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

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

Suraj K. Mallick,⁎, Malay Pramanik, Biswajit Maity, Pritiranjan Das, Mehebub Sahana

Department of Geography, Vidyasagar University, Midnapore, West Bengal 721102, India
Department of Development and Sustainability, School of Environment, Resources and Development, Asian Institute of Technology (AIT), P.O. Box 4, Klong Luang, Pathumthani 12120, Thailand
Centre for Geoinformatics, Jamsetji Tata School of Disaster Studies, Tata Institute of Social Sciences, Deonar, Mumbai 400088, India
School of Environment, Education & Development, University of Manchester, United Kingdom

HIGHLIGHTS

• Single-use plastics become a new challenge in waste management during the pandemic.
• Bio-medical waste threats throughout India enormously.
• Upsurge medical plastic waste for COVID-19 hampers the sustainable development goals.
• Needs people awareness, strict government regulations, and inclusive research.
• Sustainable policy recommendation is needed for plastic waste management in India.

GRAPHICAL ABSTRACT

The sudden surge in demand to use plastic products due to COVID-19 pandemic has increased plastic pollution. It has resulted into degradation of a broad range of habitats and ecosystems by destroying natural functions, water quality, and environmental sustainability. However, the government agencies, scientific communities, and the public, have started to give attention to this issue. So, in the present study, we used the correlation methods to check the relationship between COVID-19 affected population with the medical plastic waste (MPW) that has developed a conceptual model of the inter-linkages between the preventive measures of COVID-19 pandemic problems and the reduction challenges of plastic waste during and after pandemic scenarios. Emerging issues in the waste management during and after the COVID-19 are established by reviewing the literature, reports, policy briefs, and information from the website concerning COVID-19. Considering MPW management issues, we selected India as a case study to analyse the plastic waste footprint (PWF) due to COVID-19 pandemic. The correlation results showed COVID-19 affected population and MPW; COVID-19 affected population and PWF have a significant relationship ($R^2 = 0.60$; Area under ROC curve 81.4%). It suggests an urgent need for plastic waste management initiatives. Moreover, substantial plastic products, human awareness, strict government regulations, and inclusive research can check plastic waste footprints in India and worldwide. Then discuss the specific pathways through which the immediate and long-term impacts operate and highlight the issues of hampering the sustainable development goals (SDGs) progress in India and beyond. Finally, call for coordinated assessment, support and appropriate short- and long-term mitigation and the policy measures of plastic waste problems during and after the COVID-19 pandemic.

© 2021 Elsevier B.V. All rights reserved.
1. Introduction

Across the globe, billions of people have been affected, and millions of people died due to the novel coronavirus disease (COVID-19) (Worldometer, 2021). It has rapidly become the most significant economic and human tragedy of our lifetime (Udmal et al., 2020; Pramanik et al., 2021a, 2021b). The disease is highly infectious. The risk of transmission between people is immense and the disease mainly spreads through close contact with people and respiratory droplets (CDCP, 2020; WHO, 2020a; Pramanik et al., 2020a, 2020b). While an uncontrolled situation has been created during the COVID-19 pandemic in different countries across the world, for that reason, various national and international agencies and experts suggest the use of personal protective equipment (PPEs) (e.g., face mask, face shield, hand gloves, goggles, etc.) and maintaining physical distancing to combat the spreading this virus (WHO, 2020c; Hui et al., 2020; Fadare and Okoffo, 2020; Zambrano-Monserrate et al., 2020). In response to high PPE demand among the health care workers, service workers, and general public, the production of single-use face masks in China in February 2020 has soared to 116 million a day, around twelve times the normal amount (Birmingham and Tan, 2020). The World Health Organization (WHO) has called for a 40% increase in the output of readable PPE (WHO, 2020b). If the global population adheres to the norms of one disposable face mask and glove per day following the lockdown, the pandemic could produce 129 billion face masks and 65 billion gloves per month across the world (Prata et al., 2020).

Widespread use of protective equipment worldwide in conjunction with the pandemic leads to massive waste management difficulties and improper disposal practices worldwide. The plastic products used are correspondingly pathogenic and should be regarded as hazardous wastes as landfill manage it promoting biodegradation of plastics. Plastic waste management was considered a primary environmental concern before the beginning of the COVID-19 pandemic due to increasing concerns about pollution in marine and terrestrial ecosystems (Rajmohan et al., 2019). Worldwide waste management systems have struggled to cope with the current plastic waste satisfactorily. As a consequence of the imminent increase in COVID-19 waste volume, existing waste management systems, and healthcare capacities are in danger of being overwhelmed.

Plastic is immensely used in modern society due to its economic viability, flexibility, availability, and lightweight (Geyer et al., 2017). It's massive production, and wide usage has inundated waste management and raised environmental concerns (Patricio Silva et al., 2020b). Increasing plastic waste has resulted in the degradation of a broad range of habitats and environments, from distant lakes and coasts to the deepest oceans, by destroying ecosystems functions (Rume and Islam, 2020; Chakraborty and Maity, 2020) and water quality (Yunus et al., 2020). Plastics have been shown to adversely affect environments and habitats by altering species' distribution, causing increased mortality and entanglement of organisms (Welden, 2020). Besides, India’s plastic waste management scheme is pursuing a faulty medical waste disposal system, much of which relies on the landfilling and local incineration strategies (Corburn et al., 2020). Lack of proper waste management strategies and uncontrolled combustion of medical plastic waste has accelerated the release of greenhouse gases (GHGs) and other potentially dangerous compounds, such as dioxins, PCBs, furans, and heavy metals creating significant environmental concerns (Heidari et al., 2019).

The COVID-19 pandemic has pulled out this issue in the frontline environmental research through the increase of single-use plastics. Besides increasing the use of personal protective equipment (PPEs), plastic packaging of foods and groceries for home deliveries during the lockdown and home quarantine period (Scabotto et al., 2020; Vanapalli et al., 2020), and reducing the recycling and the reuse of solid wastes and their haphazard disposal has created an environmental burden (Singh et al., 2020; Nghiem et al., 2020). However, the government agencies, the scientific communities, and the public give less attention to this issue (Patricio Silva et al., 2020a). So, the present study intends to review the impact of plastic waste upsurge due to the preventive measures of the on-going COVID-19 pandemic and investigates the main challenges in plastic waste reduction during and post-pandemic. We have selected India as a case study to analyse the plastic waste footprints due to the pandemic, by taking into consideration the medical waste management issues. The objective of this paper also discusses the reductive challenges and policy recommendation for promoting sustainable management in the prism of sustainable development goals (SDGs), and this objective separates this article from the other published articles across the globe.

2. Conceptual framework in the context of plastic pollution due to COVID-19 pandemic

The COVID-19 outbreak has brought several positive and negative effects on the environment globally. During this outbreak, the GHGs emission, pollutants in the water, noise pollution, etcetera, have suddenly dropped due to travel restrictions and closed down industries and companies (Barceló, 2020). Moreover, plastic use has tremendously increased to protect humankind from this virus. The use of SUPs for food packaging was increased by 40% for medical purposes and 17% for other applications across the world (Prata et al., 2020). Due to the safety concern in grocery and supermarkets, the fresh food in SUPs containers have increased. On the other hand, plastic use increased for the food and groceries’ home delivery service to maintain social distancing, hygiene, and cleanliness to reduce the spreading of the COVID-19 virus. This COVID-19 pandemic seems to be preserving the UN sustainable development goals (SDGs) 2030 (namely 3.6, 11, 12, 14, and 15) by reducing pollutants in the air and water (Patricio Silva et al., 2020a). However, the increasing use of SUPs, PPE, medical waste, and household waste has directly violated the UN-SDGs (namely, 3.3, 12.3, 12.4, and 12.5). Plastic has its advantages (Klemes et al., 2020a). However, the excessive use of plastic has an adverse effect on the environment. For that reason, the 10R’s, which indicates refuse-reject, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover sustainability policy, should be financially incentivised, especially during this COVID-19 outbreak (Potting et al., 2017).

However, a conceptual model on the inter-linkages between the precautionary measures of COVID-19 pandemic problems and the reduction challenges of plastic waste has developed during and after pandemic scenarios (Fig. 1). The framework has incorporated emerging issues in waste management during and after the COVID-19. The preventive measures of pandemic were established by the review of literature, reports, policy briefs, and information from the website concerning COVID-19. At the same time, we have tried to provide some reduction strategies and policy recommendations to manage the urban environment.

3. Data and methods

3.1. Database

This study emphasised the world in general but examined India in particular. Different data were collected, which was available worldwide and published data on single-use plastics (SUPs), plastic production (Fig. S1), mandatory use of face masks (Fig. S2), and others followed by Geyer et al. (2017) and U.P.W.I. Hub (2020). Further, specifically India’s medical plastic waste (MPW) data was collected from the central pollution control board (CPCB) from 1st June 2020 to 30th
November 2020 (CPCB, 2020). The COVID-19 susceptible states in India were selected to highlight per capita medical plastic consumption variations. Besides, introduce SDGs in this present study, followed by the United Nations General Assembly report of the 71st season on the 2030 Agenda for sustainable development (2017). The World map was prepared from the map-chart platform (www.mapchart.net), and a state-wise map of India was downloaded from the Giovanni platform (www.giovanni.gsfc.nasa.gov). World population and COVID-19 affected population data were derived from Worldometer (2021), and total daily facemask, discarded facemask and daily medical waste generation data were derived from Hantoko et al. (2021). However, this study was based on different published data in the official websites, published articles in the reputed journals, authenticated newspaper reports, and our observations regarding plastic waste management.

3.2. Methods

3.2.1. Plastic waste footprint analysis

Rees (1992) first proposed the ecological footprint (EF) as a simple and elegant method for comparing resource use among the populations. EF deals with human demand for the natural resources and the amount of waste it generates that takes into account. In this present study, applied the plastic waste footprint (PWF) to highlight the plastic consumptions (medical plastic and municipal plastic) and plastic waste generation during this pandemic, followed by Klemes et al. (2021). This study focused on plastic waste generated during the pandemic situation from June 2020 to November 2020. For better understanding, we have prepared a state-wise COVID-19 affected population map, total population map, and a state-wise plastic waste map based on CPCB produced data. Finally, based on the population map, plastic production cost data, plastic deposited data, and plastic waste data generated a per capita plastic waste footprint map using the following equation (Eq. (1)):

$$\text{Plastic waste footprint (PWF)} = \frac{ST_{pw} + ST_{pp} + T_{re} + T_{rc} + T_{rd} + T_{pc}}{ST_{p}} \left( \frac{\text{person}}{\text{g/m}^2} \right)$$

where $ST_{pw}$ indicates state-wise total plastic waste (medical plastics, municipal plastic, etcetera), $ST_{pp}$ indicates total plastic production, $T_{re}$ indicates total plastic reducing reuse, $T_{rc}$ denotes the total amount of plastic recovered and converted, $T_{rd}$ denotes the total amount of plastic deposited, $T_{rc}$ indicates the total amount of plastic production cost, and $ST_{p}$ indicates state-wise total population.

3.2.2. Statistical analysis

Linear regression was used to model a quantitative variable, namely Y variable. It is one of the useful statistical models that help to analyse the degree of goodness of fit and correlation matrix. First, we have analysed regression between the COVID-19 affected populations with the MPW and then calculated the residuals between these two variables. After checking the residual distribution, the relationships between the predicted MPW with the actual MPW was calculated. Next, a correlation matrix was done between the COVID-19 affected populations and the MPW and checked the variance in inflation factor (VIF). It helps to minimise the sum of squares (SS) of the residuals. Finally, apply analysis of variance (ANOVA) to find the variability between the data. All these statistical analyses were done by XLSTAT software.

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (O_i - P_i)^2}{N}}$$

Fig. 1. Conceptual framework of plastic pollution due to COVID-19 pandemic and its reduction challenges.
3.3. Validation

The present study results were checked using the goodness of fit, Adjusted R$^2$, means square of errors (MSE), root means square of errors (RMSE), and so others (Addinsoft, 2020) and receivers operating the characteristic (ROC) curve for validation. A linear correlation matrix was done in the descriptive statistics between COVID-19 affected the population and MPW based on 35 observations in India. Then used the ANOVA table results (One-way ANOVA) for the F-test at the 0.0001 significance level. Moreover, ROC was considered for the further validation process. The area under the curve (AUC) of ROC varies from 0 to 1. If the AUC value is 0.50 or less, it will be random, and if the value is given 1, it will be perfectly matched with the actual sequence (Pontius et al., 2004).

4. Results and discussion

4.1. Plastic pollution and short-term preventive measures in the context of COVID-19 pandemic

The impacts of COVID-19 pandemic on the environment have a significant role, and most of them positively impact the environment. Nevertheless, quite a few negative consequences are there, like plastic pollution, waste generation, among others; plastic use is partially or completely banned in numerous countries worldwide, but banning becomes the only strategy to control the spreading of COVID-19 (Fig. 2). COVID-19 pandemic appears to be tortuously compensating on the way to the UN 2030 SDGs (particularly SDG 13 and 15) by growing inclusive of health and safety of towns or cities by plummeting the GHGs emissions, outside open-air pollution, noise pollution (including aquatic or underwater environmental noise due to decrease marine transportation activities), and water pollution (including river and subsurface water) among others. Nevertheless, this pandemic cannot control indoor air pollution and plastic pollution (including medical waste) along with single-use plastics (like PPEs) and the living environment.

One report has stated that plastic is more sustainable than papers if it can be reused and decomposed (Plastic Today, n.d.). Now, people are being mandated to wear masks outside and use PPEs to travel from one place to another. These plastics are single-use plastics, partially decomposed and considered solid waste (Fan et al., 2020). However, using single-use plastic (SUPs) and medical waste has been increased quickly due to the COVID-19 pandemic (Patrício Silva et al., 2020b). For precaution, the people are habituated with the PPEs to reduce the spread of the virus. Consequently, it will soon become the most popular SUPs across the globe. Moreover, in the shopping mall or supermarkets, streets, occasions during COVID-19 have well-ordered consumers and the providers for fresh-food packaged groceries in plastic containers (Patrício Silva et al., 2020a).

This pandemic has quick transmissible power and spreads from one human being to another or many people. So, people are habituated with the PPE to prevent the COVID-19. Due to its high contagious nature, doctors, virologists, and experts advise using protective equipment to combat the spread of this virus. Firstly, PPEs came for doctors and medical workers; it is now very common in ordinary people as a whole (Patrício Silva et al., 2020a). A drastic use of medical plastic and PPEs has increased. The PPEs requirement has significantly been prioritised across the world with the increasing number of COVID-19 affected population. It has been estimated that almost 130 billion face and body masks and 64 billion gloves are needed to support the world population in a month (Prata et al., 2020). Aljazeera News in December last year (2020) reported data on country-wise mandatory use of masks, but the report stated that not every country across the globe has mandatory
use of masks (Fig. S2). So, the lack of government initiatives and shortage of medical facilities has influenced many indiscriminate PPEs to use at the very beginning.

Consequently, the SUPs waste has been increasing rapidly since COVID-19 outbreak, which has become an adverse environmental concern on the earth. Moreover, most of the recycling centres were closed with an increasing rate of COVID-19 risk. For instance, the United Kingdom (UK), Spain, Italy and several European countries have stopped the plastic recycling process to avoid the risk of inception (Zambrano-Monserrate et al., 2020). In most cases, municipal solid waste (MSW) like empty bottles, plastic polythene, and other plastics have been found in disposal sites and public places. Similarly, the improper use of medical plastic waste (MPW) like PPEs, SUPs, and considerable disposal sites has negatively influenced environmental pollution widely during this pandemic.

4.2. Plastic pollution and long-term preventive measures in the context of COVID-19 pandemic

Plastics have very long-term effects on the environment. It is slowly or partly decomposed by the action of various physical and anthropogenic processes like temperature or heat and repercussions into fragmented plastics (Micro-plastics or Nano-plastics). The amount of plastic consumption and disposal cannot be under-controlled without any strict regulations. So, it is challenging to measure the amount of daily plastic use. During this pandemic, it can be estimated that a developing nation like India has 1380 million populations and requires 13,000 metric tonnes to support the total population in a day. Accordingly, the UK requires 60,000 t of plastic masks (UPWI Hub, 2020). The mask materials are used as a substantial product of plastics made by the amalgamation of polypropylene, polyethylene, and polyethylene terephthalate (Silva and Nanny, 2020). Nano-plastic is the composition of a different polymer, and it has a long-term impact on the environment (Klemes et al., 2020b). A study reported that San Francisco Bay generated seven trillion of plastic debris per year (Eriksen et al., 2013). Similarly, if we look into SUPs and PPEs use, the pandemic has become a considerable amount of waste regularly generated worldwide. It has undoubtedly impacted the environment on a long-term basis.

This pandemic has been faced new challenges with repercussions of plastics like SUPs, PPEs, and MPW. Since the outbreak of COVID-19, the medical waste generation is increased; most of them are made of single-use plastic, which increases medical waste globally. A recently published literature reported that the SARS-CoV-2 virus could exist for 72 h on stainless steel and plastic (Van-Doremalen et al., 2020). Therefore, medical equipment (masks, gloves, needles, syringes, bandages, PPE, among others SUPs) increased the magnitude of medical waste. For instance, in Ahmedabad city of India, the medical waste generation is increased 550–600 kg/day to 1000 kg/day during the first phase of lockdown; in Dhaka, around 600 m tones of medical waste generated per day during this pandemic (Somani et al., 2020; Rahman et al., 2020).

The experts are suggesting using non-pharmaceutical equipment to reduce the spread of this virus. Since the COVID-19 outbreak, plastic-based PPEs production has increased globally (Singh et al., 2020). Most people dump personal protective equipment in open places due to a lack of proper knowledge about infectious waste management (Rahman et al., 2020), threatening the spread of this virus and the environment. Some of the waste, like N95 masks for protective suits, gloves, etcetera, is made using polypropylene. It releases dioxin and toxins, and same times can persist a long time in the environment (Singh et al., 2020).

The increase in municipal solid waste and plastic waste directly or indirectly affected the environment (Fig. 3). Consequently, it blockages the sewage system, specifically in developing nations and adversely affects water infiltration and agricultural soil aeration processes. Even plastic additives release contaminated chemical matter into ambient soil that percolates into the groundwater and negatively impacts the aquatic environment like rivers, lakes, oceans, and other terrestrial ecosystems.
Moreover, iniquity in plastic pollution, tenacity and iniquity are associated with a polymer that can be imposed severe threats for the biodiversity (Klemes et al., 2020), risk of floods (Adam et al., 2020) epidemic risk, namely dengue-related to the Aides spp. (Krystosik et al., 2019). Besides, plastic wastes are considered a vector-borne pollutant, antagonistic species, and pathogen, namely SARS-CoV-2 (Hartmann et al., 2017), that can be susceptible to wide-ranging public health and well-being (Fig. 3).

4.3. Challenge in the reduction of plastic waste during and after pandemic scenarios

4.3.1. Emerging challenges in waste management

Pandemic increases medical waste along with infectious masks, gloves and PPEs composed with the non-infectious substances in a similar manner (Bourouiba, 2020). At the same time, municipal solid waste (MSW) has increased. Although proper planning manages MSW and
various difficulties, this pandemic has given a new challenge in waste management, especially MPW management. In the meantime, metropol- itan and large-scale cities MSW were minimised by 30%, but MPW has been increased by very high use of SUPs in China (+370%) (Ilyas et al., 2020). From 1st January to 31st May 2020, total MPW was accrued about 437 kt. all over China (Tang, 2020). In India, from 1st June to 30th November 2020, the total MPW accumulated was about 18,007.32 tons (CPCB, 2020). So, MPW and SUPs become a new challenge in waste management during the pandemic and post-pandemic.

4.4. Plastic waste pollution in India in the context of COVID-19 pandemic

4.4.1. Plastic waste footprint in India

The energy consumption due to hospitalisation, production of PPEs, masks, gloves, disinfectants and transportation have increased the environ- mental footprint owing to COVID-19 (Klemes et al., 2020a). The GHGs emission reported of the N-95 mask is 0.05 kg CO2eq/single-use of producing the cloth masks (Ecocain, 2020), suffering most in this pandemic situation. They have no proper planning (Technavio, 2020). Many countries partially or entirely banned plastic and antiseptics during this pandemic increases the energy and environmen- tal footprint significantly. An estimation of Technavo, the global disin- fectant market has increased 12% during 2020–2024 (Technavio, 2020). Many countries partially or entirely banned plastic bags due to their fragile nature; they recommend either paper bags or reuse plastics. Still, those countries are not banning plastics; they are suffering most in this pandemic situation. They have no proper planning for plastic waste management. So, plastic waste footprint (PWF) is the way to assess plastic waste consumption by a district, state or country. Asia is the most COVID-19 affected and plastic waste generated continent (Table S1), and India is the only state in Asia that has been flooded of COVID-19 affected population along with a huge medical waste generated country (26,453.50 tons/day) (Table S2). For that reason, we have used the Indian scenario and used published data on COVID-19 af- fected and medical plastic waste (MPW) zone map and distribution of population map of India (Fig. 4). Based on this medical plastic waste generated, plastic consumed, plastic disposed of, and total plastic pro- duced data generated per capita plastic waste footprint map (in gms) (Table 1). In India, Maharashtra state is hugely affected by COVID-19 from June 2020 to November 2020; so, it has a high mass consumption of per capita medical plastics.

Moreover, Mumbai has international significance as one of the pop- ulous and dense cities across the world. Correspondingly, the interac- tion between and among the people is much higher than the others in the world. So, people have taken maximum precautions to prevent this upsurge pandemic effect. Consequently, SUPs, PPEs, and others will likely be taken along with plastic water bottles, bottles of hand sanitizers, gloves, masks, and others indiscriminately and through these medical wastes and plastic litters in public or inappropriate places. However, the plastic waste footprint result (Fig. 4D) showed that India’s south-western part has a high consumption of plastics due to high den- sity in terms of urbanisation and maximum interaction between the people and safety concerns. Result also shows, high plastic consumption states are Goa and Delhi, which generate 60 g and 37 g plastic waste per day. Total plastic production is about 3,360,043 TPA, and the cost of this amount of plastic production is about USD 400bn, while the reuse of total plastic is about 5857 TPA only in India. However, the northern part of India has a low rate of plastic consumption due to comparatively less population and minimum interaction between and among the people than the other part in India.

Table 1

| Name of states/UTs | Plastic waste (Ton) | Population (Dec. 2020) | Plastic waste footprint (gm/person) |
|--------------------|--------------------|------------------------|-----------------------------------|
| Andaman & Nicobar | 1,155,753.69       | 417,036                | 2.771323229                        |
| Andhra Pradesh     | 630,997,062.7      | 53,903,393             | 11.70607317                        |
| Arunachal Pradesh  | 15,741,474.12      | 1,570,458              | 10.2339259                         |
| Assam              | 31,645,509.1       | 31,607,039             | 1.0301526                          |
| Bihar              | 144,360,429.0      | 124,799,962            | 1.156806943                        |
| Chandigarh         | 187,833,561.4      | 1,154,473              | 162.1389203                         |
| Chhattisgarh       | 39,453,745.65      | 29,431,261             | 1.34052957                         |
| Daman & Diu        | 2,600,899.395      | 615,724                | 4.224131908                        |
| Delhi              | 1,603,479.452      | 18,716,922             | 36.56700957                        |
| Goa                | 22,108,098.45      | 1,586,250              | 13.93733551                        |
| Gujarat            | 1,982,869,635      | 63,872,399             | 31.0442329                         |
| Haryana            | 895,357,122        | 28,204,692             | 31.74497073                        |
| Himachal Pradesh   | 67,646,063.9       | 7,451,955              | 9.076726461                        |
| Jammu and Kashmir  | 171,408,263.5      | 13,607,039             | 7.290163151                        |
| Jharkhand          | 11,203,734.75      | 38,593,948             | 9.4601112                          |
| Karnataka          | 1,449,983,723      | 37,562,388             | 88.36071946                         |
| Kerala             | 1,958,384,312      | 35,999,443             | 54.85737051                        |
| Lakshadweep        | 825,538,35         | 73,183                 | 11.28046609                        |
| Madhya Pradesh     | 930,926,496        | 85,358,039             | 9.957004874                        |
| Maharashtra        | 3,747,539,504      | 123,144,223            | 10.43211783                        |
| Manipur            | 16,194,159.44      | 3,051,545              | 10.63087235                        |
| Meghalaya          | 31,849,450.36      | 3,366,710              | 9.460111201                        |
| Mizoram            | 10,545,118.44      | 1,239,244              | 8.509115271                        |
| Nagaland           | 14,757,178.4       | 1,249,995              | 11.59552674                        |
| odisha             | 512,693,788.4      | 46,356,334             | 11.05984327                        |
| Puducherry         | 197,441,557.8      | 1,413,542              | 139.678593                         |
| Punjab             | 443,437,471.1      | 30,141,373             | 147.1192009                        |
| Rajasthan          | 500,053,072.6      | 81,032,689             | 16.71004304                        |
| Sikkim             | 15,164,504.46      | 690,251                | 21.96950587                        |
| Tamil Nadu         | 2,052,641,233      | 77,841,267             | 26.30937635                        |
| Telangana          | 345,148,512.3      | 39,362,732             | 8.76840846                         |
| Tripura            | 1,238,307,525      | 4,169,794              | 2.96970912                         |
| Uttarakhand        | 157,701,417.1      | 11,250,858             | 14.01689424                        |
| Uttar Pradesh      | 1,734,203,876      | 237,882,725            | 7.290163151                        |
| West Bengal        | 1,349,930,289      | 99,690,303             | 13.55255113                        |
become mandatory in every workplace, and the government is also reinforced to use the mask. Every municipality should set strict regulations to develop permanent municipal waste collection sites where all the wastes are gathered daily.

In India, states like Goa, Andaman Nicobar, Arunachal Pradesh, Lakshadweep, Mizoram, Nagaland, and Sikkim do not have CBWTFs (Common Biomedical Management Waste Treatment Facility). After the spreading of COVID-19, the biological medical waste (BMW) has been increased 15 times more compared to waste generated from the general patient (Faizan, 2021). Many biological waste treatment strategies are followed in India, like incineration, steam-based treatment system, irradiation methods, biological methods (including composting and burial), mechanical methods (including shredding, grinding, mixing, and compacting technologies that reduce waste volumes but do not destroy microorganisms). Delhi, Karnataka, Madhya Pradesh, Kerala, Maharashtra, Chandigarh, and Chhattisgarh have already taken some medical waste management initiatives. Still, steam sterilisation

Fig. 5. Results of linear regression, the residual plot between predicted versus standard residuals based on COVID-19 affected population and medical plastic waste (MPW) from June 2020 to November 2020.

Table 2
Correlation matrix between COVID-19 affected person with medical plastic waste generation.

|                  | COVID affected(person) | MPW(Ton) |
|------------------|------------------------|----------|
| COVID affected(person) | 1                      | 0.837    |
| MPW(Ton)         | 0.837                  | 1        |

Table 3
Regression analysis results for PWF using goodness of fit statistics.

| The goodness of fit statistics | Observations | Sum of weights | DF | R² | Adjusted R² | MSE | RMSE | MAPE | DW | Cp | AIC | SBC | PC |
|--------------------------------|--------------|----------------|----|----|-------------|-----|------|------|----|----|-----|-----|----|
|                                | 35           | 35             | 33 | 0.701 | 0.692 | 280,580.693 | 529.699 | 1512.750 | 1.838 | 2.000 | 441.002 | 444.113 | 0.335 |

Table 4
Results of ANOVA of medical plastic waste.

| Source | DF | Sum of squares(SS) | Mean squares(MS) | F       | Pr > F       |
|--------|----|--------------------|------------------|---------|--------------|
| Model  | 1  | 21,748,978.684     | 21,748,978.684   | 77.514  | <0.0001      |
| Error  | 33 | 9,259,162.853      | 280,580.693      | 7.514   | 0.0001       |
| Corrected total | 34 | 31,008,141.536 |                   |         |              |
(autoclaving), chemical disinfection, shredding/grinding/disinfection methods, disinfection/encapsulation method, Microwave or radio-wave treatment are the few sustainable waste management strategies that should be adopted in developing countries (Klemes et al., 2020b). However, the overall scenario cannot be reduced without the plastic recycle-reuse-recover process (Prata et al., 2019). Pathogen diffusion through MPW has been increased due to this infectious disease and resulted in health risk and pollution. All MPW and PPEs are needed to be well monitored for our health safety and pollution control. If the total amount of medical waste in a city will cross 10 tons/day, it would be a great risk for the global environment. If it is below 10 tons/day, there should be a recycling option or incinerate (Patrício Silva et al., 2020b). Ultraviolet-C light (UV-C), ozone (O₃), ionised hydrogen peroxide (H₂O₂) and temperature or heat to be effective sanitisation methods to rub in the PPEs, surgical and N95 mask to improve the reusable and reducing power of waste (Patrício Silva et al., 2020a). Hazardous and infectious waste should be managed by following the WHO’s guidelines (WHO, 2020a, 2020b, 2020c). All people are unaware of infectious waste disposal, so the government should implement an awareness campaign through mass media, the internet, and local authority to manage Municipal and medical waste.

4.5.2. Mitigate the negative impacts of plastic pollution under pandemic scenarios

Environmental impact assessment (EIA) and life cycle assessment (LCA) is the best way to plan and mitigate the negative impacts of SUPs, PPEs and MPW on the environment. Klemes et al. (2020a) have already been suggested in their article about LCA to give a conceptual...
framework for evaluating environmental damages. One report highlighted that substantial fossil fuel could reduce the plastic waste footprint along with GHGs (Zheng and Suh, 2019). This pandemic can be recovered from the ambient plastic pollution through strict government regulation and human perception, which is a significant move to mitigate the indiscriminate plastic waste generation and overcome the Nano-plastic (<0.01 μm) pollution during COVID-19 and post-COVID-19. Here, we have introduced an environment-economic-based conceptual framework for plastic waste management where the use of plastic becomes sustainable and economically beneficial to the producer, retailer and consumer (Fig. 7).

4.5.3. Implication for the sustainable development goals

Medical Plastic waste during the COVID-19 outbreak becomes unmanageable, and it has been increased monotonically, especially in the cities, municipalities or urban areas for extensive healthcare facilities. However, medical plastic wastes and municipal solid wastes need some specific measures to prevent the upsurge trend of plastic wastes by the intensive healthcare facilities. Plastic can have a suffocating effect on the marine ecosystem, especially SUPs pollute significantly to land and sea. Even some of the medical waste substances disrupt the hormone systems of humans and animals. So, people should think that this pandemic allowed us to make a sustainable future by minimising the waste and pollutant input to the environment.

Besides various positive impacts of COVID-19, some negative consequences like increasing medical waste, municipal waste, decline waste recycling, haphazard disposal of PPEs and SUPs, and others directly affect human health and the environment. Although regular solid wastes have been cut down by 30% across the globe, MPW has increased rapidly on the other hand (Klemes et al., 2020a). So, here we need some potential strategies for plastic waste treatment on an urgent basis like autoclaving, incineration, grinding, and chemical disinfection. Replacing and reducing fossil fuel consumption can be helpful to combat plastic waste footprint that can be influenced by sustainable consumption and production. Moreover, people’s awareness is a prerequisite for future sustainability regarding the effective and non-essential use of plastics in the post-pandemic especially in the tourism spot and marine area (Mallick et al., 2020). Otherwise, environmental stewardship will be balanced off in future. However, plastic pollution and medical waste generation hamper SDG3 (health and well-being) and 12 (sustainable consumption and production) directly by this pandemic. So, every county, especially in the developing nations, should have needed some proper thinking about plastic pollution and waste management during the post-pandemic in an exact way to retrain the principles of SDGs. SDG 6 (Health risks), 11 (Resilient and sustainable city), 14 (Protection of the sea and ocean), and 15 (Restore ecosystems and preserve diversity) still have some positive impacts on creating opportunities for sustainable use of plastic and waste management (Fig. 8). Yet, the absolute reduction in the production and use of plastic is the only option to combat the pollution in marine areas, restore the ecosystem, human health and achieve the SDGs appropriately (Mallick and Rudra, 2021; Mallick, 2021). An interlink-age has been set up between waste generation during and post COVID-19 pandemic, people awareness, and SDGs (Fig. 9).

5. Policy recommendations for the management of plastic pollution

In large quantities, plastics have been used as the COVID-19 shield. However, little focus has been paid to where the increased plastic waste ends. The trite irony is that we had real victories against plastic pollution just as the coronavirus pandemic began. In 2019, India committed to phasing out plastics for single use until 2022. The commitment required improvements in plastic collection, storage and recycling. Due to the pandemic, the situation reached out worse, particularly single-use and disposables, has increased manifold. Moreover, it also negatively impacts the environment, land and oceans, filling up the oceans, extinguishing marine life, and even invading the food chain to get into our bodies. Therefore, considering the enormous issues of emerging plastic waste in the environment, the Indian government should have to prioritise plastic management issues with actionable,
credible data and information to improve the waste inventory and plastic material balance.

Besides, the focus should be more priorities on the ban of import of plastic waste, ban on items generated by single-use plastics, establishment of a more straightforward definition of single-use plastics, a review of the use of multi-layered plastics, and the establishment of an online platform for trading in plastic credits. A bottom-up approach to waste recycling could be initiated through a government awareness programme. Everyone can know what it is all about, what can be recycled, who can recycle, and finally, how economical is the process.

The ban or phase-out of non-recyclable products, like multi-layered plastics, carry bags, any item produced by single-use plastics, could also be the priority action. Incentivise the recycling business, the segregation of plastic waste from source with active engagement and proper management strategies of municipal agencies could be established more viable and manage the plastic surge during the pandemic. According to the Extended Producer Responsibility (EPR) rules in India, the commitment made by a producer to facilitate a reverse collection mechanism and recycling of end of life, post-consumer waste; therefore, the new straightforward rules and guidelines for EPR could be enforced.

Fig. 9. Inter-linkages between medical plastic waste and UN’s sustainable development goals.
Besides, the government must also encourage eco-friendly alternatives to single-use plastics where they exist and develop options where they do not exist. Business models which use alternative systems to reduce plastic waste should be encouraged. Also, stimulation of the circulation and use of plastic waste during and after the pandemic focusing on building back greener, justice and sustainability, and developing inclusive solutions should be priorities towards the progress of UN's sustainable development agendas.

6. Conclusion

The present study examined how the COVID-19 pandemic has increased medical plastic waste (MPW) and the possible ways to reduce plastic waste. No doubt, the pandemic has increased the use of SUPs and MPW across the world and mostly in metropolitan regions. The contagious nature of the COVID-19 virus has impacted the reduced, reused, and recycled SUPs and MPW waste materials, making the dumping ground and incinerated places a more hostile environment impactful zone. Statistics show that India needs 13,000 metric tonnes of masks every day to support the total population of India. After the effect of the second wave, Asia is the most COVID-19 affected continent and also the highest contributor of plastic waste due to the COVID-19 pandemic. The result of this work also found that there is a highly significant relationship between PWF generation and COVID-19 affected population. The result of this paper also indicates that the high population density, urbanisation and maximum interaction between the people and safety concerns have resulted in the increased consumption of plastics in the western part of India. Thus, this pandemic has given a new challenge in waste management to the highly densely populated countries in Asia.

COVID-19 pandemic makes us rethink the positive measures and research on the fundamental goals of sustainable development. The government of different countries should inspect the MPW in a suitable place where negative impacts will be negligible. Moreover, concerning SUPs, where to transfer and how much can this waste be recycled and reused for human beings? Although we know plastic-free life is too difficult to continue if distributors and sellers take the plastic and government cost, plastic waste generation might be a better solution for high consumption plastic users. Moreover, people’s awareness concerning plastic pollution could have been influenced by the sustainable management of medical waste and the environment. County-specific one decision or planning of experts on the environment about this greener planet creates complexity or harmony in nature and environmental development. So, every step towards plastic waste management during the COVID-19 pandemic and post-COVID-19 pandemic should be prioritised. We are unlikely to achieve the sustainable development goals (3, 6, and 11–15) of the United Nations (2030) without concerted measures to safeguard the environment during and after the COVID-19 pandemic.

The methodology adopted in this study may be utilised for monitoring the relationship of SUPs and MPW with COVID-19 pandemic in various geographical units at multiple scales. The output of this study can influence the policymakers, government agencies and different stakeholders to give more concern on the impact of SUPs and MPW after the COVID-19 pandemic. This study's findings can be utilised to identify the effective pathways to reducing plastic waste and its effects in the post-pandemic era.

CRediT authorship contribution statement

Suraj K. Mallick: Data curation, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. Malay K. Pramanik: Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. Biswajit Maity: Methodology, Formal analysis, Writing – original draft, Writing – review & editing. Priritanjan Das: Data curation, Methodology, Investigation, Writing – review & editing. Mehebub Sahana: Methodology, Formal analysis, Writing – review & editing.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.148951.

References

Adam, I., Walker, T.R., Bezereda, J.C., Clayton, A. 2020. Policies to reduce single-use plastic marine pollution in West Africa. Mar. Policy 116, 103928. https://doi.org/10.1016/j.marpol.2020.103928.

Addinsoft, 2020. XLSTAT Statistical and Data Analysis Solution. USA, New York https://www.xlstat.com.

Aljazeera News, 2020. Which country have made wearing face masks compulsory? https://www.aljazeera.com/news/2020/04/countries-wearing-face-masks-compulsory-2020423094510867.html [Accessed 20th December, 2020]

Allison, A.L., Ambrose-Dempster, E., Aparsi, D., Bow, M., Casas Arredondo, M., Chau, C., Chandler, K., Dobrijevic, D., Halies, H., Lettigeri, P., Liu, C., Medda, F., Michie, S., Miodownik, M., Purkiss, D., Ward, J. 2020. The Environmental Dangers of Employing Single-use Face Masks as Part of a COVID-19 Exit Strategy. UCL Press https://doi.org/10.14324/111.444/00031v1.

Barceló, D. 2020. An environmental and health perspective for COVID-19 outbreak: meteorology and air quality influence, sewage epidemiology indicator, hospitals disinfecion, drug therapies and recommendations. J. Environ. Chem. Eng. 8 (4), 104006. https://doi.org/10.1016/j.jece.2020.104006.

Bermingham, F., Tan, S.L., 2020. Coronavirus: China’s mask-making juggernaut cranks into gear, sparking fears of over-reliance on world’s workshop. South China Morning Post www.scmp.com/economy/global-economy/article/3074821/coronavirus-chinasmask-making-juggernaut-cranks-gear.

Bourouiba, L., 2020. Turbulent gas clouds and respiratory pathogen emissions: potential implications for reducing transmission of COVID-19. J. Am. Med. Assoc. https://doi.org/10.1001/jama.2020.4756.

CDPC, Centres for Disease Control and Prevention. 2020. Symptoms of novel coronavirus 2019-nCoV, Feb 10 [Accessed on 10 December 2020].

Chakraborty, I., Maity, P., 2020. COVID-19 outbreak: migration, effects on society, global environment and prevention. Sci. Total Environ. 728, 138882. https://doi.org/10.1016/j.scitotenv.2020.138882.

Corburn, J., Vlahov, D., Mbuu, B., Riley, L., Caifa, W.T., Rashid, S.F., 2020. Slum health: arrest COVID-19 and improving well-being in urban informal settlements. J. Urban Health 88, https://doi.org/10.1007/s11524-020-00438-6.

CPCB, Central Pollution Control Board, 2020. Generation of COVID19 Related Biomedical Waste in States/UTs. Central Pollution Control Board, Delhi [Accessed on 1 December 2020].

Dodge, Y., 2008. The Concise Encyclopedia of Statistics. Springer.

Ecochain, 2020. The rise of the face mask: what’s the environmental impact of 17 million N95 masks? ecochain.com/knowledge/footprint-face-maskscomparison. [Accessed 5th May 2021].

Eriksen, M., Mason, S., Wilson, S., Box, C., Zellers, A., Edwards, W., 2013. Micro-plastic pollution in the surface waters of the Laurentian Great Lakes. Mar. Pollut. Bull. 77, 177–182.

Fadare, O.O., Okolofo, E.D., 2020. Covid-19 faces masks: a potential source of microplastic gear, sparking fears of over-reliance on world’s workshop. N95 masks? ecochain.com/knowledge/footprint-face-maskscomparison. [Accessed 5th May 2021].

Fan, Y.V., Klemes, J.J., Walmsley, T.G., Bertok, B., 2020. Implementing Circular Economy in municipal solid waste treatment system using P-graph. Sci. Total Environ. 701, 134652.

Geyer, R., Jambeck, J.R., Kara, L.L., 2017. Production, use, and the fate of all plastics ever made. Science. Total Environment 701, 1–18.

Hartmann, N.B., Rist, S., Bodin, J., Jensen, L.H., Schmidt, S.N., Mayer, P., 2017. Microplastics as vectors for environmental contaminants: exploring sorptions, desorption, and transfer to biota. Integ. Environ. Assess. Manag. 13, 488–493. https://doi.org/10.1002/ieam.1904.

Heidari, M., Garnaik, P.P., Dutta, A., 2019. 11 - the influence of plastic via thermal means: industrial scale combustion methods. In: Al-Salem, S.M. (Ed.), Plastics to Energy. William Andrew Publishing, pp. 295–312 https://doi.org/10.1016/B978-0-12-813140-4.00011-X.

Hui, D.S., Azhar, E., Madani, T.A., Ntoumi, F., Rock, K., Dar, O., 2020. The continuing 2019-nCoV epidemic threat of novel coronaviruses to global health—The latest 2019 novel coronavirus pandemic. Science. Total Environment 736, 133981.
