxim, T., Long, J.L., St John, M.A., Holliday, M.A., 2020. Decontamination methods for reuse of filtering facepiece respirators. *JAMA Otolaryngol. - Head Neck Surg.* 146, 734–740. <https://doi.org/10.1001/jamaoto.2020.1423>.
- SWANA, 2020. SWANA Reminds Allstate and Local Governments that Solid Waste Management Is an Essential Public Service. Solid Waste Association of North America (SWANA) <https://swana.org/news/swana-news/article/2020/03/19/swana-reminds-all-state-and-local-governments-that-solid-waste-management-is-an-essential-public-service>. (Accessed 9 June 2020).
- TEI, 2020. Solid Waste During COVID-19. Thailand Environment Institute (TEI) http://www.tei.or.th/en/blog_detail.php?blog_id=49. (Accessed 9 August 2020).
- Tenenbaum, L., 2020. The Amount of Plastic Waste Is Surging Because Of The Coronavirus Pandemic. *Forbes* <https://www.forbes.com/sites/lauratenbaum/2020/04/25/plastic-waste-during-thetime-of-covid-19/#7c4e661f7e48>. (Accessed 27 August 2020).
- The Third Interpole, 2020. Early monsoon floods show climate change impact in South Asia. <https://www.thethirdpole.net/2020/06/29/early-monsoon-south-asia/>. (Accessed 25 August 2020).
- Today Online, 2020. Singapore households generated additional 1,334 tonnes of plastic waste during circuit breaker: study. <https://www.todayonline.com/singapore/singapore-households-generated-additional-1334-tonnes-plastic-waste-during-circuit-breaker>. (Accessed 9 September 2020).
- Tol, 2020. How Unpopular Plastic Turned Saviour in COVID-19 fight. *Times of India (Tol)* <https://timesofindia.indiatimes.com/india/how-unpopular-plastic-turned-saviour-in-covid-19-fight/articleshow/76726087.cms>. (Accessed 9 October 2020).
- UNEP, 2020. Waste Management an Essential Public Service in the Fight to Beat COVID-19. The United Nations Environment Programme (UNEP) <https://www.unenvironment.org/news-andstories/press-release/waste-management-essential-public-service-fight-beat-covid-19>. (Accessed 9 November 2020).
- UNEP-IGES, 2020. Waste Management During the COVID-19 Pandemic: From Response to Recovery. The United Nations Environment Programme - Institute for Global Environment Strategies (UNEP - IGES) <https://www.unenvironment.org/ietc/resources/report/waste-management-during-covid-19-pandemic-response-recovery>. (Accessed 3 September 2020).
- UN-Habitat, 2020. Strategy guidance: Solid waste management response to COVID-19. The United Nations Human Settlements Programme https://unhabitat.org/sites/default/files/2020/05/unhabitat_strategy_guidance_swm_reponse_to_covid19.pdf. (Accessed 26 August 2020).
- Urban, R.C., Nakada, L.Y.K., 2021. COVID-19 pandemic: solid waste and environmental impacts in Brazil. *Sci. Total Environ.*, 755142471 <https://doi.org/10.1016/j.scitotenv.2020.142471>.
- U.S.A. Today, 2020. Plastic bag bans reversed: states, cities, stores are suddenly banning reusable bags during coronavirus. <https://www.usatoday.com/story/money/2020/04/08/plastic-bag-bans-reversed-coronavirus-reusable-bags-covid-19/2967950001/>. (Accessed 23 August 2020).
- van Doremalen, N., Bushmaker, T., Morris, D.H., 2020. Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. *N. Engl. J. Med.* 382, 1564–1567. <https://doi.org/10.1056/NEJMc2004973>.
- Vanapalli, K.R., Sharma, H.B., Ranjan, V.P., Samal, B., Bhattacharya, J., Dubey, B.K., Goel, S., 2020. Challenges and strategies for effective plastic waste management during and post COVID-19 pandemic. *Sci. Total Environ.*, 141514 <https://doi.org/10.1016/j.resconrec.2020.105052>.
- Wang, E., An, N., Gao, Z., Kiprop, E., Geng, X., 2020a. Consumer food stockpiling behavior and willingness to pay for food reserves in COVID-19. *Food Secur.* 12, 739–747. <https://doi.org/10.1007/s12571-020-01092-1>.
- Wang, D., Sun, B.-C., Wang, J.-X., Zhou, Y.-Y., Chen, Z.-W., Fang, Y., Yue, W.-H., Liu, S.-M., Liu, K.-Y., Zeng, X.-F., Chu, G.-W., Chen, J.-F., 2020b. Can masks be reused after hot water decontamination during the COVID-19 pandemic? *Eng. J.* <https://doi.org/10.1016/j.eng.2020.05.016>.
- WEF, 2020. The Plastic Pandemic Is Only Getting Worse During COVID-19. World Economic Forum (WEF) <https://www.weforum.org/agenda/2020/07/plastic-waste-management-covid19-ppe/>. (Accessed 9 July 2020).
- White, A.O., 2020. Plastic pollution: why chemical recycling could provide a solution. <https://theconversation.com/plastic-pollution-whychemical-recycling-could-provide-a-solution-129917>. (Accessed 24 August 2020).
- WHO, 2020a. Rational use of Use of Personal Protective Equipment (PPE) for Coronavirus Disease (COVID-19). World Health Organization (WHO) https://apps.who.int/iris/bitstream/handle/10665/331215/WHO-2019-nCov-IPCPE_use-2020-1-eng.pdf. (Accessed 9 August 2020).
- WHO, 2020b. Shortage of Personal Protective Equipment Endangering Health Workers Worldwide. The World Health Organization (WHO) <https://www.who.int/news-room/detail/03-03-2020-shortage-of-personalprotective-equipment-endangering-healthworkers-worldwide>. (Accessed 9 July 2020).
- WHO-UNICEF, 2020. Water, Sanitation, Hygiene, and Waste Management for the COVID-19 Virus: Interim Guidance. World Health Organization (WHO) - United Nations Children's Fund (UNICEF) <https://www.who.int/publications/i/item/water-sanitation-hygiene-and-waste-management-for-the-covid-19-virus-interim-guidance>. (Accessed 25 August 2020).
- World Bank, 2020. Plastics: the coronavirus could reset the clock. <https://blogs.worldbank.org/voices/plastics-coronavirus-could-reset-clock>. (Accessed 12 September 2020).
- Xiang, Y., Song, Q., Gu, W., 2020. Decontamination of surgical face masks and N95 respirators by dry heat pasteurization for one hour at 70°C. *Am. J. Infect. Control* 48, 880–882. <https://doi.org/10.1016/j.ajic.2020.05.026>.
- Yang, L., Yu, X., Wu, X., Wang, J., Yan, X., Jiang, S., Chen, Z., 2021. Emergency response to the explosive growth of health care wastes during COVID-19 pandemic in Wuhan. *China. Resour. Conserv. Recycl.* 164, 105074. <https://doi.org/10.1016/j.resconrec.2020.105074>.
- Zorko, D.J., Gertsman, S., O'Hearn, K., Timmerman, N., Ambu-Ali, N., Dinh, T., Sampson, M., Sikora, L., McNally, J.D., Choong, K., 2020. Decontamination interventions for the reuse of surgical mask personal protective equipment: a systematic review. *J. Hosp. Infect.* 106, 283–294. <https://doi.org/10.1016/j.jhin.2020.07.007>.