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Plastic pollution during COVID-19: Plastic waste directives and its long-term impact on the environment

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ABSTRACT

Majority of the million tons of plastic produced each year is being disposed after single-use. Plastic bottle, bags, food containers, gloves, and cup that end up in landfills and environment could linger for hundreds to thousands of years. Moreover, COVID-19 pandemic caused by the novel coronavirus (SARS-CoV-2), will also exacerbate the global plastic pollution as the use of personal protective equipment (PPE i.e., gloves, masks) became mandatory to prevent the spread of the virus. Plastic eventually breaking down in micro & nanoscopic bits due to physical or chemical or biological actions in the environment, can enter animal and human food web. So, plastic management programs need to be more robust with a focus on the prevention of the micro and nanoplastics entrance into the environment and food web. In the present pandemic situation, it is even more necessary to know about how much plastic waste is being generated and how different countries are coping up with their plastic waste management. In this review, we have elucidated how global plastic production rise during COVID-19 and how it would contribute to short and long-term impacts on the environment. Plastic pollution during the pandemic will increase the GHS emissions in the incineration facilities. Improper disposal of plastics into the oceans and lands would endanger the marine species and subsequently human lives. We have also assessed how the increased plastic pollution will aggravate the micro and nanoscale plastic problem, which have now become an emerging concern. This review will be helpful for people to understand the plastic usage and its subsequent consequences in the environment in a pandemic like COVID-19.

1. Introduction

Plastic is a polymeric material consisting of long carbon chains (Jakubowicz, 2003a). Due to its excellent physicochemical properties and economic viability (e.g., lightweight, flexibility, low production cost, availability), plastic is widely used in both industrial sectors and households (Geyer et al., 2017; Silva et al., 2020). About 396 million tons of plastics were produced in 2018 worldwide (PlascticsEurope, 2019), which was 48 million tons higher than the previous year and this number is expected to increase at a double rate in the next 20 years (Figure 1) (Boyle and Örmeci, 2020). 90% of the plastic production in the world consists of synthetic polymers such as polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), polyvinyl chloride (PVC), and polyurethane (PUR) (Phuong et al., 2016a). The excessive use of these synthetic plastics, coupled with their inherent resistant to degradation, is a serious environmental problem (Phuong et al., 2016b). Biodegradable plastic, an alternative to synthetic plastic have been introduced as they degrade more easily (Boyle and Örmeci, 2020). However, compared to other synthetic plastics, there is still no solid evidence that these plastics would break down in the natural environment (Boyle and Örmeci, 2020; EuropeanCommission, 2019, 2018). Around 8-12 million metric tons (Mt) of plastic generated on land ended up in oceans in 2018 alone contributing to the plastic pollution (Bondaroff and Cooke, 2020) and an estimated 13.2 billion tons of plastic waste would reach the landfills and environment (freshwater, oceans, air) by 2050 without the improvements of current plastic waste management practices (Silva et al., 2020).

Several initiatives have been proposed worldwide to prevent plastic leakage in the environment and decrease the environmental footprint of plastic. Ban of single use plastics (SUPs) and use of reusable bags has been found one of the effective preventive measures to decrease plastic waste (Schnurr et al., 2018). SUPs (e.g., plastic bags, coffee cups, soda and water bottles, etc.) are used only once before they are thrown away and have extremely low recyclability rate (~12%) (Azoulay et al., 2019;

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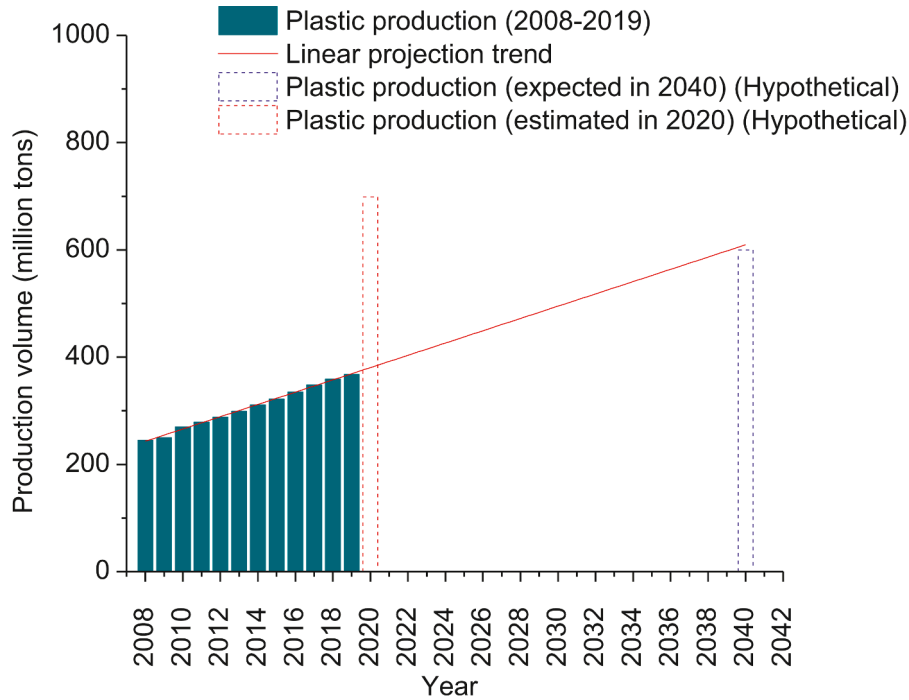

Fig. 1. Hypothetical past, present and future worldwide plastic production. Plastic production is predicted to increase to 600 million tons in 2040 based on the data available of plastic production rate between 2008 and 2019 (Tiseo, 2021) and assuming a linear trend. However, based on table 1 data, it has been estimated that COVID-19 caused a drastic increase of plastic production to around 698 million tons in only 2020. Detailed calculation is provided in the SI.

Wagner, 2017). However, COVID-19 pandemic, caused by a novel severe acute respiratory syndrome coronavirus (SARS-Cov-2), has resurrected the SUPs (Figure 1). SUP personal protective equipment (PPEs) such as face masks, surgical masks, face shields, and other PPEs both for frontline health workers and common citizens have been adopted to stop the contamination and spread of virus (Kahlert and Bening, 2020). The World Bank has already warned that this pandemic would reverse the years-long tide toward cutting down on SUPs (Bengali, 2020). Most of the PPEs are made up of PP, PVC, PS, which are rarely recycled (Kahlert and Bening, 2020). This would scale up the already existing plastic pollution in the terrestrial, atmospheric, and aquatic environment. In addition, lockdown during pandemic, has significantly impacted the plastic recycling facilities all over the world, resulting in improper and illegal disposal of plastic waste into the oceans and lands (Bondaroff and Cooke, 2020; Hernandez, 2020). Storm events would further increase the concentration of the illegally dumped plastic in the aquatic environments (Eerkes-Medrano et al., 2015).

Once these plastics are littered in the environment, they are susceptible to abiotic and biotic degradation processes (da Costa et al., 2016; Dantas et al., 2012; Jakubowicz, 2003b; Lambert et al., 2014). Macro (>25mm) and meso (5-25 mm) plastics degrade into micro (<5 mm) and nano-scale (<100 nm) plastics overtime (Boyle and Örmeci, 2020). A number of plastic research has identified that there is more plastic being discharged into the environment compared to the recorded sampling methods (da Costa, 2017). Researchers are certain that micro and nano plastics have infiltrated both aquatic and land environments (Carr et al., 2016; Eerkes-Medrano et al., 2019; He et al., 2018; Horton et al., 2017; Kosuth et al., 2018; Ng et al., 2018; Panno et al., 2019). However, there is a significant knowledge gap on how these micro and nano plastics move along different medium in the environment. Micro and nano plastics entering the human food chain impose a serious threat to human health (Bouwmeester et al., 2015; Chang et al., 2020; Paul et al., 2020)(Silva et al., 2021). Effect of microplastics to organisms besides human is also concerning (Silva et al., 2019; C. J. M. Silva et al., 2021). The plastic toxicity mechanisms includes metabolism disorders, oxidative stress, and inflammatory reactions to humans and other organisms (Chang et al., 2020; C. Silva et al., 2021)(Silva et al., 2021).

This review is aimed to provide a comprehensive overview on the short- and long-term effects of COVID-19 on plastic pollution in the environment. Using the most updated data of plastic usage during COVID-19, the scale of plastic waste generation was calculated and long-term effect on the environment was predicted using EPA's WARM (Waste Reduction Model) tool. The article also summarizes the current management steps taken by different countries and organizations to deal with this plastic overload.

2. Methodology

Data of plastic production volume from 2008-2019 was collected (Tiseo, 2021) and plotted in figure 1 and based on these data a linear trendline was assumed to predict plastic production in 2040. For a hypothetical plastic production calculation, the facemasks, gloves, gowns and goggles generated by each country was calculated using the following equations and data from table 1.

$$\text{TotalNumberProduced} = \text{NumberProducedPerDay} \times \text{Timescale} \tag{1}$$

$$\begin{aligned}\text{TotalItemNumber} = {} & \Sigma\text{TotalNumberofMaskProduced} \\ & + \Sigma\text{TotalNumberofGlovesProduced} \\ & + \Sigma\text{TotalNumberofGownsProduced} \\ & + \Sigma\text{TotalNumberofGogglesandPPEProduced}\end{aligned} \tag{2}$$

$$\text{TotalItemWeight(millionton)} = (\text{TotalNumberofItemProduced} \times \text{Itemweight})/10^6 \quad (3)$$

$$\text{Totalweight} = \Sigma\text{Totalmaskweight} + \Sigma\text{Totalglovesweight} + \Sigma\text{Totalgownsweight} + \Sigma\text{Totalgogglesweight} \quad (4)$$

The average number of days in a month per year was estimated as 30 days. Detailed calculation is provided in the supporting information.

For using waste reduction model (WARM), the plastic waste generation reported in USEPA's recent report was used (EPA, 2020). The reported value was added to the increased plastic waste from medicals and usage of facemask during Covid-19 pandemic. The increase in plastic waste during the pandemic was calculated using the common plastic waste management practices followed in the US, which is plastic incinerated 15.8%, and landfilled 75.7% (EPA, 2020). Assuming 50% reduction is recycling facility during the pandemic to stop the high risk of biohazard and lockdown in recycling facilities (Fadare and Okoffo, 2020), the recycling % was taken 4.25.

Previous scenario: $P_{W_{2018}}$

Current scenario: $P_{W_{2020}} = P_{W_{2018}} + P_{W_{Medical}} + P_{W_{Mask}}$

Where, $P_{W_{2018}}$ is the total plastic waste generated in 2018 in the US as report in EPA's recent report, $P_{W_{Medical}}$ and $P_{W_{Mask}}$ is the plastic waste generated from medical sources and mask usage. $P_{Recyled}(tons) = (P_{W_{2020}}) * \%\ recycled$, $P_{landfilled}(tons) = (P_{W_{2020}}) * \%\ landfilled$, and $P_{combusted}(tons) = (P_{W_{2020}}) * \%\ combusted$.

Emissions that occur during transport of waste to the management facility were included in the WARM and default average transport distances, 20 miles was used for the GHS emission calculation. The GHG emissions was reported as the equivalent of CO_2 and GHG emissions results estimated in WARM indicate the full life-cycle benefits waste management alternatives. Due to the timing of the GHG emissions from the waste management pathways, (e.g., avoided landfilling and increased recycling), the actual GHG implications might occur over the long-term. Further explanation of the WARM tool methodology is available on EPA's official website (United States Environmental Protection Agency, 2019).

3. Plastic waste boom during COVID-19

While government worldwide fight against the COVID-19 pandemic, there have been significant drawbacks in the use and management of plastic. Dramatic increase in the use of mask, gloves, protective medical suits, hand sanitizer bottles, all are contributing to an unforeseen crisis. In addition, syringes, tubes, catheters, packaging of saline solutions respirators, and thermometers, which are partially made of plastic, are also contributing towards this plastic pollution. Improper disposal of these potential life-saving plastic components could overload the waste management system of the cities around the world especially due to short-circuited waste collection operations during lockdown. For

Table 1
Consumption/ usage/ demand of plastic-based personal protective equipment (PPE) during COVID-19 pandemic in some countries.

Country	Consumption/usage/demand of plastic-based PPE during COVID-19	References
Canada	Number of SUP PPEs used from June 2020 to December 2020: • Gloves: 3.88 million per day • Mask: 1.76 million per day • Disposable gowns: 26.6 million	(Statics Canada, 2021)
USA	• The industrial giant, 3M alone would be supplying 1 billion N95 masks in 2021 • Demand for N95 masks increased substantially from 50 million per year to about 140 million during a 90-day peak-use period in 2020 • U.S. Department of Health and Human Services (HHS) estimated the demand of medical gloves to be 8.7 billion per month in 2020 • The Freedonia Group estimated an increase of around 312% demand of face shields during COVID-19	(Stankiewicz, 2020)(LOPEZ, 2021)(Laura Strickler, Stephanie Gosk, 2020)(Parashar and Hait, 2021)
UK	• SUP medical kits usage ranged between 7.5-12 million per day in 2020 • National Health Service Hospital (NHS) supplied more than 10 million single-use plastic PPE each day in the month of August, 2020 • Number of PPE items supplied to England healthcare services from February to June 2020: Facemasks: 421.8 million Gloves: 1.3 billion Aprons: 353 million Eye protectors: 42.4 million	(Parashar and Hait, 2021)(Way, 2020)(Way, 2020)
Brazil	• Daily use and disposal of more than 85 million facemasks	(Urban and Nakada, 2021)
China	• In February 2020, 116 million of single-use face mask got produced per day • Face mask production increased by 450% from January to February 2020 • Daily usage of facemasks was measured as 900 million pieces per day during the lockdown period.	(Parashar and Hait, 2021; Wang et al., 2020)(Silva et al., 2020)(Ragazzi et al., 2020)
India	• 2.5 million PPEs were required per day in 2020 • The Ministry has supplied 4.6 million N95 mask in June 2020 • 20 million protective gowns were expected to be supplied by the end of June 2020	(Parashar and Hait, 2021) (Bhowmick, 2020)(Pandit, 2020)
Italy	• Daily usage of facemasks was measured as 40 million pieces per day during the lockdown period.	(Ragazzi et al., 2020)
Thailand	• Around 2 million facemasks were used per day nationwide.	(Simachaya, 2020)
Bangladesh	• In the first month of COVID-19 pandemic, about 455 million surgical masks and 1216 million gloves have been used.	(ESDO, 2020)
France	• In every week, around 40 million surgical masks were used during the pandemic.	(Parashar and Hait, 2021)
Japan	• Everyday around 600 million facemasks were produced till April 2020.	(Parashar and Hait, 2021)

Table 2
Plastic waste generated during COVID-19 pandemic

Country	Plastic waste generated during the pandemic	References
China	• In Wuhan, medical waste increased to 240 ton per day (t/d) from 40 t/d, beyond the incineration capacity of maximum 49 t/d • In Hubei Province, medical waste generation increased to 370% • The total medical waste in China was estimated to be 207 kilo ton from 20 January to 31 March, 2020	(Klemeš et al., 2020; Tang, 2020)(Klemeš et al., 2020)(Klemeš et al., 2020)
USA	• A years' worth of medical waste may have been generated in first two months of COVID-19 outbreak • 70% increase in the number of plastic items were found per ocean cleanup during COVID-19 • Illegally dumped waste increased nearly 19% in the first seven months of 2020 alone in L.A.	(Bondaroff and Cooke, 2020)(Hernandez, 2020)(Hernandez, 2020)
Bangladesh	• Record shows a total of 14,500 ton of hazardous plastic waste, with about 3076 ton in Dhaka city only was generated during the 1st month of pandemic outbreak • With the generation rate of 483 ton per day COVID-19 related waste, Bangladesh ranked first among the Asian countries	(ESDO, 2020)(Parashar and Hait, 2021)
Philippines	• Ranked second (280 ton per day) in the category of most COVID-19 waste generated among the Asian countries	(Parashar and Hait, 2021)
Singapore	• Take-out and home-delivery grocery services contributed an additional 1400 tons of plastic waste during 2-month lockdown	(Bengali, 2020)
UK	• So-called fly-tipping (illegal waste disposal) increased by 300% during the pandemic.	(Duer, 2020)
Indonesia	• In Jakarta, within two months after the first COVID-19 positive case, medical waste has increased to 12,740 tons.	(Kojima et al., 2020)
Malaysia	• In Kuala Lumpur, 154 tons of additional amount of medical waste generated per day during the pandemic.	(Haque et al., 2021)
Thailand	• In Bangkok, 210 tons of additional amount of medical waste generated per day during the pandemic.	(Haque et al., 2021)
Vietnam	• In Hanoi, 160 tons of additional amount of medical waste generated per day during the pandemic.	(Haque et al., 2021)
Italy	• Around 70,000 kg of plastic waste will be generated per day from the used facemasks in the lockdown period.	(Cesaro and Pirozzi, 2020)
Spain	• In Catalonia, medical waste generation increased by 350%.	(Klemeš et al., 2020)
South Korea	• Around 295 tons of plastic containing medical wastes were generated during February-March 2020.	(Rhee, 2020)

example, some states in the U.S. have declared to stop their recycling programs from the concern of SARS-CoV-2 spreading in operation centers (Pan Demetrakakes, 2020).

3.1. Increased use of SUP during pandemic

Use of SUP has significantly increased due to the pandemic lockdown and new hyper-hygienic way of life (Table 1). Besides, panic buying, and stockpiling due to change in the consumers' behavioral changes soared the requirement for plastic-based packing materials (Jribi et al., 2020). To prevent virus transmission, there is no other viable alternative to SUP at least for now. It has been estimated that monthly use of 129 billion face masks and 65 billion gloves would be needed worldwide to slow down the spread of virus and protect the citizens (Prata et al., 2020). The demand of SUP has been predicted to increase by 57% combining packaging, medical uses, and other applications in 2020 (Prata et al., 2020). The disposable face mask market has seen remarkable increase from $800 million in 2019 to $166 billion in 2020 (E. J. Zhang et al., 2021). The Wall Street Journal has reported that plastic use in USA is expected to rise 10% in 2021, compared with only 3% last year (Pan Demetrakakes, 2020). Apart from the gloves and masks, this increase is also due to the banning of reusable bags and rescinding bans on single-use shopping bags in the supermarkets. San Francisco of California, USA has issued an order which does not allow the customers to bring reusable bags, whereas previously the use of plastic bags was banned here. Similarly the state of Massachusetts has revoked the restrictions on single-use bags in 139 municipalities (BOMEY, 2020). States like New York, Hawaii, Oregon, Connecticut, and Maine are also walking in the same path by delaying the ban of SUP use until 2021 to fight against the pandemic (Silva et al., 2020). Furthermore, plastic production and usage increase due to the increasing trend of online shopping and takeout boom (Parashar and Hait, 2021). USA has seen an overwhelming 78% increase in online shopping and takeaway services in 2020, while countries like Singapore, China, Vietnam, South Korea observed a similar trend with more than 50% increase (Parashar and Hait, 2021). This new trend of takeout and e-commerce shopping is projected to result in 1012.6 billion of plastic packaging demand by 2021, which is 103.4 billion higher than produced in 2019 (Parashar and Hait, 2021; Reportlinker, 2020).

3.2. Increased plastic waste generation during pandemic

Overflow of medical waste, need for proper PPE, surge in online food delivery and shopping, and ban on reusable bags, etc. have led to increased plastic pollution during COVID-19 pandemic. A study has estimated that packaging and medical based products can be responsible for 44.8% and 13.2% of increase in plastic waste due to the current pandemic (Sharma et al., 2020). World health organization (WHO) urged industrialists and government official for 40% escalation of SUP PPE to meet rising global demand during the pandemic (Adyel, 2020; Chaib, 2020). A serious rise in medical waste has been reported all over the world (Table 2). This drastic increase in plastic waste is weighing down the capacity of the system to manage/treat it adequately (A. L. P. Silva et al., 2021). According to a report by WHO, delivery of PPE have increased 50.4 million pieces from 5.5 million just between June and July 2020, and more than 200 million pieces in store for delivery to 138 countries (Haque et al., 2021; WHO, 2020). Most recent EPA fact sheet published in 2020 states that in USA only 8.5% of 35.68 million tons of plastic wastes were recycled while 15.8% was incinerated and 75.7% ended up in landfills in 2018 (EPA, 2020). A simple calculation was done to predict the increase of plastic waste during the pandemic alone from health-care facilities (Adyel, 2020; Cutler, 2020). U.S. hospitals generate about 5.9 million tons waste, 25% of which is plastic in 2018 (GIBBENS, 2019; Overstreet, 2018). If U.S adhered to the rate of medical waste generation for a year in just the first two months of the pandemic (Adyel, 2020), a six-fold increase in medical waste could be predicted by the end of 2020. This would result in 8.85 million tons of plastic medical waste, which is 500% higher than the medical plastic waste generated in 2018. Due to higher amount of biohazards generated during the pandemic and lockdown in recycling facilities (Fadare and Okoffo,

Table 3
Endeavors to control the amplified amount of plastic waste generated during COVID-19.

Country	Changes in plastic management plan	References
USA	Plastic wastes are ending up in the country's landfills often after being exposed to various treatment processes, including autoclaving and incineration.	(Barndollar, 2021)
Canada	Majority of PPE disposed is either i) disinfected and landfilled, or ii) incinerated. No sorting of recycling items coming to landfill.	("COVID-19: A waste management roadblock," 2020, "Guide to waste management from the health and social services network," 2017)
China	Wuhan city authorities implemented mobile incineration facilities which were upgraded from 50 t/day to over 263 t/day to manage the 240 t medical waste generated per day.	(Klemeš et al., 2020; Yu et al., 2020)
UK	In UK, the recyclable waste was collected once a week in double-layered bags, COVID-19 labeled, and independently stored. • UK used dedicated vehicle for the COVID-19 waste collection.	("Guidelines for Handling, Treatment and Disposal of Waste Generated during Treatment/Diagnosis/Quarantine of COVID-19 Patients," 2020, "Waste Management Prepared for the Epidemic Caused by the Coronavirus," 2020)
Bangladesh	Without having proper incineration facilities, authorities burnt their wastes in their backyards or mix them with the regular city corporation bins. • In Dhaka, Bangladesh, medical plastic waste generated was sealed in biosafety bags and transferred to on site storage in some places. From storage, the wastes are collected in open drums and transported to Landfill station.	(Shammi and Tareq, 2021)
Norway	Norway's government has permitted a temporary change in landfill permits and allowed to transport wastes elsewhere to deal with the medical waste surge, if necessary.	("Municipal Waste Management and COVID-19," n.d.)
Spain	In Spain, it was recommended that cement plants can co-incinerate medical wastes upon request to ramp up processing capacity.	("Municipal Waste Management and COVID-19," n.d.)
South Korea	In south Korea, the medical wastes were needed to be taken out for incineration on daily basis as opposed to before pandemic when it could have been stored up to 7 days. Wastes including the used masks are incinerated or landfilled without any recycling.	(Rhee, 2020)
Nigeria	Special waste collection bins to collect disposable PPEs were provided in buildings (residential, government and hospitals), and public places. These should be emptied daily, decontaminated and disposed in landfills.	(Benson et al., 2021b; "Coronavirus (COVID-19) Guideline," 2020)
Portugal	The Portuguese Environmental Agency recommended that all potentially contaminated PPE used by ordinary citizens should be disposed in sealed and leak-proof garbage bags as mixed wastes (not recyclables) and should be incinerated or landfilled.	(Ambiente, 2020)
India	Indian municipalities are following a flawed system of medical waste disposal and management, which mostly rely on landfilling and local burning strategies. COVID-19 plastic waste such as googles, hazmat suits, nitrile gloves should be disinfected/shredded/recycled and used masks, head caps, shoe covers must be incinerated.	(Corburn et al., 2020; "Guidelines for Handling, Treatment and Disposal of Waste Generated during Treatment/Diagnosis/Quarantine of COVID-19 Patients," 2020)
Finland	In Finland, wastes are treated by crushers and then in waste incineration plants.	("Waste Management Prepared for the Epidemic Caused by the Coronavirus," 2020)
Italy	In Italy, COVID-19 plastic waste must be collected in sealed double layered bags with no need to separate the waste on source collection. However, non-impacted COVID-19 plastic waste must be collected employing separate collection system.	("Prime Indicazioni Genarali Per La Gestione Rifiuti – Emergenza Covid-19," 2020)
Sri Lanka	In Sri Lanka, plastic waste should be segregated at the source itself using colored-coded containers. All the contaminated waste including plastic-based PPEs shall be incinerated or autoclaved following proper safety protocol.	(Mashood et al., 2020)

2020), it is expected that there will be a decrease in the recycling of medical waste in the year 2020. If it is assumed only 4.25% of medical plastic waste was recycled, which is 50% less than the year 2018, then 8.6 million tons of additional medical plastic waste is going to be either combusted, landfilled, or illegally dumped. Considering the risk of the spread of the virus, the recycling % could be even lower, which means

more plastic waste will go to landfill and incineration facilities. This phenomenon is going to be the same or even worse in countries all over the world as table 1 shows few examples of the increased usage and demand for plastic-based PPE during COVID-19 in different countries. As shown in Table 2, existing treatment systems of almost all the countries designed based on the quality and quantity of waste generated under normal conditions had to cope with abnormal increases in plastic waste.

4. Changing face of plastic waste management during COVID-19 pandemic

Due to the pandemic, household and medical plastic waste has been amplified which is aggravating the current plastic pollution (Benson et al., 2021a). The most extensively used techniques of this plastic waste management across the globe are mechanical recycling, incineration, and landfilling (Alabi et al., 2019). However, incineration can release hazardous gases like furans and dioxins and could promote greenhouse gas emissions into the environment ultimately fueling global warming (Batterman and World Health Organization. Water, 2004). So, it is not an ideal solution for long term scenario. Landfill is at the bottom of the scientific disposal pyramid. Despite, some countries landfill their wastes. Plastic waste generated during COVID-19 has caused increased load on waste dumps, and landfills, overwhelming their capacity. It would lead to tremendous space constraints, and leaching of harmful chemicals (Azoulay, David, Priscilla Villa et al., 2019). Moreover, uncapped collection and transportation of virus infected wastes over such a long distance are certainly dangerous for public health.

Most of the countries improvised their existing waste management facilities both quantitively and qualitatively (Table 3). Furthermore, specific guidelines and advisories have been issued by various international organizations (WHO, UNICEF, UN-Habitat, UNEP, European Commission, Asian Development Bank (ADB) etc.) to manage plastic waste containing COVID-19 (Parashar and Hait, 2021). The WHO has recommended high-temperature burn incineration or deep burial for the treatment of infectious waste (Chartier, 2014; Organization and (UNICEF), 2020; Sharma et al., 2020; WHO, 2020). According to WHO, gloves, masks, goggles, fluid-resistant apron) must be collected in clearly marked lined containers, and stored, preferably on-site prior to treatment and safe disposal. These waste should be treated by autoclaving or high temperature burn incinerators (Organization, 2020). According to ADB, plastic PPEs must be double bagged before treatment/disposal and domestic/medical waste (plastics included) should not be recycled and must undergo incineration or sanitary landfilling ("Managing infectious waste during the COVID-19 pandemic," 2020). According to UN Habitat, used PPEs should be placed in colored double bags tied with string or adhesive tape. They could be stored on-site for 72 h before disposal followed by incineration or landfill if incineration is not possible ("Strategy guidance: Solid waste management response to COVID-19," 2020). Despite these guidelines and advisories, some Asian nations like Cambodia, the Philippines, Thailand, India, Malaysia, Indonesia, Bangladesh, Vietnam, and Palestine have been reported to dump their infectious plastic waste in open landfills (Sangkham, 2020). Moreover, countries like Brazil, Guatemala, Haiti, India, Indonesia, Kenya in the developing world have disruption in their recycling facilities due to severe fund crunch. In this article we tried to gather practices followed in different countries for plastic waste management, being aware that situations are diverse and dependent on the national and local constraints as well as means available.

Besides these management practices, focus should be given towards the efficiency of the workforce that is involved in the process of waste management as well. They should be provided with the right kind of tech-enabled tools, such as artificial intelligence enabled automated systems for segregation, that would enable them to overcome their operational challenges and be more productive and efficient in their job roles. Moreover, this could improve the efficiency and speed of recycling and enhance the quality and value of recycled products (Chidepatil et al., 2020).

Even if all the necessary steps are taken to manage these plastic wastes, it will not be fruitful without public contribution. It is important that the people at large adopt a zero-waste approach and become more concerned about environmental safety (Avee Mittal, 2021). They should be aware of how much plastic they are consuming and discharging in the environment and what would be their consequences. Moreover, people can decrease the recycling workload by doing home separation. This could be done by utilizing campaigns, advertisements, social media, etc.

5. Long-term impacts of the plastic pollution outbreak on the environment

Management of plastic waste has been problematic even before the start of COVID-19 and it was already pilling up in aquatic, terrestrial, and atmospheric environments (Xanthos and Walker, 2017). Amount of mismanaged plastic waste, 8-12 million metric tons (Mt), generated on land ended up in oceans in 2018 alone contributing to the plastic pollution (Bondaroff and Cooke, 2020). Plastic pollution problem has exacerbated due to the hygiene concerns and greater dependence on take-away food during COVID-19. It was anticipated that a staggering global production of 129 million of face mask by the end of 2020 might result in 1.56 billion masks in the oceans (Bondaroff and Cooke, 2020). This contributes to 5159-6878 tons of plastic pollution alone from masks produced during the pandemic (Bondaroff and Cooke, 2020). From plastic waste management perspective worldwide, recycling, incineration, and landfilling are the commonly employed methods. However, unprecedented boom in plastic waste generation and lockdown have led to a sharp decline in plastic recycling across the world (Parashar and Hait, 2021). This would lead to mismanagement of plastic waste resulting in improper incineration, illegal dumping, and overloading the landfill capacity. For instance, illegal dumping increased nearly 19% in the first seven months of 2020 alone in L.A., U.S and 70% more plastic waste were being found in per ocean clean up during the pandemic (Hernandez, 2020).

5.1. Greenhouse Gas (GHG) emission

GHG, such as CO_2 and CH_4 production during the decomposition of plastic waste in landfills is a major concern (Prata et al., 2020). Environmental impact due to the increased medical waste during pandemic was calculated using EPA's WARM (Waste Reduction Model) tool. There is an increase in the generation of medical plastic waste from 1.48 million tons in 2018 to 8.85 million tons in 2020 in USA as estimated in section 3.2. In addition, it has been reported that 24.83 million tons of plastic waste was generated from the usage of facemask in the US (Benson et al., 2021a). It has been estimated that about 32.35 million tons of additional plastic waste would go to landfill and incineration facilities. Considering the risk of the spread of the virus, if the recycling % is even lower, the GHS emissions from landfills and incineration facilities would be even higher due to higher % of waste going to landfills and recycling facilities. Using the WARM tool, it was calculated that 67.42 million metric tons CO_2-eq (GHG) emission would increase in U.S if 15.8% (EPA, 2020) plastic waste to be incinerated as it was in 2018 according to EPA report. This increase is equivalent to adding over 14.3 million cars in the road for one year. This is certainly an alarming number especially when only two main sources of plastic waste have been considered in the calculation. Now with the 78% increase in online shopping and takeaway services in 2020, use of PPE, and ban on reusable bags in supermarket, the number is going to be even more worser for U.S. The number is expected to be staggering across the world as well. For instance, the total carbon footprint emission from only 200 pieces of plastic glove was estimated to be 42 kg CO_2-eq (Usubharatana and Phungrassami, 2018). So the total emission would be around 14 million tons CO_2-eq from the estimated recommended monthly

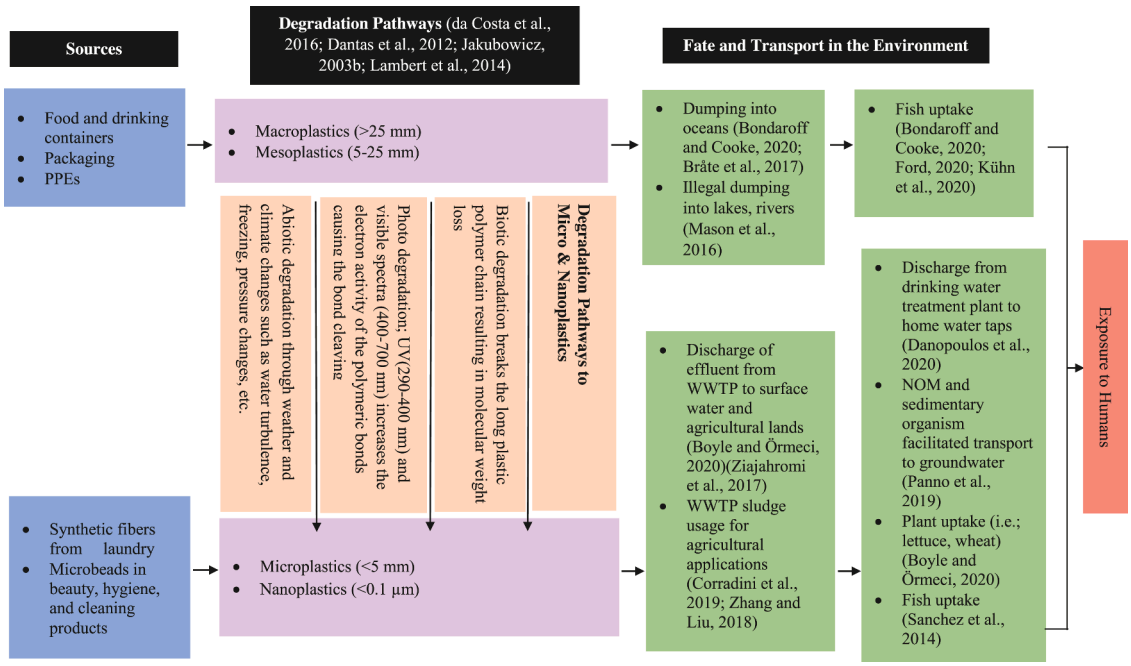

Fig. 2. Plastic Waste Directive; Fate and Transport of Micro and Nanoscale plastics in the Environment.(Bråte et al., 2017)(Sanchez et al., 2014)(Corradini et al., 2019)(Danopoulos et al., 2020)(Kühn et al., 2020)(Mason et al., 2016)(Zhang and Liu, 2018)(Ziajahromi et al., 2017)

consumption of 65 billion gloves globally (A. L. P. Silva et al., 2021). Improper burning of plastics waste releases dioxins, heavy metals, PCBs, dioxins and furans, which are listed as hazardous chemicals and directly linked to health risks such as respiratory disorders (A. L. P. Silva et al., 2021).

5.2. Marine plastic pollution

It has been estimated that 3% of the total 359 million metric tons globally produced plastic ended up in oceans in 2018 (Bondaroff and Cooke, 2020), which is equivalent to 1 garbage truck's worth of plastic per minute being dumped into oceans (Ford, 2020). Marine ecosystem has been ravaged by plastic waste and poses a serious threat to marine wildlife. Marine plastic pollution kills about 0.1 million marine mammals and turtles annually as plastic products are easily be mistaken for jellyfish, a favorite food of sea turtles (Bondaroff and Cooke, 2020; Ford, 2020). COVID-19 has worsened the problem of marine plastic pollution. The global plastic packaging market size has been estimated to increase 5.5% by the end of 2021 as a result of pandemic response (Asia, 2020). Non-recyclable SUPs such as take-out plastic containers and masks could increase the marine plastic waste by 30% more than 2019 (Fadare and Okoffo, 2020). A skyrocketing increase in the demand of masks and gloves, plus a decline in recycling programs during the pandemic would result in the indiscriminate littering (Ammendolia et al., 2021). SUP PPEs and their fragmented debris ingestion by such marine wildlife due to misidentification would impact their food chain in the long run. Improper incineration, illegal dumping, and unscientific landfilling would result in the leakage of plastic waste, which may further cause microplastic pollution in marine ecosystem (Fadare and Okoffo, 2020; Prata et al., 2020).

5.3. Micro and nanoscale plastic in water and wastewater treatment plant

After usage, discarded plastic masks and gloves, thrown in inappropriate places, are advected by wind, rainfall runoff, drainage systems, and wastewater (Eriksen et al., 2013), which eventually ends up in the oceans and surface waters. Even though majority of the previous studies have focused on plastic pollution in marine environment, there are more recent studies that have showed that these plastics would end up in freshwater and land environment too (Fendall and Sewell, 2009; Lechner and Ramler, 2015). We need to understand how plastics end up in drinking water system from fresh water to develop a detailed, integrated mass balance of plastics in the environment and identify the future research needs. Discarded plastic items present in freshwater, usually break down into microplastics (<5 mm) and nanoplastics (<100 nm) (Law and Thompson, 2014) via chemical, mechanical, biological etc. processes (e.g. hydrolysis, UV photodegradation, wave action, biodegradation, etc.) over the years (Gigault et al., 2016; Lambert and Wagner, 2016; Naik et al., 2020; K. Zhang et al., 2021)(Zhang et al., 2021). Micron sized plastic fibers from the washing of clothes and plastic polymer microbeads, used in personal care products like facewash or toothpaste, also enter wastewater treatment plants (WWTPs) through drainage systems and eventually end up in surface water (Fendall and Sewell, 2009; Lechner and Ramler, 2015). These micro and nanoscale plastics gets released into the freshwater environment with effluent of WWTPs, (Fendall and Sewell, 2009; Leslie et al., 2013) as the sheer number and size of these plastics allows them to bypass the filtration system employed by WWTPs (Carr et al., 2016; Murphy et al., 2016). It has been estimated that microplastic pieces, around 8 trillion per day, enters surface water through WWTP (Rochman et al., 2015). Moreover, these plastics retained in sewage sludge (Magnusson and Norén, 2014; Ziajahromi et al., 2016) when applied for agricultural purpose, also pose unknown life threat to human or livestock (Nizzetto et al., 2016a, (Nizzetto et al., 2016b)). Subsequently, these released micro or nanoscale plastics in the freshwater or surface water, will eventually end up in drinking water treatment plant as surface water is one of the main sources of water in drinking water plant. Narrow plastic fibers can pass through conventional filters, and those caught up may dislodge over time, and eventually can be found into our drinking water. A report found presence of microplastics in tap water samples from some major cities around the world and in the world's renowned 11 bottled water brands (Mary Kosuth, E.V.W., Sherri A. Mason, Christopher Tyree, 2017). Due to the little information on the outcome of these micro and nanoscale plastic particles in the environment, this has become a recent concern. Figure 2 summarizes the plastic waste directive in the environment and shows how small-sized plastics can make their way into

Table 4
Effect of microplastic on aquatic organisms (PE: Polyethylene, PS: Polystyrene, AC: Acrylic).

Aquatic Organisms	Plastic	Size, Concentration	Exposure	Impacts	Reference
Sea urchin (*T. gratilla)*	PE	10–45 μm,10^3 - 3 × 10^5items/L	5 days	Reduced body weight and survival	(Kaposi et al., 2014)
Calanus helgolandicus	PS	20 μm,7.5 × 10^4items/L	6 days	Reduced egg size	(Cole et al., 2015)
Marine isopod (*I. emarginata)*	PS	1–100 μm,20 fragments/mg food	6-7 weeks	No significant effects on survival and growth	(Hämer et al., 2014)
Marine isopod (*I. emarginata)*	AC	0.02–2.5 mm,0.3 mg/g food	6-7 weeks	No significant effects on survival and growth	(Hämer et al., 2014)
Mussels (*M. edulis*)	PE	0–80 μm,2.7 × 10^7 to 3.6 × 10^7items/L	3–96 hour	Increase inflammation and reduced lysosomal membrane stability	(Von Moos et al., 2012)

human food chain.

5.4. Human and aquatic life exposure to plastics

Micro and nanoscale particles (Syberg et al., 2015), can penetrate human cell barrier due to their small size and cause cytotoxicity and metabolic disorders (Lewinski et al., 2008; Yousefi and Tufenkji, 2016). Ingestion, inhalation and absorption by skin from using plastic products, mainly associated with micro and nanoscale plastic, could also have an impact on human health (Van Cauwenberghe and Janssen, 2014; Wright and Kelly, 2017). Among all, ingestion of seafood or drinking water contaminated with plastic is the main source of plastic entrance in human body (Lehner et al., 2019) (Figure 2). Studies showed that nanoparticles derived from polystyrene plastic polymers could generate reactive oxygen species (ROS) in human liver cells and affect the epithelial cell function and physiological processes (Liu et al., 2018; McCarthy et al., 2011). Human exposure to microplastics could be through the ingestion of seafood, sea salt, sugar, honey, and beer as their presence has been confirmed in these items (Cox et al., 2019; Kosuth et al., 2018; Mason et al., 2018). Additives and plasticizers used during plastic manufacturing can leach out over time. Adsorption of these chemicals through skin can be harmful for humans as they are carcinogenic and mutagenic in nature (Lithner et al., 2011). However, a major issue when determining the risks of microplastics to human health is the limited in vitro and in vivo information about the capability of micro and nanoplastics to cross epithelial barriers of lungs and intestines (Vethaak and Legler, 2021). Although some studies have shown that microplastics are capable of accessing all organs, and crossing cell membranes, major knowledge gaps still exist regarding their absorption, distribution, metabolism, and excretion (Yong et al., 2020). Moreover, dose-dependent effects of microplastics in humans also remains unknown.

Similarly, microplastics ingested by aquatic organisms and other wildlife results in toxicity Table 4 as plastics can sorb organic pollutants like organochlorine pesticides, PAHs, PCBs, PBDEs, dioxins, and metals as well as pharmaceuticals, endocrine disrupting chemicals and personal care products (PPCPs) (Besseling et al., 2013; Cole et al., 2013; do Sul and Costa, 2014; Mato et al., 2001; Rochman et al., 2013; Von Moos et al., 2012). Microplastics in marine environment also influence the feeding, growth, spawning, and existence of aquatic organisms. However, these effects of varies based on their size, concentration, exposure time etc. Moreover, majority of the current ecotoxicological studies of small size degraded plastics have been conducted on marine (77%) as opposed to freshwater (23%) organisms. This is of concern since freshwater organisms are directly affected by stormwater runoff, wastewater and other discharges which contains more plastics.

6. Conclusions and outlook

As the COVID-19 pandemic has exacerbated the plastic pollution problem, people should be aware of the future consequences of their plastic usage and disposal. Based on our summarized data and hypothetical calculations, enormous amount of plastic has been generated globally due to the COVID-19 pandemic. Mismanagement of this plastic waste handling and illegal dumping during the pandemic is going to result in both short and long-term effects on biological, ecological, and human health. Accumulation of plastic waste is not only destroying the marine and terrestrial environment now, rather it will degrade in small size micro and nanoscale plastics in future. These micro and nanoscale plastics have the potential to cause even more irreparable harm to humans and environment. There is a need for innovative technologies in plastic waste management to deal with this plastic overload as the current technologies are being overwhelmed. Hence, it is important to impose regulations on plastic usage, and educate people on plastic waste reduce, reuse, recycling, and management. Future work should be directed towards contingency plans for future plastic pollution and plastic waste management in critical situations. Moreover, future research should be focused on the fate and transport of micro and nanoscale plastics as current disposed plastic eventually breaks down to micro and nanoscale plastic. However, the size, shape, and types of plastics play a vital role in their fate in the environment, which makes them extremely dynamic for research purpose. Few studies have been conducted on the fate and transport behavior of the micro and nanoscale plastics. Yet, further research needs to be done to better understand the effect of plastic sizes and their surface properties in their fate and transport behavior. It can be predicted that aggregation in the environment would be a dominating mechanism governing their behavior and provide insight into how they may be transported in the environment or remove in the treatment plants. By doing so, the long term impacts of the global plastic pollution could be managed in a more systematic way.

Declaration of Competing Interests

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

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Supplementary materials

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