Challenges and solutions in COVID-19 related pandemic solid waste management (PSWM) - A detailed analysis with special focus on plastic waste.

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Abstract. A pandemic like novel coronavirus ²’ (SARS-CoV-2) not only poses serious public health repercussions but also affects the socio-economic and environmental conditions of the affected countries. The increased consumption of material resources in conjunction with ‘containment and preventive measures’ is generating an unprecedented amount of potentially infectious solid waste, especially that of plastic origin, which if mismanaged, is bound to affect the ecosystem and public health, as the virus can survive on fomites for longer duration. COVID-19 related pandemic waste, such as Personal protective equipment (PPEs), sanitizer and water bottles, disinfection wipes, and Single use Plastics (SUPs) products has already found its way to the aquatic and terrestrial environment. Even before the start of the COVID-19 pandemic, the management of plastic waste, an environmental stressor with trans-boundary migration capabilities, was a major environmental issue for every stake-holder.

In this paper, we propose a separate domain in the waste management framework for the effective management of pandemic related solid waste. Factors and sources contributing to increased plastic waste generation are discussed in detail. A concise picture of global plastic demand through sectors and polymer types is presented and speculations are made on how COVID-19 is going to affect the plastic demand. Current solid waste handling and management practices in developed and developing countries are critically examined from the perspective of this pandemic. We identified various challenges that waste management sectors are facing currently and offered possible solutions.

Concerns of transmission through fomites is bringing a change in public behavior and consumption pattern which affects 3R practices, while fear of secondary transmission from occupational infections is interfering with 3R practices at end-of-life plastic waste management. The legislative and restrictive frameworks on plastic use being currently put-on hold at the governmental level to ensure public safety are being used by the plastic industry to lobby for increased plastic consumption. The inability of the governments to win public confidence is further escalating unsustainable practices and slowing the shift towards sustainable economy. It is
imperative to enforce sustainable practices without putting public safety at risk and to ensure that an unsustainable societal attitude wouldn’t be reinstated in the post-pandemic world. Lastly, eight research and policy points suggested here may guide future studies and governmental frameworks in the domain of COVID-19 pandemic related solid waste handling and management.

Keywords - COVID-19, SOLID WASTE MANAGEMENT, PLASTIC WASTE, 3R, PSWM

1. Introduction

During an outbreak of COVID-19, “preventive and precautionary measures” have been shown to be effective. Accordingly, social distancing, cluster and national lockdowns, quarantine, isolation, and halting economic and transportation activities are being implemented regionally, nationally, and globally, to contain the spread of the virus. These preventive measures are showing a direct impact on socio-economic and environmental conditions at the local and global level [1-9].

Nationwide lockdowns disrupted the regional, national and global economy due to the shutdown of transportation, business, industries, and recreational activities. Such measures showed a positive short-term positive on the environment such as decrease in atmospheric pollutants, reduction in carbon footprint, and decreased demand for fossil and petroleum fuels (due to restriction on traveling and industrial productions). Substantial reductions in environmental emission indices such as carbon, NOx, ozone (O3), SO2, particulate matter (PM)2.5 and (PM)10 were recorded in major cities, around the globe [10-15].

Besides the positive impact of ‘preventive and restrictive measures’ on the ecosystem, the negative consequences of COVID-19 on the environment are a major growing concern worldwide. One of the major environmental issues of COVID-19 related pandemic is a sudden global surge in liquid and solid wastes. Relevant global and national agencies tasked to deal with COVID-19 have issued advisories, guidelines and standard operating protocols to be used by healthcare professionals, first responders, and common public. To minimize human to human transmission of the virus, social distancing, good hygiene practices, frequent hand-washing, and respiratory etiquettes such as face-covering, using face masks, and coughing in elbows has been recommended [16-18].

These life-saving recommendations are generating an enormous amount of waste. The global campaign to adopt better hygiene practices and frequent washing of hands resulted in acute water demand and subsequent increase in wastewater generation [19-21]. Similarly, the volume of solid waste is also increasing, as medical solid waste keeps increasing, especially the plastic waste composition in medical waste and municipal solid waste, as demand for plastic-based materials is an all-time high in the healthcare sector and society. With no effective treatment protocols available, healthcare workers rely on personal protective equipment (PPE) for their protection. Similarly, demand for medical plastic equipment like ventilators, and disposal plastic consumables like syringes, blood bags, drip sets, etc. have drastically increased with an increase in number of cases. Additionally, the consumption pattern of the public is changing, as visible from increased consumption of single-use plastics (SUPs), which is generating more solid waste. The public fear of contacting with the virus from a contaminated surface, as the virus possess capability to adhere to the surface of various materials up to 11 days, is swaying sustainable 3R practices, which is further contributing to the municipal solid waste generation [21-33].

The burden of handling and managing solid waste, especially plastic waste has long been an important challenge for waste management facilities, and any significant change in volume or composition is likely to overwhelm waste handling and management infrastructure, as these systems are designed to cater to fixed volume of waste and have little margin for surplus volume [34]. The major composition of COVID-19 related solid waste is made up of plastic, an environmental stressor that the world was already struggling to manage. The COVID-19 related plastic waste will further add to the problem at an unimaginable scale. The extent of the problem can be understood by the
projected global monthly consumption rate of facemasks and gloves (129 billion and 65 billion respectively), a figure obtained through extrapolation of monthly demand in Italy [35-36].

The unsustainable plastics use, in combination with poor waste management practices, and governmental apathy towards the environment has created a new type of anthropogenic pollution, which is persistent in nature. The eco-toxicological impact of plastic pollution on biotic and abiotic environment has drawn significant attention from academia, public, and government resulting in accelerated research and governmental intervention [37-39].

Medical waste requires special waste handling and disposal practices, due to possible toxicity and the infectiousness of the waste. The municipal solid waste handling and management, apart from seeing a significant change in volume and composition, have to deal with logistical and operational challenges as well, such as low workforce, fear of secondary contamination, and feasibility. Clinical waste originating from temporary shelter houses and quarantine facilities can be potentially infectious. The direct impact (change in volume and composition) and indirect impact of the pandemic such as increased advocacy for plastic consumption, change in consumption pattern, plummeting oil price and increasing popularity of unsustainable lifestyle changes, in conjunction call for immediate actions from all stakeholders, if we are to keep moving towards a sustainable circular economy. Long term surge and potential toxicity of pandemic related solid waste require scientific and sustainable waste handling and management approach accommodating changing variables amid pandemic. Given the severity and nature of pandemic, pandemic related safety and precautionary measures are likely to remain in place till mass vaccination and a significant reduction in cases.

The central focus of this manuscript is to discuss the handling and management of COVID-19 related pandemic solid waste (PSW) with special emphasis on the plastic composition of the waste. Sources of pandemic related plastic waste have been identified and discussed in detail. The polymeric composition of plastics and demand trend by various sectors is reviewed and the effect of the pandemic on plastic demand in near future is speculated. The factors affecting the generation of pandemic related plastic waste and challenges in its handling and management have been discussed in brief, and the possible solutions for pandemic waste handling and management have been proposed. Moreover, the impact of the pandemic on sustainable circular economy from ‘reduce, recycle, and reuse’ perspective is reviewed and discussed. We also summarized the status of solid waste management practices in developing and developed countries from the pandemic perspective. Lastly, we suggest policy points and give a future perspective on which further studies can be conducted.

2. Sources of plastic waste amid COVID-19 pandemic

Any disaster event creates a stream of solid waste that requires efficient end-of-life management as the safety of public health and quality of the environment is directly correlated with these wastes [40-42]. The COVID-19 related solid waste generating from various sectors (medical facilities, quarantine centers, municipal solid waste from affected sectors, etc.) if not handled properly, creates a risk of secondary infection by exposing the public with the virus. In particular, under the COVID-19 pandemic, it is of paramount importance to not only ensure public safety but also minimize the environmental damage from pandemic related solid waste [36,43].

Given the extent at which the habitats are infected, sectors that are involved in containment of the virus, and material resources being used directly (PPE) or indirectly (SUPs), it is imperative to define COVID-19 related solid waste in waste management framework, and to do so, here we propose using the term ‘Pandemic solid waste (PSW)’ to club all the pandemic related solid wastes under one umbrella which also covers epidemic events. Pandemic solid waste (PSW) can be defined as “any solid waste, generated during a pandemic or epidemic event, with the potential of impacting human and animal health, regardless of whether they have potential to cause direct offense and infection or not, but not limited to healthcare facilities, households, quarantine centers, isolation centers, testing centers and so forth."

To simplify, and for effective waste management, PSW can be classified, based on point of origin, as medical solid waste (MLSW), clinical solid waste (CSW), and municipal solid waste (MSW). Medical waste incorporates all types of waste originating from healthcare facilities. Clinical solid waste includes “any waste that has the potential to cause injury, infection, or offense, arising but not limited to medical, dental, podiatry, healthcare services and so forth” [44]. Municipal solid waste
includes all types of solid waste generating from municipalities excluding medical, clinical, electronic, and nuclear waste.

The exponential growth in consumption of plastic, a versatile, cheap, and adaptable material and subsequent unsustainable mismanagement of plastic waste is now considered as global environmental menace. Due to adaptive properties, the plastics form the backbone of the healthcare industry. The monetary value of plastic in the global healthcare sector was valued at USD 23.5 billion in 2019 and is expected to grow at the rate of 8.6% from 2020 to 2027, with 7,667.6 kilo-tons of plastic being expected to be consumed in 2020. This figure will keep increasing as demand for the plastic is surging both for medical and public consumption [27]. The urgency fueled global demand of PPE has disrupted the overall life cycle and end-of-life waste management as supply chain is disrupted at upstream, while discarded PPE is creating waste management problems at downstream. The demand for medical plastic products (PPE, disposable plastic components for ventilators, and general plastic consumables) varies with the number of people infected by the virus [37]. The potentially infectious COVID-19 related plastic waste is observed to be originating from 3 sectors, discussed below:

a. COVID-19 related plastic waste from hospitals
Initially, the human-to-human transmission of COVID-19 was conceptualized to be droplet transmission, but new shreds of evidence suggest that aerosol transmission is also possible [46]. Past experiences in dealing with infectious outbreaks, mandate the preventive measures as crucial in minimizing the transmission and containment of infectious diseases. The preventive measures depend upon the level of contact and surroundings [47]. Standard precaution in form of PPE equipment, proper hygiene including regular sanitization, safe disposal of medical waste, and respiratory etiquettes by healthcare workers, first responders, and patients, to prevent contact transmission is recommended by concerned agencies. Face shields, respiratory masks, hazmat suits, and social distancing are used to avoid droplet and aerosol transmission of the virus [48-50].

This medical wisdom came in very handy during the early days of COVID-19 breakout resulting in a surge in demand of these items putting healthcare systems under unprecedented strain. Shortage of PPE including facemasks, for health professionals, first responders, and the common public, has been a matter of criticism on traditional and social media. Media reports of using common household items such as plastic bags by healthcare workers drew global criticism [51-53].

Plastic is the most widely used material in the healthcare industry and commonly used for the manufacturing of costly medical instruments to cheap protective gear. The most commonly used protective items (such as gloves, facemasks, face shields, respiratory masks, head caps, hazmat suits, etc) and consumables (like parts of ventilators, blood bag, drip set, pill casing, and a body bag, etc.) from medical industry end up in waste after single use due to its infectious nature. The urgency of plastic-based PPE and medical consumables is without a doubt, crucial for fighting this pandemic, though this may further aggravate an already existing epidemic, the world is facing, i.e. plastic pollution.

b. COVID-19 related plastic waste from quarantine centers, testing facilities, research laboratories, and shelter homes
The ongoing pandemic requires efforts on all fronts, from treating infected patients in hospitals, putting people (asymptomatic people, people with frequent travel history, migrants and people planning to migrate) in isolation and quarantine centers, and advances in scientific research. These efforts utilize ample resources, especially that of plastic origin, which is subsequently discarded as waste. People in isolation centers, quarantine centers, and shelter homes, may or may not be infected by the virus. The testing and research facilities are making huge efforts in testing for the virus for confirming the positive cases, finding treatments, and development of vaccines. The waste from these sectors knows as clinical solid waste, is infectious in nature and contains an ample amount of plastic products (PPE, medical consumables, consumables used in virus sequencing, testing swabs, swab containment bags, plastic consumables) used in testing and research and SUPs products used for general consumptions [54-55].
c. COVID-19 related plastic waste from households, workplaces, educational institutions, recreational centers, community centers, leisure industry, etc.

The plastic composition in 2.01 billion tonnes of municipal solid waste generated annually was around 12% in 2019. COVID-19 pandemic stopped the mobility of people as authorities are implementing nationwide or clustered lockdown. The closure of public facilities, workplaces, educational centers, recreational facilities, and leisure industry affects the generation of municipal solid waste, with initial reports suggesting a lesser quantity of municipal solid waste being generated during the lockdown. The unsustainable lifestyle change, which changes the consumption pattern of the public, is observable from the increased consumption of SUPs, plastic bags, food containers, and plastic packaging materials. Mandatory use of PPE in public settings is further adding to the demand for facemasks and gloves. The fear of contamination from material surface (fomite) puts hold on sustainable 3R (reduce, recycle, and reuse) practices. All these factors combined to increase the generation of municipal plastic waste amid ongoing pandemic [36,43].

The plastic waste from the aforementioned sectors is of diverse nature which plays a crucial role in its handling and management. Identifying the polymeric composition, the plastic consumption behavior, and sector-wise demand for plastic will help us in assessing the sectors likely to generate more plastic waste further helping in drafting od suitable mitigation policies.

3. Types of plastic waste, polymeric composition, and demand by various sectors

The variation of polymeric composition and distribution across various sectors has grave implications for plastic waste management. The annual plastic waste generated globally is growing exponentially, in line with exponential growth in global plastic production and consumption. Plastic waste generated from all the sectors discussed in the previous section is likely to increase amid ongoing pandemic. It’s too early to speculate whether this increasing trend returns to normalcy, once the pandemic subsides.

PPE (masks, gloves, and protective shields for eyes/face, head and shoe cover, apron, etc.) is mostly made from plastics due to its impervious properties which obstructs contaminated droplets to come in contact with skin by trapping them on the outer surface of the PPE. It’s a common practice among healthcare professionals to change their PPE every eight hours but some PPE may require disposal after a single use [22]. Therefore, it’s very challenging to estimate the quantity of PPE based on the consumer end. The dramatic increase in demand for PPE (made up of various plastic and rubber items) by healthcare industries, first responders, and the common public have been reported globally [22,24,29,30]. Similarly, the consumption of single plastic products and packaging products has also increased significantly which is made of various polymers. It’s imperative to understand the polymeric composition of these items; their origin and nature to assess and devise effective waste management practices.

Table 1. Origin, category, type, and polymeric composition of COVID-19 related plastic waste.

| Origin | Category | Type | Polymer Composition | References |
|--------|----------|------|---------------------|------------|
| Medical and clinical solid waste | PPE | Gloves | Nitrile and Vinyl | Avacare Medical, 2020 |
| | | Masks (Respiratory) | Polypropylene, Polyurethane, Polycrylonitrile | Czigány and Ronkay, 2020 |
| | | Masks (Surgical) | Polypropylene Polystyrene, Polycarbonate, Polyethylene, and Polyester | Henneberry, 2020 |
| | | Gowns and Body Suits | Polyethylene, Polypropylene and Polyethylene Terephthalate | Ajmeri and Joshi, 2020 |
| | | Head Caps | Polyvinyl Chloride, Polypropylene, Polystyrene, Nylon | McKeen, 2014 |
| | | Face Shields | Polystyrene, Polyethylene, Polyethylene Terephthalate, Polyimide, Polycarbonate | |
| | | safety glasses | | |
| | | Body Suits | | |
| | | Shoe covers | | |
### Medical Consumables
- Disposal syringes
- Blood bags
- Catheters
- Pill casings

### Municipal Solid Waste
- **PPE**
  - Disposable Gloves
  - Nitrile and Vinyl
  - Avacare Medical, 2020

- **PPE**
  - Disposable Masks
  - Polyethylene
  - WHO, 2020h

### SUPs
- Bags, trays, containers, food packaging film
  - Light-density polyethylene
  - UNEP, 2018

- Milk bottles, freezer bags, shampoo bottles, ice cream containers
  - Light-density polyethylene

- Bottles for water and other drinks, dispensing containers for cleaning fluids, biscuit trays
  - Polyethylene Terephthalate

- Cutlery, plates, and cups
  - Polystyrene

- Hot drink cups, insulated food packaging, protective packaging for fragile items
  - Expanded polystyrene

- Microwave dishes, ice cream tubs, potato chip bags, bottle caps
  - Polypropylene

### Consumer Goods
- Milk bottles, freezer bags, shampoo bottles, ice cream containers
- Light-density polyethylene

- Bottles for water and other drinks, dispensing containers for cleaning fluids, biscuit trays
- Polyethylene Terephthalate

- Cutlery, plates, and cups
- Polystyrene

- Hot drink cups, insulated food packaging, protective packaging for fragile items
- Expanded polystyrene

- Microwave dishes, ice cream tubs, potato chip bags, bottle caps
- Polypropylene

### Summary

Besides PPE, due to high mortality rates, body bags are needed in huge quantities to dispose of the deceased body. Additionally, medical consumables such as pill casings, disposal syringes, catheters, and blood bags are essential in the functioning of hospitals. These materials are often composed of plastic material and subsequently end up as medical waste. The staggering amount of plastic waste originating from medical facilities amid COVID-19 is going to be a challenge for waste management facilities for safe disposal [57-58].

Apart from the medical sector, plastic waste composition in municipal solid waste is also affected due to pandemic. Due to social distancing, better hygiene practices, and concern for personal and public safety, disposable gloves and face masks are being used by the public in social and public settings to avoid contact with the outer surfaces and prevent droplet transmission. Local governments in countries like India have made it mandatory for the public to use face masks (gloves in few places) whenever they leave their homes [59-60].

The pandemic is causing a shift in public lifestyle as people are being more cautious to avoid contacts with potentially exposed surfaces in fear of coming in contact with the virus. The lifestyle changes include avoiding going out, eating out, online shopping, avoid outside leisure activity, and avoiding reuse practices. To avoid human contact and due to lockdown, people are ordering more home deliveries and opting for takeaway, which means increasing amounts of SUPs (packing materials, disposable meal boxes, carry bags, spoons, straws, and plates, etc.) being used. These items are generally made up of polyethylene, polypropylene, and polystyrene as highlighted in [table 1]. Thus, it’s safe to say that the fear of contracting COVID-19 virus has pushed people to use more plastic than ever before.

The distribution and demand for plastics on basis of polymers and sectors are depicted in fig 1 & 2. The plastic consumption in the medical sector, packaging sector, and leisure industry are expected...
to rise due to pandemic. “The global packaging sector which accounted for 40% of total plastic
consumed in 2018 is forecasted to grow from USD 909.2 billion in 2019 to USD 1,012.6 billion by
2021 at a rate of 5.5% amid COVID-19 pandemic. Similarly, the global medical sector which
accounted for 17% of total plastic consumed in 2018 is forecasted to grow from USD 22.8 billion in
2019 to USD 31.7 billion by 2024 at a rate of 6.8% amid COVID-19 pandemic”. Polyethylene and
polypropylene are the most dominant polymer being produced and used worldwide in both the
healthcare industry and SUPs manufacturing industry. Polypropylene, a non-woven single-use
polymer, is largely used in making PPE. Demand for all the polymer is expected to increase in 2020
and 2021 due to the looming uncertainty of COVID-19 pandemic [61-62].

Fig 1. Global plastic consumption by segments in 2018 (adopted from Plastic Europe, 2018).

Fig 2. Global plastic demand by polymer type in 2018 (adopted from Plastic Europe, 2018)

4. Factors affecting the quantity of COVID-19 related plastic waste
The COVID-19 pandemic has highlighted the importance of plastics as a resource (material) in the
healthcare industry and public utility. The direct and indirect socio-economic impact of pandemic
governs the quantity of plastic waste generated, which interferes with its handling and management.
In a sustainable circular economy, the solid waste handling and management (SWHM) are based on
material balance and waste hierarchy, which advocate for lower consumption of resources at
production end and prioritize 3R practices at consumer and disposal end. This is accomplished by
the active participation of all stakeholders through legislative frameworks and awareness campaigns [63-
65]. The irony here is that pandemic is not only affecting the public health but also creating indirect
drivers that hamper all the efforts made towards the circular economy. The key factors affecting the
quantity of COVID-19 related plastic waste are discussed below:
a. Plummeting oil price: Immobility of humans and stoppage or reduction in industrial activities leads
to a decrease in demand for fossil fuels like crude oil and natural gases [66]. While demand decreased,
the global oil and gas production maintained a steady rate, resulting in a surplus of stock with no demand [67]. The economic interdependence of the plastics and fossil fuel industry, where fuel economy governs the economy of plastic production, consumption, and disposal, saves each other at the time of economic crisis.

Plummeting oil and gas prices indirectly affect plastic production, consumption, and recycling. Plastic is produced from byproducts of fossil fuels (oil and gases). With oil and gases being cheaper than ever before, to avert an economic crisis, the fossil fuel industry is over-producing the plastics. The upstream production of cheaper virgin polymers and downstream increase in demand creates a material imbalance, which may have drastic environmental consequences. This type of economic phenomenon has also been observed in past [68-70]. With a decrease in monetary value and increased production, the entire value chain of plastics is now imbalanced. At one hand demand for plastic is skyrocketing due to increased consumption in the healthcare industry and SUPs by society; industries that produce plastic products are facing a dilemma, whether plastic recycling is still an economically viable option to curb plastic pollution which puts end-of-life plastic management at risk [71].

The overproduced cheap plastic already has demand in the market. The PPE of single-use nature, originating from households and society will end up being part of MSW. Similarly, though SUPs products are being discouraged, the infectious nature of COVID-19 is driving take-away culture and online shopping upwards, which drastically increases the demand for single-use and packaging plastics. Reusable plastic products are now treated as SUPs as the virus can survive on the surface of plastic products. This change in societal attitude, exponentially increases the plastic composition in municipal solid waste, while medical and clinical plastic waste is being generated at an unimaginable scale.

b. Legislative setbacks: The ongoing pandemic kick-started rapid production of PPE on the war front, globally, to meet the demand of the healthcare industry and public. The governments are trying to support healthcare systems while common masses are hoarding these products for personal use. As mismanaged discarded PPEs and SUPs are ending in the environment, due to ongoing pandemic, national and international environmental regulatory agencies are either scrapping, roll-backing, or delaying the laws and regulations, on the use of plastic products [72-74, 36]. While these decisions seem temporary, given the nature of pandemic and increased concerns among the public, how long these regulatory policies remain dormant will be a matter of heated scientific discussion. Suddenly, environmental issues such as circular economy and pollution reduction have taken a backseat in governmental and societal attitude and the pandemic is of priority concern at the moment, rightly so, but the environmental consequences, especially in form of increased plastic pollution of an already polluted ecosystem are long-term phenomena, and are going to affect our fight with pollution.

This pandemic is changing the attitude of the common public to think that SUPs remain the safest choice. The plastic industries are set to lobby against any laws in the future that limit the use of SUPs. Understandably so, the latest research highlights that the COVID-19 virus survives the longest on plastic when compared with both cardboard and meta [33]. This finding is bound to be used by advocates of the plastic industry to push further SUPs. Earlier, the restrictive regulations saw opposition from plastic manufacturing and consumer industries. Public information campaigns were held globally to discourage the use of SUPs and encouraging a sustainable lifestyle. Now, the plastics industry is trying to capitalize on public fear by promoting the use of SUPs products. Plastic industries will lobby against any future regulatory frameworks that will address post COVID-19 plastic pollution by using public fear and pandemic associated uncertainties.

c. Duration of pandemic and mass vaccination: Given the trajectory of outbreak and progress in finding a vaccine, experts suggest that the effect of COVID-19 will be seen until 2022 [75]. The increased stream of COVID-19 related plastic waste is directly related to the duration and severity of the pandemic. Increased duration of pandemic means increased hospitalization leading to an increase in medical waste generation. Also prolonged pandemic means prolonged social distancing and precautionary measures, resulting in increased PPE consumption by the public. Additionally, the unsustainable lifestyle practices might be observed till the end of pandemic, thereby increased consumption of single used plastics, increasing the volume of plastic waste.
5. Challenges in handling and management of COVID-19 pandemic related solid waste

The unprecedented consequences of waste generated due to environmental disasters (such as earthquakes, cyclones, tsunamis) on waste management facilities have been well researched by the scientific community and waste researchers [43]. However, such a body of knowledge is not available for the infectious wastes generated during pandemic or epidemic events. The increased generation of pandemic related solid waste is in addition to the normal Municipal and medical solid waste and warrants scientific management. The pandemic has created supply chain problem of necessary resources (plastic based products) while also affecting the management of solid waste at downstream end. The sudden change in volume and composition of medical and municipal solid wastes has shocked the waste management facilities, a problem that needs urgent attention [45].

Best practices in solid waste management are crucial for maintaining both public health and the quality of the eco-system. It is important to mention here that, during the initial phase of lockdowns, municipal solid waste collection halted or operated at reduced capacity [76]. The lower volume of waste collected will subsequently be reported; hence any assessment made from short-term waste collection data can’t reflect the waste generation curve of the entire pandemic. Additionally, the trend will also vary from locality to locality, depending upon waste management infrastructure, for example, household waste in Italy and China were observed to be lower while higher for Thailand during the lockdown [36]. The thumb rule that ‘in a linear economy as the consumption of material in society increases, the subsequent waste generation will also increase’ shall be used for making a predictive assessment. “The demand for medical, commercial and household plastic products is expected to keep increasing as the number of COVID-19 cases increases and the waste generation curve will match global pandemic curve” [45].

a. Volume of solid waste: Due to the pandemic, medical waste management facilities are dealing with an unprecedented increase in the volume of medical waste. The staggering amount of medical and municipal solid waste being generated daily, penetration of pandemic, infection, and hospitalization rate, and with no vaccine in sight, COVID-19 led waste management is a global issue that requires urgent attention. To stop the spread of disease, quarantine and isolation facilities are being set up at village, town and city level, where asymptomatic people, people with travel history, and incoming travelers are being accommodated for a certain period before allowing them to assimilate with society. Given the number of such centers, the high number of inhabitants, and the duration of stay, the total waste generated from these facilities is very high.

Given the severity of the pandemic and vast campaign for adopting better hygiene practices and preventive measures, it’s very hard to have an estimate on the volume of PPE being disposed of daily. Here we try to propose a rough estimation on daily PPE generation from public settings and in medical facilities by modifying the equation proposed in the literature [32].

\[ N = P \times AR \times DPU \]  

\[ N = \text{Total number of PPE waste generated daily in a town, city village.} \]

\[ P = \text{Total Population of habitat (Rural/Urban, Developing/Developed)} \]

\[ AR = \text{Factor to account for the type of habitat (Rural/Urban, Developing/Developed).} \]

| Setting                          | Value of AR (between 0 to 1) |
|----------------------------------|-------------------------------|
| Rural area in a developing country | 0.6                          |
| Urban area in a developing country | 0.8                          |
| Rural area in a developed country     | 0.8                          |
| Urban area in a developed country     | 1                            |

DPU = Daily PPE Use (varies depending upon local regulation, and public motivation). It is recommended to change PPE (masks and gloves) daily, in such cases DPU = 2.
To calculate the total number of PPE waste generated daily in a country, total waste generated in a rural area and urban area of the country needs to be calculated separately using urban or rural population of the country and daily PPE used. The summation of rural and urban PPE waste generated will yield statistics for the whole country.

b. Change in Composition: Solid waste management facilities deal with municipal waste and medical waste separately but due to pandemic, clinical waste from quarantine center is being mixed with municipal solid waste, which is not only dangerous but also putting strain on MSW management plants [77]. The pathogenic nature of clinical and medical solid waste requires a diligent approach in handling and disposal. The medical waste management facilities are capable of handling medical waste at the steady-state condition with a fixed volume of waste being generated periodically (Daily/weekly/monthly) and of pre-recognized composition. Any deviation from a normal condition such as a change in the volume, flow rate, or composition will lead to failure or ineffectiveness of the system. Most of the facilities are based on incineration or pyrolysis with sterilization where the medical waste is properly decontaminated and disposed of following very strict guidelines. The problem here is such guidelines are based on normal operating conditions but amid pandemic, the volume and composition of waste being generated daily are far more than the anticipated protocols, leading to the inability of facilities to deal with such wastes.

Similarly, with the onset of pandemic, the plastic composition in municipal solid waste changed rapidly due to the extensive use of PPE, sanitizers, and SUPs. Making lots of variations in the composition and volume of plastic waste generated daily. The waste handling and management (medical, clinical, and municipal solid) procedures are being modified to accommodate the effect of the pandemic. These modifications are directly changing the composition of wastes. The most common modifications that can be seen globally are treating recyclable products such as plastic bags and food containers in clinical solid waste as hazardous waste.

c. Infectious nature of the pandemic related solid waste: The COVID-19 related solid waste poses a threat to the health of those who work on the frontline in the waste management sector such as trash collectors, transporters, rag pickers, street cleaners, waste segregator, etc. During the onset of the pandemic, emphasis was put on containing the spread of the virus and treating patients, solid waste implications were largely overlooked. Initially, the waste management practices were put on hold and in few cases augmented. While in countries like Australia, China, the USA, India, France, Italy, New Zealand, etc., concerned authorities have put forth guidelines for the management of medical and clinical solid waste due to the toxic nature of such waste, the municipal solid waste remains overlooked. The fact that virus can survive on various materials up to 3 days puts the lives of those involved in the waste management sector at risk due to strong possibility of secondary transmission [78].

The medical waste generated due to COVID-19 is being handled carefully and poses no additional problem relating to secondary transmission due to diligent approach being practiced for managing medical wastes. The clinical solid waste originating from quarantine centers, testing facilities, affected households poses the risk of contamination and is recommended to be handled through the same waste management procedure used for managing medical waste [79-80]. The real concern here lies with municipal solid wastes originating from households, public places, workplaces, and leisure and entertainment centers. As per WHO and other national agencies, the number of asymptomatic COVID-19 cases keeps increasing which makes it tough not only for health professionals for early detection but also have grave consequences for those involved in waste management.

Asymptomatic patients may generate contaminated municipal solid waste, as the virus can sustain on various surfaces, and in absence of modified municipal solid waste management protocols, it poses a threat to waste workers in both formal and informal sectors and may spread the disease further in community. The municipal solid waste management procedures vary across countries. The waste generated from individual habitat is collected and transported to waste management facilities. The person responsible for door to door collection or kerb-side collection and transporting the waste can come in contact with the virus persisting on the surface of wastes if the waste is not handled safely. In waste facilities, waste is segregated for resource recovery (separating the material that can be recycled or reused). Those involved in doing these tasks are also at risk of contracting the virus. At treatment
and disposal end, whether thermal decomposition method or landfills, personnel responsible to carry out these tasks may come in direct contact with the contaminated waste.

The body of scientific knowledge on the survival of viruses after waste disposal is very limited with the majority of them focusing on enteric viruses only [81-83], though influenza virus (H6N2) inactivation rate was up to 600 days in landfills, confirming that virus was active after disposal [84]. Secondary transmission of COVID-19 virus from solid waste to workers and reactivation rate of virus from the waste has not been studied yet, hence the secondary infection from occupational sectors can’t be overlooked and requires scientific studies on priority basis.

The problem increases manifold where the systematic waste management is not in practice. In developing countries, municipal solid waste is disposed directly at dumping sites, or in the low-lying fields, where it remains in an open environment, depending upon whether the dumped waste is collected and transported for final disposal, mostly in open solid waste dumping sites away from the community, or left there for a prolonged duration, in either case, there exists greater risk for both waste workers and common public. More so, in the informal waste management sector, where waste or rag pickers, who work on the frontline to keep our habitats free from waste, indulge in waste scavenging, collect, recycle and reuse various items from municipal solid waste or garbage, as part of their livelihood, are at most risk, as they don’t have access to personal protective equipment for their safety. The most scavenged items are plastic-based, which find way back to the community when scavengers sell the recycled plastic either to recyclers or plastic product manufacturing industries. The spread of disease in this instance is not limited to those who are directly involved. They may get infected by the virus and go on with their daily life, starting to interact with their family members and the general public, putting the health of anyone who comes in contact with them at risk.

**d. Logistical and operational challenges:** The systematic solid waste handling and management infrastructure designed to handle steady-state volume are under overwhelming stress, due to an increase in waste volume, changing composition, and associated risk of secondary infection. While waste professionals tasked with dealing with medical and clinical solid waste have already undergone safety training programs to deal with hazardous and toxic waste, those involved in the MSWM sector require immediate training campaigns, to follow better safety protocols and practices to use PPE.

Additionally, the medical waste management facilities need to develop ways to not only deal with the increased volume and changing composition of waste, but also consider their possible impact on waste to energy plants. The plastic waste management facilities are based on the concept of optimum resource recovery and energy production. The integrated solid waste management involves aspects of traditional solid waste management strategies coupled with energy recovery facility such as incineration. The ISWM also uses landfills to dispose of residue from incineration plants obtained after energy recovery. Plastic has very high calorific value, making it fit for waste to energy conversion using incineration plants. The changing volume and composition of solid waste creates logistical and operational challenges. The energy recovery based waste management facilities are not able to operate efficiently due to the change in the composition of waste. If recycling and segregation are being avoided, it creates a fiscal and operational imbalance. The operation on ISWM relies heavily on the recycling of waste, which is no longer possible due to COVID-19. The mass migration of people in developing countries may decrease the available manpower. In absence of segregation, the cost of waste management may increase significantly.

**6. Unsustainable Lifestyle changes and its impact on the circular economy, 3R practices, and waste management**

Any disaster event, natural or man-made, changes public perception on various facets of human life and often creates a socio-cultural and environmental shift. This changed behavior is observed through increased concern for the environment, advocacy for a sustainable lifestyle, and shift in consumption pattern of resource (material & product). The direct impact of the pandemic on public health like an increase in cases, increased hospitalization and morbidity is unprecedented, though remains manageable. However, the indirect impact of the pandemic on public health and especially on the ecosystem can be far worse and sustain for a longer duration. The public fear and control measures put sustainability and environmental concerns on hold. The most significant impact can be seen on the
circular economy, especially on 3R practices, where each of the components is now affected at the individual, community, and governmental levels.

a. Reduce: The advocacy and public motivation to reduce the waste to curb carbon and plastic footprint remains dormant amid ongoing pandemic. The increased risk perception among the public due to media coverage and social media discourse, government, and concerned agencies urging to adopt social distancing and better hygiene practices, and scientific knowledge on the role of fomites in spreading infectious disease motivated the public to change their sustainable lifestyle. The key observable changes are increased consumption of SUPs, disposable items, and PPE, and increased solid waste generation. For better hygiene practices, the public opted for PPE, disinfecting wipes, tissue papers, and sanitizer bottles. Lockdown and social distancing put restrictions on mobility, leading to increased consumption of SUP products such as plastic plates, cups, spoons, forks, water bottles, straws, and food packaging containers. Much of this waste is of single-use type, which will end up being part of the waste as their usability ends. The public information campaigns and advocacy to reduce SUPs in recent years which changed public perception is facing major setbacks as the public is more concerned about looming COVID-19 threat than to reduce their carbon footprint. The major governmental emphasis has been put on saving lives that require the utilization of resources on a global scale. To meet the demand for resources, governments directed industries to stop their production and start creating more medical resources. This changes the reduction policy and interferes with resource balance. The increased consumables, mostly toxic, will end up as waste, increasing the carbon, energy, and waste footprint.

b. Reuse: The ongoing pandemic has not only increased the consumption of SUPs but also created a public perception to avoid reusing many products that have come in contact with the outer environment. New studies infer that the SARS-CoV-2 virus persists and remains active on the surface of various materials that the public uses from several hours to several days. The survival time of SARS-CoV-2 on plastic, paper, and cardboard surfaces has been a matter of discussion on traditional and social media. Lack of governmental and authoritative guidelines to address the reuse practices, widespread penetration of information relating to transmission of the virus through fomite created panic causing behavioral and lifestyle changes. Fears of contamination and convenience, hamper with the reuse practices. The increased consumption of products results in visible changes that include disposal of reusable products such as cardboard, paper products, and especially plastic bags after a single-use, regardless of the reusable nature of the products.

c. Recycle: In a resource scarce world with increased waste generation, the sustainable lifestyle requires recycling of the waste products at individual and community levels which forms the foundation of a circular economy. Amid COVID-19, the recycling practices have either been reduced or completely stopped. The fear of secondary contamination from the waste creates fear among those waste workers that are tasked to segregate and recycle waste in the formal sector. Logistical problems, especially the reduced workforce is forcing waste management officials to prioritize treatment and disposal of the overwhelming volume of waste, which can’t be stored for longer duration due to special constraints. Informal waste and rag pickers also stopped their activity as governments are restricting mobility.

Additionally, as the recycling plants are shut down or working at reduced capacity, the production of recycled waste remains low, and increased logistical and operational challenges increase the cost of recycled waste. The sectors that utilize recycled waste is also affected by the pandemic. Their remains lower demand for recycled waste as the industries are operating at lower capacity and fear of secondary contamination from recycled waste.

The recycling business is also affected by the reduced cost of virgin plastics. To cope up with the low demand for fossil fuel, the oil industries are increasing the production of plastics at a cheaper cost. As the cost of plastic drops, the cost of plastic products will also drop and during the glooming financial uncertainties, the people will opt for cheaper products even if it contributes to an increase in carbon footprint. Sectors that consume recycled plastic waste as feed material has now access to cheaper original plastic, it will be very crucial to see if these industries priorities environment or economy.
Lastly, the plastic lobbying industries are capitalizing on the pandemic to further push their agenda where they are trying to change the public perception at the public level and asking the government to consider a more lenient approach towards plastic consumption [85]. The effect of the pandemic on circular economy is going to be long-term and rectification measures will depend upon how fast the public perception and unsustainable consumption patterns will change to a more sustainable and eco-friendly one. Pushing the reset button to move towards a sustainable circular economy will require participation from all stakeholders.

7. Solution and suggestion for handling and management of COVID-19 related pandemic solid waste

Environmental and man-made disasters have a devastating impact on both biotic and abiotic components of the environment. Presently global and national authorities are struggling to contain the spread of the virus and finding a vaccine. The emphasis has been put on saving lives and on public health, overlooking the other far-reaching consequences to the environment. The control and preventive measures adopted by authorities are generating an overwhelming amount of solid waste, which if not handled efficiently will keep deteriorating the ecosystem. The global solid waste and plastic waste generation was all-time high even before the pandemic. Finding a scientific and sustainable way to manage solid and plastic waste has been the focus of attention among authorities and the scientific community.

The unprecedented amount of COVID-19 waste is far too much for waste management facilities to handle. To effectively manage this waste, the waste-management and handling procedure should be such that it involves all stakeholders and simultaneously address the future concerns of sustainability. Keeping the current COVID-19 crisis in mind, here we propose a Pandemic Solid Waste Handling and Management (PSWM) strategy that can be modified and used to manage solid waste (medical waste, clinical solid waste, and municipal solid waste) during any pandemic event. The strategy involves all stake-holders and addresses all key components of traditional solid waste management strategy, with special attention on the infectious nature of the waste.

During the onset of a pandemic event, the authorities should immediately identify waste generation points. Temporary waste collection centers can be set-up depending upon proximity to treatment facilities and the volume of the waste generated. Concerned authorities should issue public guidelines on how to collect and store generated waste at the point of generation (hospitals, quarantine centers, households, etc.). The guidelines should ensure minimization of the risk of secondary contamination. On waste handling end, training and educational campaign for personnel safety is the key to avoid waste personal from contracting the disease.

A proper waste collection, transportation, storage, treatment, and disposal strategy needs to be communicated to the waste management agencies. Increased financial and personnel support, distribution of PPE, sanitation liquids, and allocation of dedicated equipment must be priorities. The ongoing pandemic highlights the crucial role that plastic plays in our life. On one hand, increased demand for PPEs and SUPs generates substantial amounts of plastic waste, and on the other hand, due to infection fears, the public is moving away from sustainable practices mainly 3R (reduce, reuse, recycle), further adding on to the plastic problem. The plastic footprint created during the pandemic event can be seen up to thousands of years and hence it requires special attention. The increased plastic waste can be good for waste to energy recovery facilities, but polluting emissions will also increase.
The ISWM which is usually designed on certain assumptions (steady-state flow rate of waste generation and percentage of recycled and reuse) are no longer valid. The concept of Plastic Waste Footprint (PWF) can be used to track the role of a pandemic event on plastic waste management strategy. The concept of PWF which accounts for 3R practices makes it an effective tool in understanding the impact of a pandemic on sustainability practices. “PWF is defined as the total mass of plastic waste used for a process, product or service minus amount of plastic avoided reused + recycled + reprocessed” [45]. Calculating PWF before a pandemic, during a pandemic, and after pandemic will help us in assessing the waste management strategies severely hit by the pandemic and can be used to strengthen those facilities.
The waste management facilities are facing major operational challenge to accommodate the increased volume of solid waste that too of changed compositions. Clinical solid waste is to be treated as medical waste is hazardous and requires separate handling, treatment, and disposal methods. The already stressed medical waste treatment facilities require adequate modification and treatment alternatives other than existing facilities. In this regard, municipal solid waste incineration plant and cement plant can be used to reduce the load with appropriate modifications that can effectively reduce the dangers associated with toxicity. The incineration temperature to ensure the destruction of waste and pathogens varies with countries. Additionally, various countries (Germany, China, Norway, and Spain) have contingency plans already in place to cope with the surge in medical and clinical waste [45].

Streamlining waste handling and management practices, making a circumstance (COVID-19) based substantial changes in existing solid waste management practices, advocacy for sustainable practices, public awareness, and safety campaigns can be way forward to maintain a circular economy and deal with the solid waste generated during the current pandemic. Appropriate awareness campaigns to counter plastic advocating lobby, deescalating the public fear, promoting safe 3R practices on the governmental level will ensure that behavioral changes won’t be long-term, or else, it will be very challenging to return to sustainability, once this all over.

8. Status of solid and plastic waste handling and management in developed (high-income group) and developing (low-income group) countries

Global solid waste generation is all-time high with 2 billion tons of waste being generated annually. The annual waste generation rate is expected to rise 70 percent by 2050 if we keep business as usual. The figure calculated by World Bank in 2018, doesn’t account for any unforeseen global disasters such as an ongoing pandemic. Additionally, the rate of solid waste generation along with solid waste handling and management policies that threaten our eco-system, varies from country to country, especially among developed and developing countries [63].

The severity of the global pandemic varies from country to country and accordingly the response to pandemic varies. As discussed earlier, the severity and level of response affect resource consumption and subsequent waste generation. It will be interesting to compare the status of pandemic solid waste generation from developed and developing countries and also the waste handling and management practices.

The virus first started from China and quickly spread across the developed nations such as Italy, Spain, Germany, and the USA, with Wuhan, New York, and Italy becoming the hotspots for COVID-19 by end of March 2020. The other nations, though comparatively less affected, undertook containment and precautionary measures. With the continued spread of the virus more countries like Russia, India, Brazil, Mexico, and Iran, etc. also became global hotspots. Reports of the second wave of disease in already affected China and South Korea are surfacing [89]. The solid waste generation trend will follow the spread of the virus with areas that are already affected generating more waste.

High-income countries generate (34 percent) nearly seven times as much waste generated by the lower-income group (5 percent) as shown in figure 4, confirming that advancement, development, and affluence generate more waste. The resource-rich developed countries have better infrastructure for solid waste management with optimum waste collection to efficient engineered waste treatment and disposal.

The integrated waste management including comprehensive collection of segregated waste is the foundation of waste management. Solid waste generating from the municipalities must be collected in entirety, to minimize the threat from mismanaged waste. Developed countries collect almost all the waste (100%) while developing countries are struggling with waste collection (30%). The management of solid waste also varies country wise. Traditionally, open dumping was practiced throughout the globe to deal with waste.
Fig. 4. Solid waste generation rate based on the income level of countries (based on data reported by [63])

As the rate of waste generation increased and the scientific body of knowledge on waste management developed, landfills, incineration plants, and recycling methods started gaining popularity [90]. 40% of waste is disposed of in landfills while only 19% of the waste is recycled for material recovery. Energy recovery from waste to energy-based incineration plants though remains problematic and handles 11% of global solid waste [63]. “The Global Waste Index which ranks 36 countries within the Organization for Economic Co-operation and Development (OECD) on basis of most environmentally-friendly methods of waste management on per capita basis highlights that developed countries like Spain, Italy, Canada, USA, New Zealand and Israel not only generate an enormous amount of waste but also found to be less efficient with waste recycling and management, despite having better infrastructure” [91].

The COVID-19 related PSWM requires a joint effort from both developing and developed countries as the trans-boundary migration of contaminated waste is a possibility that cannot be overlooked. Developed countries with efficient collection and management systems with contingencies can handle the PSW by modifying the existing protocols to accommodate the diverse nature of pandemic waste and strict enforcement of waste disposal laws among the public.

Resource challenged COVID-19 affected developing countries are diverting their resources in healthcare infrastructure and sanitation drive. The manpower responsible for waste collection is mostly engaged in sanitizing the habitats creating logistical problems in waste management. Open dumping of solid waste is prevalent where landfills are not yet available or available in limited quantity and 93% of waste being dumped in open dumping sites, or local water bodies. This coupled with the possibility of secondary transmission due to pandemic affected waste raises an alarming concern. This may further worsen as the number of cases in developing countries keeps increasing. [Table 2] summarizes the top 10 countries with the highest number of reported COVID-19 cases and solid waste generation and recycling rate.

The amount of plastic waste generated throughout the years has threatened every aspect of our ecosystem. It has been estimated that 6300 million tonnes of plastics waste was generated between 1950 and 2015. 80% of plastic waste was mismanaged (figure 5) and directly discarded either in the environment or in landfills, where they persist for thousands of years [92].
Table 2. Top 10 countries with the highest number of reported COVID-19 cases and solid waste generation & recycling rate. *(Source: Data accessed on 15-June-2020 from https://www.worldometers.info and [63])*

| S.No. | Country | Cases   | Death  | Population   | MSW (tons/year) | Medical Waste (tons/year) | Plastic composition (%) | Recycling rate of municipal solid waste (%) |
|-------|---------|---------|--------|--------------|-----------------|---------------------------|-------------------------|--------------------------------------------|
| 1     | USA     | 2,142,224 | 117,527 | 330,912,290  | 258,000,000.00  | 2,600,000.00              | 12.90                    | 34.60                                      |
| 2     | Brazil  | 850,796  | 42,791  | 212,488,104  | 79,889,010.00   | 260,063.00                | 13.50                    | 1.40                                       |
| 3     | Russia  | 520,129  | 6,829   | 145,931,723  | 60,000,000.00   | -                         | 14.21                    | 4.50                                       |
| 4     | India   | 321,626  | 9,199   | 1,379,344,820| 168,403,239.95  | 160,784.50                | -                        | 5.00                                       |
| 5     | UK      | 294,375  | 41,662  | 67,869,522   | 31,567,000.00   | 4,218,205.00              | 20.20                    | 27.30                                      |
| 6     | Spain   | 290,685  | 27,136  | 46,753,986   | 20,151,000.00   | 2,980,346.00              | 9.00                     | 16.80                                      |
| 7     | Italy   | 236,651  | 34,301  | 60,465,633   | 29,524,000.00   | 16,071,024.00             | 11.60                    | 25.90                                      |
| 8     | Peru    | 225,132  | 6,498   | 32,948,535   | 8,356,711.13    | 7,176.00                  | 10.52                    | 4.00                                       |
| 9     | Germany | 187,423  | 8,867   | 83,771,837   | 51,046,000.00   | 8,821,344.00              | 13.00                    | 47.80                                      |
| 10    | Iran    | 184,955  | 8,730   | 83,939,011   | 17,885,000.00   | 1,609,650.00              | 8.50                     | 5.00                                       |

**Fig. 5. Solid waste generation rate based on the income level of countries (based on data reported by Geyer et al., 2017)**

Besides the physical damage, they pose to wildlife and ecosystem, the indirect association with toxic chemicals and pathogens is threatening the biodiversity of environmental matrices. These mismanaged plastic waste also generate microplastics, small pieces of plastic with a size range below 5 mm. Besides plastic pollutant that is already present in an aquatic and terrestrial environment, an additional 5 to 13 million tons are being disposed of annually. This quantity will further increase due to ongoing pandemic which is generating a flux of plastic waste. The daily PPE consumption by the top 10 countries with the highest number of reported COVID-19 cases is calculated using equation 1 and shown in table 3. Based on our assumptions, 3.75 billion PPE waste is generated daily from 10
countries. The figure will likely to be lower, considering the acceptability rate varies with public perception.

Table 3. Top 10 countries with the highest number of reported COVID-19 cases and estimated daily PPE waste generation.

| S. No. | Country | Population | Urban Population (%) | Acceptance Rate | Rural Population | Acceptance Rate | Daily PPE Use | Daily PPE waste Generated |
|--------|---------|------------|----------------------|----------------|----------------|----------------|---------------|--------------------------|
| 1      | USA     | 330,912,290 | 83                   | 1.00           | 57,247,826     | 0.80           | 2             | 6.39E+08                 |
| 2      | Brazil  | 212,488,104 | 87.1                | 0.80           | 27,410,965     | 0.60           | 2             | 3.29E+08                 |
| 3      | Russia  | 145,931,723 | 74.8                | 1.00           | 36,774,794     | 0.80           | 2             | 2.77E+08                 |
| 4      | India   | 1,379,344,820 | 34.9             | 0.80           | 897,953,478    | 0.60           | 2             | 1.85E+09                 |
| 5      | UK      | 67,869,522  | 83.9                | 1.00           | 10,926,993     | 0.80           | 2             | 1.31E+08                 |
| 6      | Spain   | 46,753,986  | 80.8                | 1.00           | 8,976,765      | 0.80           | 2             | 8.99E+07                 |
| 7      | Italy   | 60,465,633  | 71                  | 1.00           | 17,535,034     | 0.80           | 2             | 1.14E+08                 |
| 8      | Peru    | 32,948,535  | 78.3                | 0.80           | 7,149,832      | 0.60           | 2             | 4.99E+07                 |
| 9      | Germany | 83,771,837  | 77.5                | 1.00           | 18,848,663     | 0.80           | 2             | 1.60E+08                 |
| 10     | Iran    | 83,939,011  | 75.9                | 0.80           | 20,229,302     | 0.60           | 2             | 1.26E+08                 |

The management of plastic wastes either through landfill or thermal methods, though generates energy, is not environmentally friendly due to emissions and scarcity of land. Life-cycle assessments of plastics management show that 3R based integrated plastic management practices are more economical and eco-friendly with significantly lower greenhouse gas footprint when compared with other methods. [93-94].

This is very crucial information for developing countries where informal plastic waste recycling is prevalent. Secondary transmission of the virus from dumped contaminated plastic waste especially gloves and masks can be threatening for those involved in such sectors. Governments of developing countries must take immediate action to address this problem. As the income level of the country increases, the resource utilization will further increase. The existing ‘produce-consume-dispose’ led linear economy is unsustainable in the future. The concept of a circular economy is being explored and there is an increased concern towards emissions from waste to energy plastic management plants, the advocacy for 3R based waste management keeps increasing. The sustainable circular economy to reduce carbon, energy, and plastic footprint coupled with more environment-friendly plastic waste treatment and disposal to reduce the emissions needs to be long term priority of government and industries with due consideration being given to the effect of the pandemic.

9. Future Research and Policy Priorities

COVID-19 which started from Wuhan has turned into a global pandemic on March 11, 2020. The widespread transmission around the globe has affected most of the nations in all continents. A pandemic has deleterious effects not only on public health but also on the environment. The priority concern right now is containment and eradication of the pandemic, ensuring the safety of public.

However, COVID-19 related control and mitigation strategies are generating a whooping amount of pandemic related solid waste, if not managed properly, not only poses the risk of the secondary outbreak but also has a long-term effect on the environment. The pandemic is also affecting the circular economy and all efforts made towards sustainability are in grave danger. A pandemic of such
scale is a wakeup call for us and needs to be used to priorities the environment, ecosystem, and public health simultaneously. Keeping that in mind here we highlight a few important points that need to be a priority concern for researchers and policy makers.

**a. Pandemic solid waste handling and management guidelines**
The mismanagement and threat of solid waste generating during current pandemic calls for the creation of separate domain in the waste management field dedicated to biological disasters. Pandemic solid waste handling and management (PSWM) guidelines that focuses on dealing with medical, clinical, and municipal solid waste management should be prioritized. The guidelines must address the sudden shift in volume and composition of waste. Waste collection, transportation, storage, segregation, treatment, and disposal of pandemic solid waste should be such that it minimizes the risk of secondary contamination to the waste workers. Additional funds must be allocated to deal with logistical and fiscal challenges amid pandemic.

**b. Collaborative response**
The scale at which the current pandemic has spread calls for collaborative response encompassing all countries and regions on all fronts. The policy and guidelines to address pandemic solid waste should not be limited to local scale. The trans-boundary migration of pandemic related solid waste poses the risk of secondary transmission, migrates the disease to unaffected areas, and presents an eco-toxicological threat to the eco-system. The government and academia must work together to identify transport mechanisms through which COVID-19 related solid waste is migrating must be identified and preventive measures should be adopted to stop it.

**c. The utility of plastics during a pandemic and finding an alternative**
The current pandemic highlights the importance and dependence of plastics on making human life safe and comfortable. Additionally plastic forms the backbone of medical care. On the individual level, single-use plastic products have now become not only convenient but also safe to use. The skyrocketing demand for PPE is merely the tip of the iceberg. The world was already fighting with plastic pollution, this pandemic has both long-term and short-term impact on the way we perceive and consume plastic. The need of searching the alternative of plastic material is now more than ever. Collaborative studies on replacement of plastic used in the health-care industry with eco-friendly material must be undertaken by researchers. Additionally, a logistical and efficient framework needs to be prepared for the effective allocation of plastic resources keeping sustainability and public health priority in mind for any future events.

**d. Countering fake information and increased advocacy for a sustainable lifestyle and circular economy**
The sustainable circular economy is not some abstract concept and groundbreaking progress by re-imagining resource utilization with pollution mitigation is observable in many places. Advocacy and mass campaign for sustainable practices such as 3R yielded concrete public behavioral changes where people were more cautious of practicing recycling and reuse while avoiding consumption of single-use plastics. The pandemic halted this crucial progress and public perception changed towards single-use plastics. The spread of fake information and lack of prompt governmental response encourages behavioral changes in the consumption and recycling of plastics. Plastic industries are now lobbying against banning single-use plastics by citing results of studies on the survival of viruses on fomites [85].

The argument made so far is unscientific and twisted to create a pro-plastic narrative to persuade people towards unsustainable consumption of plastics. The governments need to contain the spread of such fake news, to ensure that people don’t fall back to the linear system economy in the post-pandemic world which is known to have the negative consequence to people, environment, and eco-system as a whole. The prompt governmental response for containment of the virus also suggests that the governments can address unsustainable practices. Detailed studies and campaigns on consumer (fresh plastics and recyclable plastic) end are required to transcend the benefits of circular economy
and sustainable lifestyle. Lastly, a swift governmental response towards plastic recycling industries is also important to ensure that sustainable recycling practices are not compromised.

**e. Contingencies and plan of action to deal with the indirect impact of a pandemic on waste management**

A pandemic or any disaster is known to bring societal and behavioral changes. The environmental and economic impact across different sectors and geographical scales is going to create many future challenges. Other indirect impacts include a change in consumption pattern and migration of the workforce. The consumption and behavioral changes amid pandemic may influence the environmental footprints such as carbon footprint, water footprint, and plastic waste footprint. These frameworks need to be reassessed and recalibrated to address the impact of the pandemic to give us a better understanding of ways a pandemic affects the environment.

Additionally, pandemic related sudden mass migration puts pressure on the local eco-system. The scale and duration of such migration and impact on local environmental resources should be a research priority. Additionally, the mass migration will interfere with the social and economic dynamics at origin and destination end. For example, mass migration also reduces human resource in the waste management sector. Government and researchers need to handle this issue on a priority basis to manage the increased pandemic solid waste and social science and economic experts’ needs to study the effect of migration in detail as the local economy is intertwined with the national circular economy and environment.

**f. Creation, development, and application of scientific or engineering tools and frameworks to deal with pandemic related solid waste**

The severity of COVID-19 calls for the advancement of technologies to be used in fighting and controlling the pandemic. Contact tracing using a smart-phone application is an important tool that is being used by governments during this pandemic. Additionally, fab lab and 3D printing are being widely used at local levels for fabrication of face masks and medical items such as cotton masks, face shields, and ventilators for hospitals. The application of artificial intelligence and machine learning for optimum allocation of waste management resources during pandemic events will ease the burden and may eliminate possibility of mismanagement or error. From predicting and identifying the waste hot spots that require immediate collection, finding optimum waste collection frequency based on affected clusters, optimum pickup routes to efficient treatment and disposal methods can easily be accomplished. Sensor based monitoring, data collection, analytics and AI can further help in optimizing local and regional solid waste response strategies which will transcend the coordinated effort on national level. Using drones to identify pandemic waste, robotics for collection of contaminated wastes needs to be explored for feasibility. The data obtained from COVID-19 can be analyzed to create a technological framework that can be used during future pandemic or epidemic events.

10. Concluding remarks

The anthropogenic pollution of the environment is a priority concern for scientists, governments, and the public. Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) pandemic has affected most nations throughout the globe. The severity and reach of the contagion resulted in prompt governmental response with various containment and mitigation measures regionally and globally. These measures brought short-term positive environmental changes. The long-term adverse environmental impact of this pandemic in terms of a sudden surge in increased solid waste generation requires immediate attention of all stakeholders.

The major composition of pandemic solid waste is comprised of plastic. The sudden surge in the volume of plastic waste due to increased consumption of PPE, medical consumables, and appliances and SUPs, along with unsustainable lifestyle changes, puts a burden on solid waste management facilities. Pandemic solid waste, such as gloves and masks, has already found its way to the environment. These pandemic related plastic waste, if not managed properly will further pollute environmental matrices as they are known to persist for a long time.
The plastic waste generation sources are highlighted and discussed in detail. Further, we examined the consumption pattern of various polymer types and identified the plastic types and sectors that will keep surging in near future. During the onset of the pandemic, the volume of medical solid waste and clinical solid waste increased drastically. This trend will continue as the number of cases and rates of hospitalization increase. The demand for PP, PE, PS, PET, nylon, and nitrile, commonly used to manufacture PPE, medical consumables, SUPs, packaging material, food containers, and bottles will keep increasing at a steady rate. The demand for plastic is expected to increase in medical, leisure, and online shopping sectors, this trend is also expected to maintain a steady pace in the post-pandemic world. Among various factors that affect the quantity of plastic waste, the duration of pandemic and unsustainable change in lifestyle seem to be dominant.

The solid waste management facilities were already operating at extreme conditions to cope with ever-increasing solid waste. The pandemic solid waste generates overwhelming stress on these facilities. The major challenges include an increase in volume and change in solid waste composition. The logistical and operational challenges require additional resources. There is an urgent need to formulate COVID-19 pandemic solid waste handling and management action plan, prioritizing the safety of waste workers.

Amid fear of contacting viruses from fomites, the sudden change in lifestyle, behavior, and consumption pattern puts sustainable circular economy on hold. On the governmental level, restriction on SUPs is either lifted or temporarily put on hold. The public is increasing the consumption of SUPs while avoiding 3R practices. Plastic industries are already lobbying against the existing ban or restrictions on plastics. All of these factors are collectively in play, which not only generates a whopping amount of plastic waste but also hampers with the efforts to shift from an unsustainable linear economy to a sustainable and environment-friendly circular economy. The delayed governmental response will not only decelerate the shift but all the progress made towards public awareness may be lost.

The solution lies in involving all the stakeholders and streamlining effective pandemic solid waste management response. Though developed countries are thought to be efficient in solid waste management, with engineered waste disposal systems, the progress made by developing countries can’t be overlooked in this regard, given the dynamic nature of environmental pollutants and trans-boundary migration, the effective waste management system should start from regional level and streamlined to the global scale.

Prioritizing public health while ignoring environmental concerns may be a valid short-term response, but in the longer run, both aspects require equal attention due to their interdependence. The future governmental outlook and research priority can use the points discussed in the relevant section. In the post-pandemic world, creation of an environment friendly, energy-efficient, and wholesome earth should be the priority of government, public and scientific community. The post-pandemic world needs a global initiative that involves all stakeholders to rebuild mother earth.

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