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Review article

Plastic waste management during and post Covid19 pandemic: Challenges and strategies towards circular economy

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ABSTRACT

Global petroleum consumption suffered drastically as lockdowns were put in place to contain the Coronavirus Disease 2019 (COVID-19). As a result, oil costs dropped, making virgin plastics more cost-effective than recycled plastics. The usage of plastic has increased as a result of lifestyle modifications, cost-based incentives, and other factors, further obscuring the issue. The utilization of personal protective equipment (PPE) during the pandemic had resulted in a significant surge in the quantity of plastic waste. The plastic packaging industry achieved a revenue milestone of US$ 909.2 billion in 2021, boosting a compound annual growth rate of 5.5 %. The escalating dependence on plastics imposed additional pressure on waste management systems, which were proven to be ineffective and insufficient in addressing the issue. This situation exacerbated the problem and contributed to environmental pollution. Globally, 40 % of plastic waste ended up in landfills, 25 % was incinerated, 16 % was recycled, and the remaining 19 % infiltrated within the environment. By investing in circular technologies like feedstock recycling and enhancing infrastructural and environmental conditions, it expected to become viable to manage plastic waste flows during such a period of crisis. Investing in valorization strategies that transform plastic waste into value-added goods, such as fuels and building materials, receives a compelling macroeconomic signal when both plastic waste and plastic demand are on the rise. A robust circular economy can be accomplished by finalising the life cycle of plastic waste. The concept of Plastic Waste Footprint (PWF) aims to assess the environmental impact of plastic products throughout their intended usage period. In the midst of the emerging challenges in waste management during and post pandemic period, this research study has been conducted to explore the challenges and strategies associated with plastic waste in the environment.

1. Introduction

Governments, companies, and communities throughout the world have organized to tackle the problem of plastic pollution [1]. Social, technological, and institutional advancements such as i) restriction on single-use plastics; ii) businesses promising to minimize plastic waste; iii) several charitable organizations attempting to clean up beaches and oceans; iv) changes in public behaviour and all of these could lead to progressive outcomes in the foreseeable future [2,3]. Furthermore, the regulation of the trade in plastic waste has improved by legally-binding framework in the Basel Convention on Control of Transboundary Movements of Hazardous Waste and its Disposal, which was ratified by more than 180 countries in 2019 [4]. After the UN's declaration of polymer pollution, a number of

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businesses have modified their commercial strategy in order to get ready for the shift to a circular economy [5]. Lockdowns and the closing of dining venues (cafés, restaurants, etc.) have led to a rise in the transportation of meals and groceries, which has sparked the production of various plastic wastes including High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE), Polypropylene (PP), and Polyethylene Terephthalate (PET). During the COVID-19 pandemic, various types of plastics were extensively used in medical equipments to ensure safety and hygiene. High-density polyethylene (HDPE) and polypropylene emerged as commonly employed materials due to their durability, flexibility, and resistance to contamination. These plastics played a crucial role in the manufacturing of personal protective equipment (PPE), such as face shields, disposable gowns, and gloves, providing frontline healthcare workers with reliable protection. Additionally, polyvinyl chloride (PVC) was utilized in the production of medical tubing and components for devices like ventilators. The choice of using these plastics in medical equipment during the pandemic underscored the importance of materials that could meet stringent health standards while ensuring the effectiveness and reliability of essential medical tools.

Plastic waste from medical equipment poses a significant challenge due to its potential for contamination with infectious materials, necessitating careful disposal measures to prevent the spread of diseases. Plastic waste pollution poses extensive threats to ecosystems and human health. In marine environments, plastic debris entangles and endangers marine life, while ingestion of plastics by animals can lead to internal injuries and fatalities. Chemicals from plastics can leach into water, affecting aquatic organisms and disrupting ecosystems. Additionally, the specialized nature of medical plastics often makes recycling difficult, contributing to the environmental burden and raising concerns about long-term sustainability in healthcare waste management [6]. Human health is directly affected through exposure to plastic-derived chemicals, both from food chain contamination and direct contact. Microplastics in the air and drinking water also raise concerns. Beyond health impacts, plastic pollution has economic and societal consequences, with substantial costs for cleanup efforts, potential damage to tourism, and the depletion of natural resources. A comprehensive approach is essential to mitigate plastic pollution, encompassing reduced plastic usage, improved waste management, and the development of sustainable alternatives.

A sizable amount of plastic can be found in the personal protective equipment (PPE) used to guard against viral infections and transmission [7]. According to the World Health Organization, PPE manufacturing has increased by 40 % during the epidemic. It could be predicted that the pandemic might results into generation of 129 billion face masks and 65 million gloves (Assuming each human use one disposable mask per day) [8]. Various government organizations emphasize the importance of properly managing of both hazardous and non-hazardous waste to mitigate the adverse environmental effects [9,10]. In response to this, the research study has conducted comprehensive research on the management of plastic waste and delves into the concept of the plastic waste footprint (PWF) as a solution to address the challenges associated with burning plastic in the context of a circular economy.

2. Technologies involved in the treatment pathway of plastic waste

A number of countries, including China, India, Pakistan, and Bangladesh, have reported difficulties in managing the plastic trash generated by their citizens, especially during the unexpected surge in clinical wastes. Owing to the contagious nature of the COVID-19 virus, both frontline health professionals and the common people have had to adopt plastic-based Personal Protective Equipment (PPE) as a crucial measure to protect against viral infection. This increased necessity for essential PPE has led to a significant surge in demand resulting in extensive global-scale production and distribution of plastic materials [9]. According to the World Health Organization (WHO), there are around 80:20 non-hazardous to hazardous clinical waste materials. High levels of debris, pollution, heavy metals, natural and inorganic pollutants, and pollutants on the outer layer of plastic can cause organic pollution [10,11]. Plastic waste to energy refers to the process of converting plastic waste materials into useable energy through various technologies. This approach addresses two significant environmental challenges simultaneously: the proper disposal of plastic waste and the generation of renewable energy. The methods involved in treatment of plastic wastes are discussed briefly as [6] -

A) Sterilization technology
  - Sterilization of used and un-used medical equipment's (121 °C to 130 °C for 15–20 min at 15 lb pressure) to eliminate any microbial or endospore contaminations.
  - Eco-friendly and low-cost technique
  - Highly bacteriocidal

B) Chemical treatment:
  - Highly recommended in intensive medical care units
  - Chemicals like chlorine dioxide, sodium hypochlorite, ethylene oxide, formaldehyde etc. are used.
  - **Chlorine dioxide:** Has high oxidising power and therefore, can kill microorganism through wall damage.
  - **Ethylene oxide treatment:** Sanitization of clinical equipment's (Temp: 35-55 °C; Moisture content: 70–80 %; Duration: 5–10 h) including googles, PPE, gloves etc.
  - **Sodium hypochlorite treatment:** 5–10 % of chlorine gas; Used in decontamination of googles, PPE, gloves etc.

C) Microwave treatment
  - Utilization of electromagnetic wave of wavelength of 1–1000 mm and a frequency of 3000 MHz.
  - Innovative technology towards treatment of bio-hazardous wastes through legitimate inactivation of microbes.

D) Incineration and Pyrolysis

- **Incineration:** COVID wastes are burnt at high temperatures of at least 1100 °C. Dioxins and furans are released into the environment during incineration, which can cause endocrine disorders in animals alongwith generation of heat and this underlying biological principlescan be used to produce steam and drive turbines for electricity generation.
- **Pyrolysis:** Pyrolysis can be performed at temperatures ranging from 550 °C to 800 °C which involves numerous types of degradation processes such as plasma pyrolysis, laser-induced pyrolysis, and oxidation pyrolysis which makes it more technologically comprehensive method than incineration. Plasma pyrolysis efficiently breaks down dioxins by employing ignitable vapour in the combustion chamber at temperatures ranging from 900 to 1000 °C.
- LDPE: 350–500 °C for pyrolysis; 25–39 % oil yield; HDPE: 400–600 °C for pyrolysis; 27–70 % oil yield.

E) Gasification:
- Converts plastic waste into a synthesis gas (syngas) consisting of hydrogen and carbon monoxide.
- Syngas can be used as a fuel for electricity generation or converted into liquid fuels and chemicals.

Estimates for incineration and reprocessing climbed by roughly 0.7 percent per year annually between the years 1980 and 1990. In 2015, approximately 55 % of global trash made of plastic was dumped, 25 % was incinerated, and 20 % was reused. Upon extrapolation of such data to 2050, it shows an increase in the rate of incineration by 50 %, recycling by 44 % and dumping by 6 % [12]. While these technologies offer potential benefits in terms of waste reduction and energy generation, it's important to consider the environmental impact, energy efficiency, and economic feasibility of each method. Additionally, efforts should focus on reducing overall plastic consumption, promoting recycling, and developing sustainable alternatives to plastic to address the root causes of plastic pollution.

3. Plastic wastes: before and after covid 19 pandemic

The COVID-19 pandemic has brought attention back to the crucial function that plastic plays in our day-to-day lives. Plastics are produced with unrefined petroleum. Therefore, during the financial crisis of COVID-19, there has been a global decline in oil demand, which has led to a sharp drop in oil prices and thereby making virgin plastics more cost-effective than recycled plastics [13]. In addition, there has been a widespread lockdown, social isolation, travel and public gathering bans, constant hand sanitizer use, and the wearing of generally plastic-based personal protective equipment (PPEs) as defensive measures, such as surgical face masks, gloves for regular residents, protective clinical suits, aprons, and face shields for clinical health workers has unprecedentedly increase the consumption of plastics during the pandemic [14,15]. Low-density polyethylene (LDPE), polyurethane (PU), polycarbonate (PC), polypropylene (PP), and polyvinyl chloride (PVC) are commonly used in the production of Personal Protective Equipment (PPE) due to their specific properties: 1) **Low-density polyethylene (LDPE):** LDPE is flexible and resistant to moisture, making it suitable for items like gloves and protective aprons. 2) **Polyurethane (PU):** PU is known for its durability, flexibility, and ability to provide a protective barrier. It is often used in face shields, masks, and gloves. 3) **Polycarbonate (PC):** PC is valued for its optical clarity, high impact resistance, and ability to withstand high temperatures. It is commonly used in face shields and protective eyewear. 4) **Polypropylene (PP):** PP is lightweight with good chemical resistance, and is suitable for making items like masks and coveralls due to its breathability and barrier properties. 5) **Polyvinyl chloride (PVC):** PVC is often used in medical applications due to its chemical resistance and durability. It can be found in items like medical gloves and face shields. The selection of these polymers for PPE is based on the specific requirements of each type of equipment and the need for materials that provide protection, comfort, and durability [16]. Inspite of many limitations over the use of Single Use Plastics (SUP), the nationwide lockdown has imposed customers to get rely on online shopping and home delivery services for essential items which has surreptitiously increased the use of plastic-based packaging items like SUPs [17–20]. Such SUPs are mainly composed of organic compounds like high-density polyethylene (HDPE), low-density polyethylene (LDPE), polystyrene (PS), and polyethylene terephthalate.

Since 1950, there were 1.5 million metric tons (Mt) of plastic was produced which increased dramatically, reaching approximately 360 Mt in 2018 and exceeding 8.3 billion (bn) Mt globally. The production of plastic waste has significantly increased due to the growing use of Single-Use Plastics (SUPs), plastic-based packaging materials, and the heightened demand for medical Personal Protective Equipment (PPE) during the pandemic [21–23]. The WHO anticipated that during the COVID-19 pandemic, there would be a

Table 1
Estimated total plastic waste generation (tonnes) by continents during COVID-19 pandemic (June 2020).

Continents	Generation of estimated total plastic waste (Tonnes)	Estimated disposal of facemask (daily)	Per day estimated plastic waste generation (Tonnes)
Europe	56,072,702	445,022,934	153,623
Asia	348,079,108	1,875,181,681	953,641
Africa	100,544,861	411,814,854	275,465
North America	27,665,223	244,335,150	75,795
South America	49,046,434	380,414,703	134,373
Oceania	3,200,83	21,682,379	8769
Total	584,609,165	3,378,451,702	1,601,666

Data collected from https://www.worldometers.info/population/

monthly need for 76 million gloves, 89 million facial masks, 30 million gowns, 2.9 million hand sanitizers, coupled with 1.6 million goggles as protective measures for frontline health workers [24]. The monthly consumption of medical gloves and face masks for the 7.8 billion people throughout the world is 129 billion and 65 billion, respectively [25]. Global plastic garbage production is expected to be 1.6 million tons/day since the COVID-19 pandemic (Table 1). According to estimates, the COVID-19 pandemic is responsible for the daily disposal of almost 3.4 billion face shields or single-use facemasks. China, the world's most populous nation, is thought to generate almost 702 million disposable facemasks per day, and by the end of 2020, the amount of plastic garbage get intensified to 108 million tonnes. Asia is predicted to have the biggest daily per capita use of facemasks (1.8 billion) which is followed by Europe (445 million), Africa (411 million), Latin America and the Caribbean (380 million), and Asia (445 million). Around 22 million facemasks were manufactured daily by North America and Oceania countries which amounts to 244 million production. China, which has a population of 1.4 billion people, discards almost 702 million facemasks per day. The daily facemask disposal range estimates from 386 million in India (1.3 billion people), 219 million in the US (331 million people), 212 million in Brazil (212 million people), and 75 million in Nigeria (206 million people) [9,26,27]. The production of total plastic garbage and the daily use of COVID-19 facemasks by the top 35 nations are depicted in Table 2. It can be inferred that the fluctuation in daily face mask consumption is influenced by factors including population size, the prevalence of COVID cases, public perception shaped by literacy levels and mass campaigns that influence the acceptance rate of face masks, and the average daily usage per capita.

The biomedical waste (BMW) generation in India surrounds over 2907 hospitals, 20,707 quarantine centres, 1539 sample collecting centres, and 264 pathological labs during COVID-19 [28]. The RT-PCR (Reverse Transcription-Polymerase Chain Reaction) tests used in every 1000 coronavirus testing samples generate around 22 kg of plastic trash which amounts to generation of 14.5 tpd (Tonnes per day) of plastic garbage in India. The Covid-19 pandemic caused about 609 tpd of regular biomedical waste and 101 tpd of

Table 2
Estimation of total global plastic waste and daily facemask generation by counties during COVID-19 pandemic (June 2020).

Country	Population	Total COVID-19 cases	Total daily face mask use (pieces)	Medical waste (tons/day)
Afghanistan	3,89,92,638	36,542	1,95,89,901	144.34
Armenia	29,63,706	38,196	21,14,901	150.87
Azerbaijan	1,01,46,497	31,560	17,12,729	124.66
Bahrain	17,05,531	40,755	3,43,835	160.98
Bangladesh	16,48,20,045	2,34,889	9,91,55,739	927.81
Bhutan	7,72,280	101	2,78,639	0.4
Brunei	4,37,813	141	2,76,698	0.56
Cambodia	1,67,36,949	234	31,86,715	0.92
China	1,43,93,23,776	84,292	98,91,03,299	332.95
Hong Kong	75,01,879	3152	47,11,180	12.45
India	1,38,10,85,714	16,43,416	38,11,79,657	6491.49
Indonesia	27,37,53,080	1,06,336	15,92,14,791	420.03
Iran	8,40,77,062	3,01,530	5,06,48,022	1191.04
Iraq	4,02,88,721	1,21,263	3,09,73,969	478.99
Israel	91,97,590	70,379	73,58,072	278
Japan	12,64,43,231	33,049	9,27,58,754	130.54
Jordan	1,02,11,202	1191	74,25,586	4.7
Kazakhstan	1,87,94,372	89,078	86,75,482	351.86
Kuwait	42,75,450	66,529	29,41,510	262.79
Lebanon	68,22,802	4334	27,56,412	17.12
Macao	6,50,024	46	5,20,019	0.18
Malaysia	3,23,98,441	8964	70,49,901	35.41
Maldives	5,41,266	3719	1,48,090	14.69
Mongolia	32,82,334	291	17,67,209	1.15
Myanmar	5,44,39,424	353	1,35,00,977	1.39
Nepal	2,91,76,450	19,547	1,90,46,387	77.21
Pakistan	22,12,13,683	2,78,305	6,17,62,860	1099.30
Palestine	51,10,066	11,548	31,80,505	45.61
Philippines	10,96,94,822	89,374	4,89,67,769	353.03
Qatar	28,07,805	1,10,460	13,41,008	436.32
Saudi Arabia	3,48,55,542	2,74,219	2,33,67,155	1083.17
Singapore	58,54,053	51,809	43,64,782	204.65
South Korea	5,12,72,891	14,305	1,45,61,501	56.5
Sri Lanka	2,14,20,649	2814	1,71,36,519	11.12
Syria	1,75,31,446	738	1,10,09,748	2.92
Taiwan	2,38,20,377	467	70,50,832	1.84
Tajikistan	95,53,361	7366	60,83,580	29.1
Thailand	6,98,14,554	3310	1,02,20,851	13.07
Turkey	8,44,10,984	2,29,891	2,60,66,112	908.07
United Arab Emirates	98,99,794	60,223	79,19,835	237.88
Uzbekistan	3,35,06,746	23,558	1,34,56,309	93.05
Vietnam	9,74,08,737	509	4,62,88,632	2.01
Yemen	2,98,74,304	1726	90,33,990	6.82

Data collected from https://www.worldometers.info/population biomedical waste with plastic trash to be produced in India [28]. (Fig. 1).

Pandemic lockdowns have forced people to turn to online shopping and home delivery for essential goods, including food. This shift has led to a rise in demand for single-use plastic (SUP) delivery packages and other types of plastic packaging. When a pandemic strikes, customers frequently shift their behaviour and demand, stockpiling food items, making panic purchases, and hoarding supplies of food. This leads to an increase in the use and production of plastic-based packaging materials in various countries [17,18,20]. According to estimates, Spain's and the US's respective sales growth rates may raise plastic output and consumption by 40 % and 14 %, respectively [22]. A annual growth rate of 5.5%is projected for plastic packaging, which is expected to expand from USD 909.2 billion in 2019 to USD 1012.6 billion by 2021 due to the impact of the Coronavirus pandemic on the use of plastic-based products [29].

Many nations, including the UK, the US, Portugal, and Canada, temporarily postponed their SUP bans during the COVID-19 pandemic as a precaution against cross-infection brought on by the reuse of plastic objects and containers, as encouraged by the plastics industry. During the pandemic-induced lockdowns, transportation-related activities get decreased which leads to a sharp drop in the cost of producing plastic due to the collapse in petroleum oil prices. This led to a significant increase in the supply and manufacturing of plastic goods to meet public demand [30]. As a result, during the COVID-19 pandemic, plastic-related companies chose plastic manufacture over plastic recycling as the most economically feasible technique.

4. Impact of plastic wastes on environment

Plastic management has been recognized as a critical environmental issue even before the COVID-19 pandemic due to growing awareness of marine and terrestrial contamination. The use of plastic in various forms, including personal protective equipment (PPE), has played a crucial role in safeguarding frontline healthcare providers and the general public during the epidemic [31]. Concern over the astonishing rise of single-use plastics (SUPs), such as surgical masks, medical gloves, protective clinical aprons, hand sanitizer packs, food and supermarket packaging has grown since the onset of the coronavirus pandemic [32–35]. Single-use plastics that have been used once and discarded are visible all over the place, including in parking lots, seashores, sewers, hospitals, and shopping carts [36,37]. The amount of plastic waste from the Coronavirus pandemic is increasing rapidly, posing a challenge to current waste management systems and the healthcare sector. Existing waste management systems have struggled to effectively handle the growing volume of plastic waste.

The most popular methods of managing plastic wastes include mechanical recycling, burning, and sanitary landfilling [38]. According to estimates, 16 % of all plastic garbage was recycled, 25 % was burned, 40 % was dumped, and the other 19 % was released into the environment due to poor management [39]. However, the surge in garbage generation during the COVID-19 pandemic exacerbates the situation, diminishing the likelihood that these techniques alone would fully address the challenge of managing residual plastic waste.

The main obstacles to mechanical recycling of plastic wastes include cross-contamination of polymers, the presence of additional materials, the existence of inorganic contaminants, insufficient segregation at the source, and partial polymer degeneration [40].

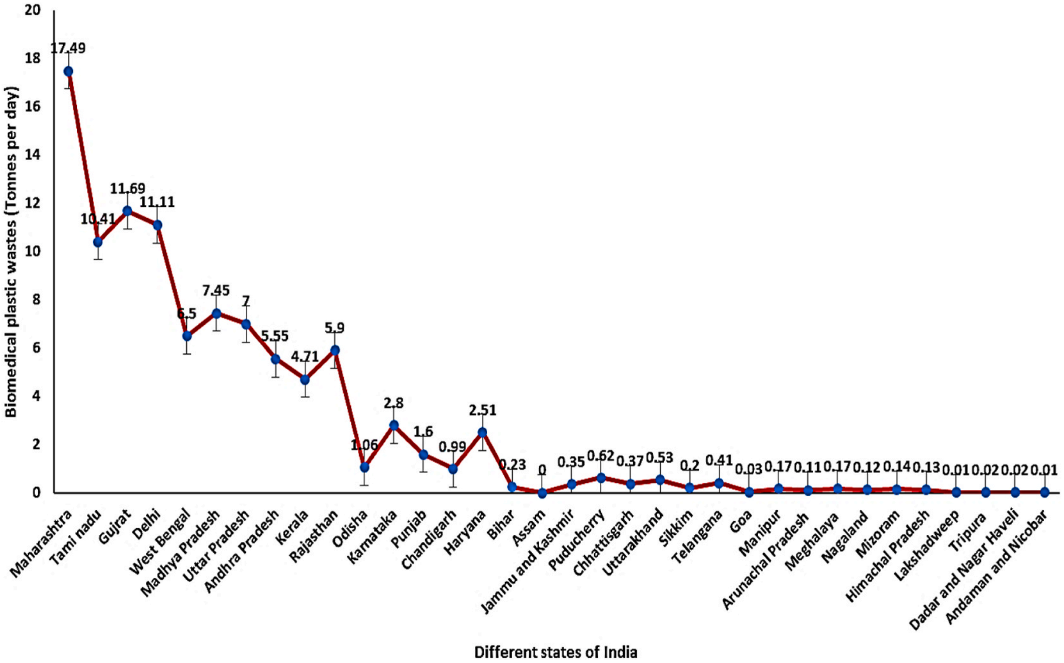

Fig. 1. Daily average biomedical waste containing plastic waste generation in India (state-wise) during COVID-19 pandemic. Error bars represent the percentage error at 5 %. Data collected from CPCB (2020b).

Single-stream plastics with little impurity, such as Polyethylene Terephthalate (PET) bottles, have been successfully recycled in manufacturing processes with approximately 80 % recycling rates in several countries (including India) [41]. Multi-layered plastics are challenging to recycle primarily due to their complex composition. These plastics often consist of different layers of materials, each with its own set of properties and characteristics. The layers may include various types of plastics, metals, and other materials, making the separation and processing during recycling more difficult [42]. The multiple layers are often tightly bonded together, making it labor-intensive and technically challenging to segregate and recycle each component effectively. This complexity in composition and the intricate separation process reduce the economic viability of recycling multi-layered plastics, contributing to their difficulty in the recycling process. As a result, these plastics often end up in landfills or incineration facilities, causing environmental concerns due to the persistence of plastic waste. However, the pandemic-related decrease in oil prices, combined with technological constraints and high pre-processing costs, led to a substantial reduction in the production cost of new plastic. This, in turn, had a notable impact on recycling efforts in many countries [43,44]. Also, the industry for recycling plastic garbage has been impacted by a lack of workers due to concern over the COVID-19 infection during the time of waste collection and handling as well as restricted transportation [45].

The incineration of plastic-based personal protective equipment (PPE) and other contaminated plastic waste has been mandated by WHO [46]. The traditional incineration method is inadequate to address the staggering rise in plastic waste production. The accumulation of around 240 tonnes of medical wastes has been estimated in Wuhan per day, where China has the highest incineration capacity of 49 tonnes per day [13]. According to British Gas Lurgi (BGL), improper and poorly managed incineration techniques generate hazardous toxins such as dioxins and furans, leading to air pollution. Dioxins and furans are known to disrupt the normal functioning of the immune system, making it less effective in defending the body against infections and diseases. Additionally, these toxins can interfere with the endocrine system, which regulates hormones that control various physiological processes. Disruption of the endocrine system may lead to hormonal imbalances, affecting growth, development, metabolism, and reproductive functions. The damaging effects on the immune and endocrine systems can result in a range of health problems, including increased susceptibility to illnesses, developmental issues, and reproductive complications. Therefore, controlling and improving incineration techniques is crucial to mitigate the release of these harmful substances and protect human health. The inefficient incineration of plastic garbage alone resulted in the release of 5.9 million metric tons of CO_2 emissions in the United States and 16 million metric tons of CO_2-like greenhouse gases globally in 2015 [47]. The World Health Organization (WHO) ordered a 40 % increase in plastic manufacturing during the Coronavirus pandemic to meet the rising global demand for plastic, which ultimately ends up in the waste stream [24].

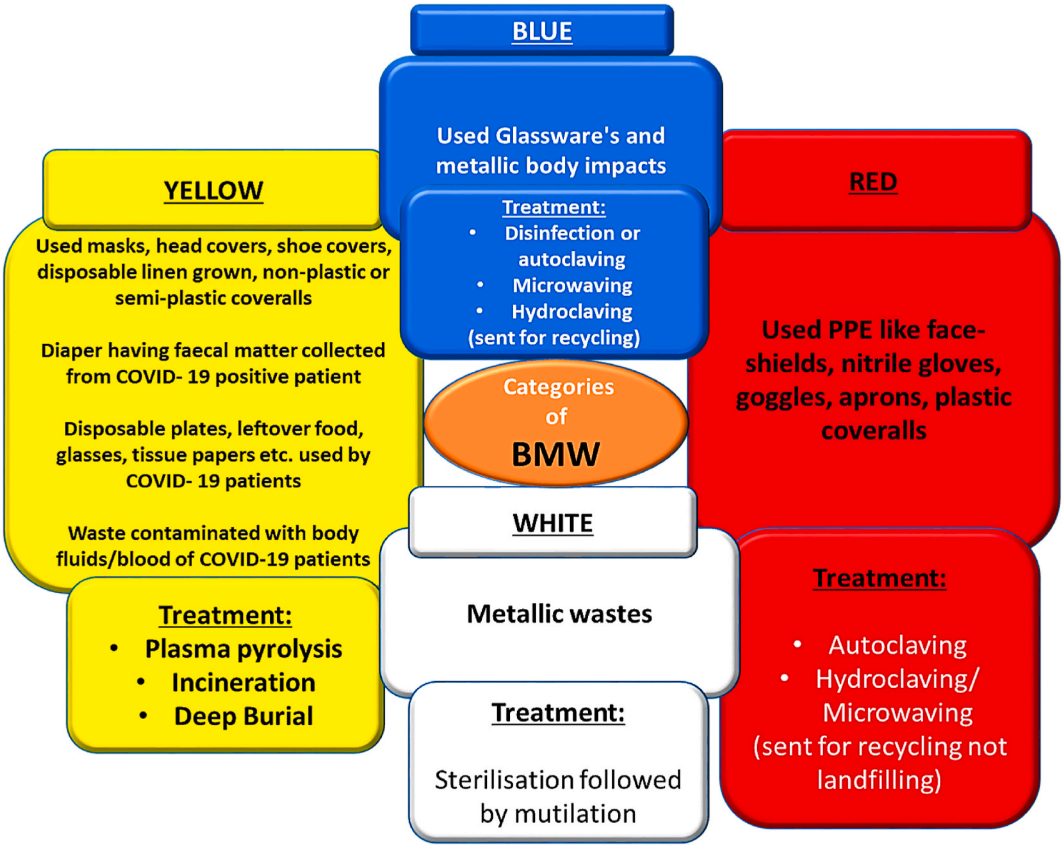

Fig. 2. Segregation of different types of solid wastes and treatment methodologies (Colors are used as suggested by CPCB 2020) (Adapted from Ganguly and Chakraborty, 2021; https://doi.org/10.1016/j.cscee.2021.100087)

Ineffective recycling practices increase the amount of plastic garbage that is burned, which eventually results in greenhouse gas emissions that contribute to global warming.

In many poor countries, people often prefer dumping plastic waste in landfills, even though it's not the best option. After the pandemic, there's been a global increase in poorly managed dumping. This causes leaching of harmful substances which create pollution and health risks. It emphasizes the need for better waste management in these areas [48]. Open surface burning in landfills also releases dangerous air pollutants such furans and dioxins [47]. Increased production of plastic waste, a compromised recycling sector, and capacity constraints in incineration have collectively resulted in mounting plastic waste loads at dumpsites. This situation has pushed landfills to their maximum capacity (Fig. 2.). Also, during the COVID-19 epidemic, ineffective application of environmental legislation along with the inefficiency and inadequacy of standard plastic waste management systems generated major environmental dangers.

During Covid-19 pandemic, improper disposal of PPE, like masks and gloves, occurs for several reasons. One primary factor is the increased usage of disposable PPE during the pandemic, leading to a surge in the quantity of discarded items. Many people may not be aware of the correct disposal methods for PPE, contributing to improper disposal. Inadequate waste management infrastructure and systems can also play a role. Lack of convenient and accessible disposal options may prompt individuals to dispose of PPE improperly. Once improperly discarded, PPE, along with other plastic waste, can find its way into rivers and waterways. Rainfall and wind can transport this waste to the ocean, causing marine pollution. This uncontrolled disposal poses environmental risks and threatens marine life, highlighting the need for proper PPE disposal practices and improved waste management systems [49–51]. It's estimated that about 270,000 tons of various-sized plastic pieces are now in the world's water surfaces [52] (Fig. 3.). Marine plastic pollution is primarily caused by widespread mishandling of plastic waste throughout the global supply chain. The problem is exacerbated by inadequate waste disposal practices, a lack of sufficient recycling infrastructure, and the pervasive use of single-use plastics. Coastal areas face additional challenges due to storm water runoff and improper waste disposal. The discarded plastic particles are broken down into nano- or micro-plastic like smaller fragments that infect the marine and terrestrial environment by a variety of ecological factors such as wind speed, sunlight, UV radiation, and physical environmental processes [53].

During the Coronavirus pandemic, the usage of facemasks and other single-use plastics (SUPs) has been increased dramatically which aggravate the plastic waste management system leading towards the production of smaller microplastics which have an adverse effect on the aquatic ecology (Fig. 4). Plastic-based packaging materials and surgical masks include polymeric components are the significant source of microplastic contamination globally [49,54]. Plastic garbage that is improperly disposed contaminates the environment, groundwater, and living things. During the COVID-19 pandemic, improper landfill practices and the increasing leakage of environmental plastic waste have intensified microplastic contamination. The Personal Protective Equipment (PPE) and

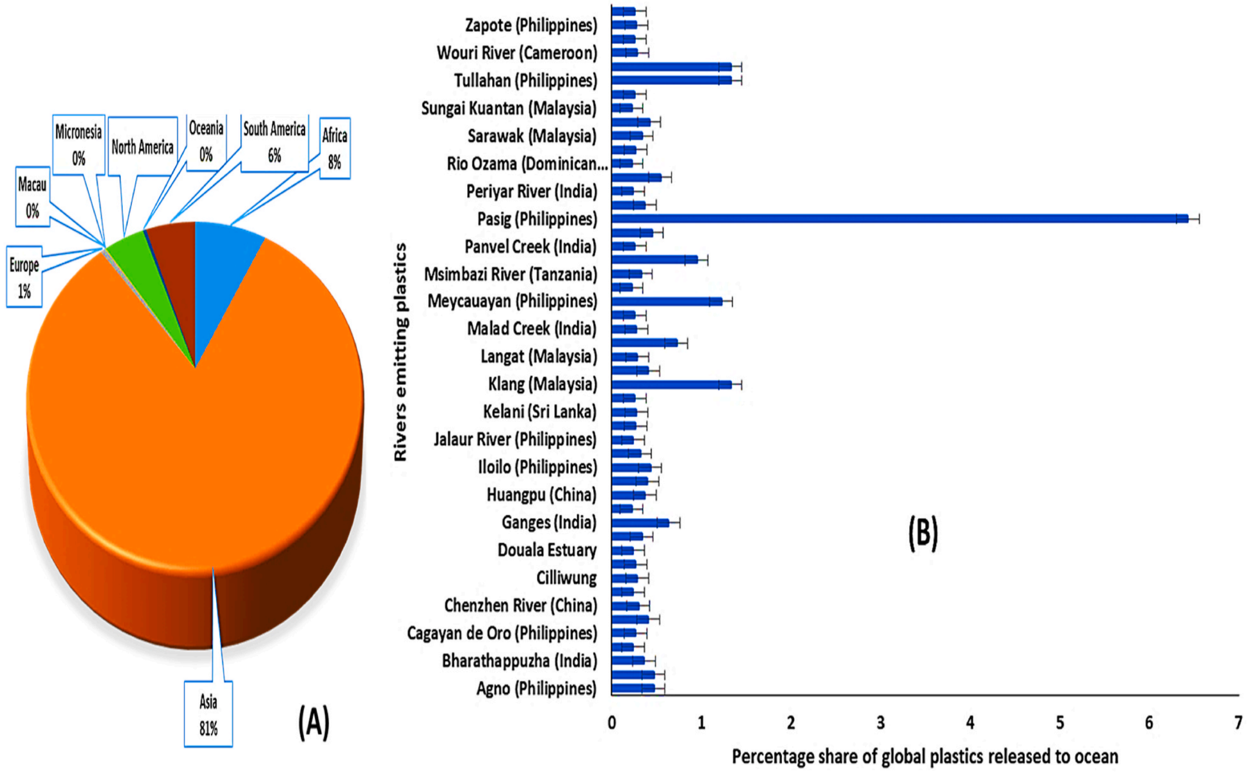

Fig. 3. (A) represents the amount of plastic wastes emitted to ocean by different countries. (B) Represents the contribution of rivers in releasing plastics to ocean. Error bars represent the percentage error at 5 % (Data adapted from Meijer et al., 2021).

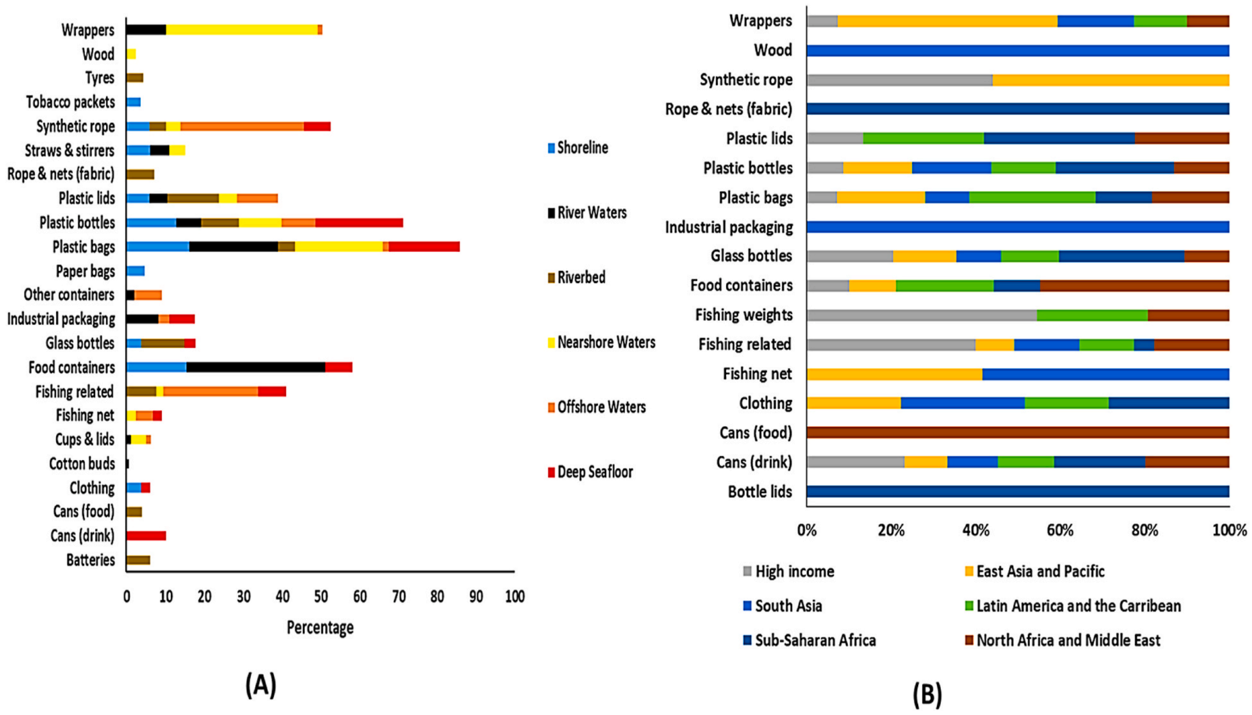

Fig. 4. (A) represents different plastic items found in different regions of aquatic ecosystem; (B) represents the plastic wastes generated by different countries (Data adapted from Morales-Caselles et al., 2021).

microplastics are inadvertently ingested by various marine creatures, including fish and sea turtles, posing a significant threat to the food chain. This situation has long-term consequences on the entire ecosystem [9,49].

5. Plastic waste footprint and circular economy

Hospitalization, manufacturing of disinfectants, personal protective equipment (PPE) like masks and gloves along with their

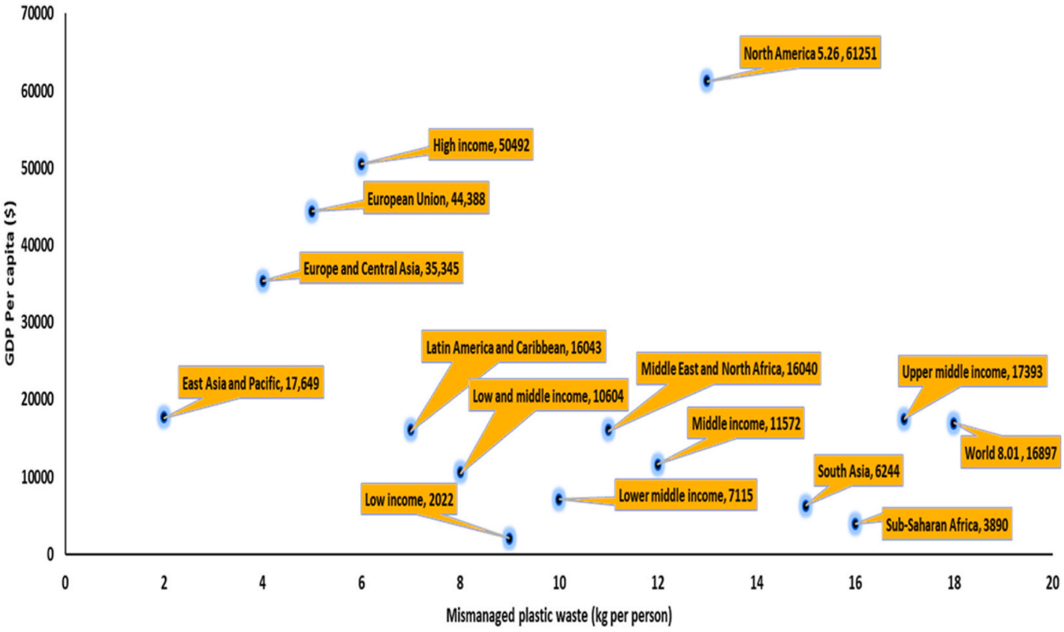

Fig. 5. Generation of mismanaged plastic wastes by different countries (Adapted from Meijer et al., 2021).

transportation became significantly costly during the COVID-19 pandemic. However, one positive aspect was the reduction in the environmental pollutants which have positive impact on healthcare. This was achieved by lowering the energy consumption in the production of PPE, masks, gloves, disinfectants, and their transportation. The pandemic prompted a revaluation of healthcare practices, fostering efforts to make these processes more environmentally sustainable [55]. The N-95 mask generates 0.05 kg CO_2 eq/single-use and 0.06 kg CO_2 eq/single-use of its manufacture, whereas surgery masks emit the most during their transit, according to Ecochain, 2020 [56,57]. According to Technavo, the market for disinfectants is anticipated to grow by 12 % between 2020 and 2024 [58]. Due to the fragility of plastics, many countries have either partially or entirely prohibited the use of plastic bags, while promoting the adoption of paper bags or reusable alternatives. As a result, the Plastic Waste Footprint (PWF) serves as a tool to estimate the quantity of plastic waste generated by various localities, states, and countries.

India is the only nation that has witnessed a COVID-19-related influx of plastic medical waste (26,453.50 tons/day) among the most COVID-19-affected countries across the world. In Maharashtra state, where COVID-19 is expected to be common from June to November 2020, there is a large per capita usage of medical plastics. Mumbai, being a globally significant metropolis with high population density has also experiencedextensive interaction and communication among its residents with regard to the mode of usage and disposal of pollutants. The community has actively worked to mitigate the impact of the pandemic. With the swift increase in Single-Use Plastics (SUPs), Medical Pathology Waste (MPWs), and Municipal Solid Wastes (MSWs), it is crucial for both national and local governments to promptly monitor and regulate plastic consumption in the region. Several Indian states, such as Goa, Andaman Nicobar, Arunachal Pradesh, Lakshadweep, Mizoram, Nagaland, and Sikkim, did not use the CBWTF system (Common Biomedical Management Waste Treatment Facility). The amount of medical biowaste (BMW) has increased 15-fold since the advent of COVID-19 [59].

The global environment would face significant peril if medical waste in a metropolis were to reach 10 tonnes per day. To mitigate this, PPEs, surgical instruments, and N95 masks can be effectively sanitized using methods such as UV-C light, ozone (O3), ionized hydrogen peroxide (H_2O_2), temperature, or heat. This approach aims to maximize reuse and minimize the generation of waste [60]. In most of the developing countries, availability of incinerator is not well developed owing to its high market price and hence, majority of the wastes are used in uncontrolled landfills. Such mismanaged wastes impart toxicity to environment (Fig. 5). Planning and reducing the negative environmental effects of SUPs, PPEs, and MPW are possible through environmental impact assessment (EIS) and life cycle assessment (LCA). The relationship between production and management significantly influences the recycling of plastic waste. This dynamic management process is influenced by external factors like oil prices, delays in implementing bans, and the adoption of policies can create negative consequences. For instance, replacing single-use plastic (SUP) bags with bio-based, biodegradable alternatives can have unintended drawbacks. Understanding and navigating these interconnected factors is crucial for effective plastic waste

Table 3
Different guidelines used by the agencies to mitigate Covid waste.

WHO (World Health Organization):	The WHO recommends segregating hazardous biomedical waste at the source, such as hospitals, using appropriately colored bins. Infectious waste generated during patient treatment can be disposed of on-site through high-temperature treatment, autoclaving, or incineration. Waste from healthcare waiting areas, deemed non-hazardous, should be placed in black bags, sealed, and, if waste removal facilities are unavailable, controlled burning is suggested.
CPCB (Central Pollution Control Board, INDIA):	The CPCB advocates for the use of color-coded bags and containers for the proper segregation of Covid waste. Covid waste should be temporarily stored in a designated room before being handed over to the Common Biomedical Waste Treatment Facility (CBWTF). General or non-hazardous waste should be disposed of following standard solid waste disposal protocols.
EU (European Union):	Individual waste bags for patients, containing infected items such as paper tissues, face masks, and gloves, are recommended, followed by proper closure. Waste bags, once filled, can be collected and placed in a general waste bag without necessitating special collection activities.
SNPA (National System for Environmental Protection):	The municipal waste is categorized into two domains - T1 includes municipal solid waste from households with Covid-19 positive patients, requiring double-layered bags and complete sterilization. T2 comprises household waste from negative Covid-19 individuals or quarantine houses, allowing sanitary workers, equipped with proper PPE, to collect them in double-layered bags.
OSHA (Occupational Safety and Health Administration, US):	In handling SARS-CoV-2 contaminated waste, sanitation workers are advised to utilize standard personal protective equipment (PPE) and manage it similarly to other non-infectious waste. Biomedical waste from Covid wards should follow the procedures outlined for regulated medical waste, as Covid-19 does not fall under the category of a Class A infection.
Environmental Protection Agency (EPA):	In the United States, the EPA provides guidelines for managing household hazardous waste, including materials potentially contaminated with the virus. The EPA emphasizes the importance of proper disposal methods for items like used masks and gloves, encouraging households to follow local waste management regulations.
Centres for Disease Control and Prevention (CDC):	In the United States, the CDC provides specific guidelines for healthcare facilities on managing COVID-19-related waste. The guidelines address the safe handling and disposal of waste, emphasizing the use of standard precautions and personal protective equipment (PPE). CDC guidelines include recommendations for the disinfection of waste and highlight the importance of training healthcare personnel in proper waste management procedures.
European Centre for Disease Prevention and Control (ECDC):	Recommendations include the safe disposal of contaminated materials, the use of appropriate PPE during waste handling, and ensuring that waste management practices align with public health priorities.

Data obtained from Ganguly and Chakraborty, 2021.

management [61].

The selection and execution of policy instruments that provide the most effective ways of achieving objectives will determine the establishment of favourable circumstances for plastic waste recycling and an improvement in plastic waste recycling rates (Table 3) (Iacovidou et al., 2020a). Achieving the sustainability in respect of plastics demands, a paradigm shift in the pattern of commodity requirement has been resulted. This entails scrutinizing stakeholder relationships, placing emphasis on connections within the plastic system, and comprehending the intricate cause-and-effect relationships. Such an approach is vital for guiding well-targeted and well-informed policymaking processes that address the complexities inherent in the plastic ecosystem [62,63]. A discussion regarding what should be "preserved" should be sparked by its “complex value” in terms of sustainability. Complex value refers to the measurable positive and negative impacts on the environment, economy, society, and technology which are influenced by socio-economic and political factors. Life Cycle Assessment (LCA), Ecologically Extended Input-Output Analysis (EEIOA), Cost-Benefit Analysis (CBA), and Multi-Criteria Decision Analysis (MCDA) play crucial roles in plastic waste management as follows [64].

1. Life Cycle Assessment (LCA): LCA evaluates the environmental impacts of a product or system throughout its entire life cycle. In plastic waste management, LCA helps assess the environmental footprint of different waste treatment options, from production to disposal, allowing for informed decision-making on more sustainable practices.
2. Ecologically Extended Input-Output Analysis (EEIOA): EEIOA extends traditional input-output analysis to include environmental impacts. It quantifies the direct and indirect environmental effects of economic activities. In plastic waste management, EEIOA aids in understanding the broader ecological consequences of different waste management strategies and their implications on various sectors of the economy.
3. Cost-Benefit Analysis (CBA): CBA evaluates the economic feasibility of different projects or policies by comparing their costs and benefits. In plastic waste management, CBA helps assess the financial implications of adopting specific waste treatment methods, taking into account both economic costs and the monetary valuation of environmental and social benefits.
4. Multi-Criteria Decision Analysis (MCDA): MCDA involves evaluating alternatives based on multiple criteria and objectives. In plastic waste management, MCDA assists in considering diverse factors such as environmental impact, economic feasibility, social implications, and public acceptance. It provides a systematic approach to decision-making that considers various perspectives and trade-offs.

In a synergistic model, the four methodologies can be integrated as follows.

- Initial Assessment (LCA): Conduct a life cycle assessment to understand the environmental impacts of different plastic waste management options.
- Expand the Scope (EEIOA): Use EEIOA to extend the analysis to the broader economic context, identifying indirect environmental impacts and interconnections.
- Economic Evaluation (CBA): Perform cost-benefit analysis to evaluate the economic feasibility of each waste management strategy, considering both monetary and non-monetary values.
- Multi-Criteria Decision Analysis (MCDA): Apply MCDA to integrate environmental, economic, and social criteria, allowing for a comprehensive evaluation and ranking of alternative plastic waste management approaches.

This synergistic model ensures a holistic and informed decision-making process, considering the intricate relationships between economic, environmental, and social aspects in plastic waste management.

The CVORR (Complex Value Optimization for Resource Recovery) is a distinctive tool that provides a systematic process for users, including legislators, decision-makers, and practitioners. It guides them in embracing all practices, structures, and values associated with a resource recovery system, specifically within the entire plastics value chain. In the context of the circular economy, the analysis of capital inflows, including financial inflows, assets, trade, infrastructure, acquisitions, expenses, and profits, is closely aligned with modeling material flows across the manufacturing, consumption, and maintenance phases. The prospect of a circular economy involves the development of efficient valorization technologies, achieved through mechanical or chemical recycling of plastic wastes. This process can result in the production of fuels, road construction materials, bricks, and various other value-added substances, contributing to the enhancement of the circular economy. The CVORR technique identifies five knowledge domains, referred to as the five degrees of information, to help uncover opportunities and obstacles in sustainable practices within the plastics system. These levels of information are integrated and interwoven. For example, as part of the new Ocean Plastics Initiative, the United States International Development Financing Corporation (DFC) has allocated a $2.5 billion economic stimulus. This funding aims to reduce the flow of plastic waste and marine litter into water bodies and oceans. The Ocean Plastics Initiative encourages private sector investment in projects that promote effective waste management, recycling, and infrastructure upgrades in underdeveloped countries [65]. Nevertheless, few countries have the financial resources necessary to achieve these goals. Many developing nations lack both the necessary infrastructure and the financial means to construct it. It is estimated that 3.5 billion people globally do not have access to garbage disposal services offered by the government [66,67].

The production of solid waste globally is expected to increase by 70–75 % by 2025 [67], which would put all governments of the world under pressure. This situation is made worse by this prediction. Several international organizations like The World Bank allocate billions of dollars for the development of garbage disposal infrastructure. Despite the potential of Extended Producer Responsibility (EPR) legislation to sustain ongoing investment in the domestic plastic recycling industry, additional incentives are deemed essential. In May 2019, a significant global shift occurred as the majority adopted a regulated model for global commerce. As part of this shift, Polypropylene (“PP") waste was included in the materials requiring proper transfer and disposal under the Basel Convention. The Basel Convention is designed to promote waste reduction and environmentally responsible waste disposal. It stands as the only globally binding instrument with a constitutional mandate to safeguard human health and the environment. The convention achieves this by regulating the transboundary movement of both toxic and non-hazardous wastes. Moving any kind of plastic garbage outside of its nation of origin is now against the law. The Basel Convention (May 2019) on Sustainable Development unanimously endorsed the Plastic Waste Amendments in May 2019, which build new plastic waste categories in Annex II, Annex VIII, and Annex IX. The Convention distinguishes three forms of waste when it comes to transboundary waste transfers. The Plastic Waste Amendments added additional entries to each of the Annexes that were influenced by.

- Annexe II includes various types of waste that require special care.
- Annex VIII incorporates hazardous plastic wastes.
- Annexe IX contains a list of wastes that aren’t deemed dangerous.

The newly added category includes nonhazardous plastic garbage as long as it is planned for reprocessing in a sustainable way and is practically free of contaminants alongside other types of debris. Non-hazardous recyclable plastics mentioned in Annex IX may be transferred between Parties without restriction under the Convention. For example, waste from low-density polyester and other polymers used in manufacturing are deemed non-hazardous and hence exempted from specialized supervision if it is headed for environmentally sound management (ESM).

The SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) method is a valuable tool for assessing the current state and future prospects of plastic waste management (Ławińska et al., 2022).

- **Strengths:**
  1. Recycling Infrastructure: Regions with well-established recycling facilities have a strength in efficiently managing plastic waste.
  2. Technological Advancements: Innovations in waste-to-energy technologies and new recycling methods can enhance the efficiency of plastic waste management.
  3. Public Awareness: Increasing awareness about plastic pollution and the importance of recycling can garner public support for effective waste management initiatives.
- **Weaknesses:**
  1. Limited Recycling Capacity: Inadequate infrastructure and technology may limit the capacity to recycle certain types of plastics.
  2. Single-Use Plastics: The prevalence of single-use plastics poses a challenge, as they are harder to recycle and often end up as pollution.
  3. Policy Gaps: Weak regulatory frameworks and enforcement can impede the implementation of effective waste management practices.
- **Opportunities:**
  1. Circular Economy Initiatives: Embracing a circular economy model can create opportunities for reducing plastic waste by promoting recycling and reuse.
  2. Innovative Technologies: Investment in research and development of advanced recycling technologies can open new avenues for sustainable waste management.
  3. Public and Private Partnerships: Collaboration between governments, businesses, and communities can lead to comprehensive and effective plastic waste management solutions.
- **Threats:**
  1. Increasing Plastic Production: The continuous production of single-use plastics exacerbates the challenge of managing plastic waste.
  2. Lack of Global Coordination: The lack of international cooperation in addressing plastic pollution can hinder effective waste management efforts.
  3. Environmental Impact: The environmental consequences of improper plastic waste disposal, such as ocean pollution and harm to wildlife, pose significant threats to ecosystems.

A thorough SWOT analysis can guide stakeholders in developing strategies that leverage strengths, address weaknesses, capitalize on opportunities, and mitigate threats to create a more effective and sustainable plastic waste management system.

6. Conclusion

The COVID-19 epidemic showed the plastic recycling sector’s susceptibility to macroeconomic shocks when recycled plastic demand declined drastically because lowering of oil prices that made the manufacture of virgin plastic resin less expensive. A multifaceted framework is required that integrates different policies for effective plastic waste management as follows.

- **Regulatory Policies:**
  1. Plastic Bans:

Objective: Prohibit or restrict the use of specific types of single-use plastics.

Implementation: Enforce bans on plastic bags, straws, and other non-essential single-use items.
Impact: Reduces the generation of plastic waste at the source.

2. Extended Producer Responsibility (EPR):

   Objective: Hold producers responsible for the entire lifecycle of their products, including disposal.
   Implementation: Implement a system where producers contribute to the collection and recycling of their products.
   Impact: Encourages producers to design more sustainable and recyclable packaging.

3. Deposit Return Systems:

   Objective: Encourage the return of plastic containers for recycling by offering a monetary deposit.
   Implementation: Establish collection points where consumers can return plastic bottles for a refund.
   Impact: Increases recycling rates and reduces litter.

- **Incentive-based Policies:**
  1. Tax Incentives for Recycling Industries:

  Objective: Encourage the growth of recycling infrastructure and industries.
  Implementation: Provide tax breaks or other financial incentives for businesses involved in plastic recycling.
  Impact: Boosts recycling capacity and creates economic opportunities.

2. Consumer Awareness Programs:

   Objective: Educate the public about the environmental impact of plastic and promote sustainable alternatives.
   Implementation: Launch campaigns, workshops, and educational programs.
   Impact: Encourages responsible consumption and waste reduction.

- **Technological and Innovation Policies:**
  1. Research and Development Grants:

  Objective: Foster innovation in plastic alternatives and recycling technologies.
  Implementation: Provide grants to researchers and businesses working on sustainable solutions.
  Impact: Accelerates the development of new technologies.

2. Plastic-to-Fuel Conversion Facilities:

   Objective: Convert plastic waste into energy through advanced technologies.
   Implementation: Invest in facilities that can convert non-recyclable plastics into fuels.
   Impact: Reduces the amount of plastic in landfills and provides an alternative energy source.

- **Community Engagement Policies:**
  1. Community Clean-up Initiatives:

  Objective: Mobilize communities to participate in plastic cleanup activities.
  Implementation: Organize regular cleanup events and provide resources for local initiatives.
  Impact: Reduces plastic pollution and fosters a sense of responsibility.

2. Community Recycling Centres:

   Objective: Improve accessibility to recycling facilities, especially in underserved areas.
   Implementation: Establish community recycling centres with convenient drop-off points.
   Impact: Increases recycling rates and promotes community involvement.

- **International Cooperation:**
  1. Global Plastic Agreements:

  Objective: Collaborate with other nations to address the transboundary nature of plastic pollution.
  Implementation: Participate in international agreements and partnerships for shared responsibility.
  Impact: Enhances global efforts to combat plastic pollution.
  Integration of these policies could create a comprehensive and adaptive framework for plastic waste management, addressing

issues from the legislative level down to community engagement. The success of such a model depends on effective implementation, continuous evaluation, and adjustments based on evolving technologies and social behaviours.

CRediT authorship contribution statement

Ram Kumar Ganguly: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Susanta Kumar Chakraborty:** Writing – review & editing, Investigation.

Declaration of competing interest

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

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Abbreviations

PPE	Personal Protective Equipment
PWF	Plastic Waste Footprint
SUP	Single Use Plastic
MPW	Medical Pathology Waste
MSW	Municipal Solid Wastes
CBWTF	Common Biomedical Management Waste Treatment Facility
EIS	Environmental Impact Assessment
LCA	Life Cycle Assessment
EEIOA	Ecologically Extended Input-Output Analysis
MCDA	Multi-Criteria Decision Analysis
CVORR	Complex Value Optimization for Resource Recovery

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