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## Review

# Plastic wastes in the time of COVID-19: Their environmental hazards and implications for sustainable energy resilience and circular bio-economies



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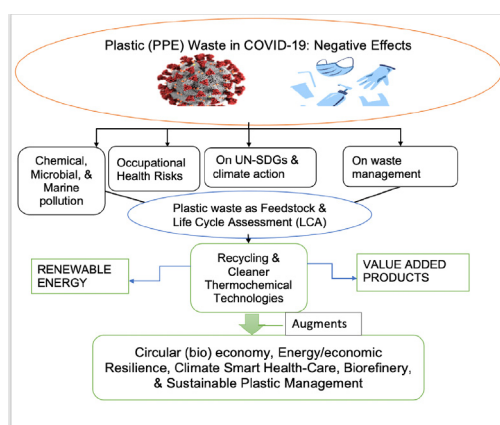
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## HIGHLIGHTS

- Increased plastic waste disposal in COVID-19 can perturb the environment and biota.
- Weathered micro/–nano scale plastics can impose occupational and human health risks.
- Long-term critical assessment is needed on the effects of plastics pollution in COVID-19.
- Plastic waste can act as potential biorefinery feedstock for sustainable plastic management.
- Prioritizing circular bioeconomy principles should be kept in plastic waste management.

## GRAPHICAL ABSTRACT



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## ABSTRACT

The global scope of pollution from plastic waste is a well-known phenomenon associated with trade, mass consumption, and disposal of plastic products (e.g., personal protective equipment (PPE), viral test kits, and vacuum-packaged food). Recently, the scale of the problem has been exacerbated by increases in indoor livelihood activities during lockdowns imposed in response to the coronavirus disease 2019 (COVID-19) pandemic. The present study describes the effects of increased plastic waste on environmental footprint and human health. Further, the technological/regulatory options and life cycle assessment (LCA) approach for sustainable plastic waste management are critically dealt in terms of their implications on energy resilience and circular economy. The abrupt increase in health-care waste during pandemic has been worsening environmental quality to undermine the sustainability in general. In addition, weathered plastic particles from PPE along with microplastics (MPs) and nanoplastics (NPs) can all adsorb chemical and microbial contaminants to pose a risk to ecosystems, biota, occupational safety, and human health. PPE-derived plastic pollution during the pandemic also jeopardizes sustainable development goals, energy resilience, and climate control measures. However, it is revealed that the pandemic can be regarded as an opportunity for explicit LCA to better address the problems associated with environmental footprints of plastic waste and to focus on sustainable management technologies such as circular bio-economies, biorefineries, and thermal gasification. Future researches in the energy-efficient clean technologies and circular bio-economies (or biorefineries) in concert with a “nexus” framework are expected to help reduce plastic waste into desirable directions.

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**Contents**

1. Introduction . . . . . 2

2. Plastic-waste pollution and the effects of an increased environmental footprint during the pandemic . . . . . 3

2.1. Chemical pollution . . . . . 4

2.1.1. Atmospheric pollution and air quality . . . . . 4

2.1.2. Marine pollution. . . . . 5

2.2. Microbial pollution. . . . . 5

3. Health hazards in COVID-19 . . . . . 6

4. Effect of plastic pollution during the COVID-19 pandemic on climate and sustainable development goals . . . . . 6

4.1. The effects of plastics pollution on SDGs . . . . . 7

4.2. Plastic pollution in COVID-19 and its implication on climate change . . . . . 7

5. Sustainable management of plastics during the COVID-19 pandemic . . . . . 8

5.1. Energy resilience. . . . . 9

5.2. Circular economy . . . . . 11

6. Challenges and prospects . . . . . 12

7. Conclusions . . . . . 13

CRediT authorship contribution statement . . . . . 13

Data availability . . . . . 13

Declaration of competing interest . . . . . 13

Acknowledgments . . . . . 13

References . . . . . 13

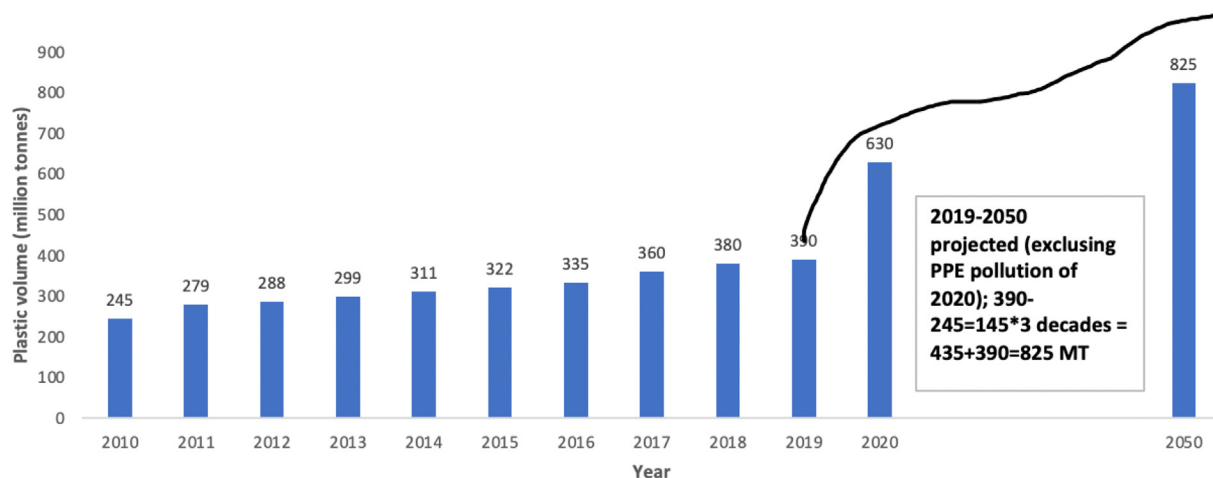
**1. Introduction**

Demand for personal protective equipment (PPE) such as masks, gloves, gowns, and eye protectors has surged during the coronavirus disease 2019 (COVID-19) pandemic (Parashar and Hait, 2021). Advances in polymeric chemistry, nanoscale science, and 3D printing have helped augment the effectiveness of PPE in safeguarding human health (Mallakpour et al., 2022). However, mass consumption and the disposal of PPE and packaged plastic waste are recognized as serious hazards that can threaten environmental sustainability, energy resilience, and ‘climate-smart health care’ (Dorey et al., 2021; Wise, 2022). Therefore, the global contamination of health-care waste during COVID-19 influenced several sectors, especially in countries with poor governance or leadership, inadequate resources, and limited health system resilience in terms of the preparedness for disaster like COVID-19 (WHO, 2022).

Since the beginning of the COVID-19 pandemic, the quantity of plastic waste has increased dramatically and is now projected to exceed 800 million tons by 2050 (Zuin and Kümmerer, 2022). This estimate is based on the abrupt increase in production and disposal of PPE or other COVID-19

related health-care waste (John, 2022). China, for example, reported a 370 % increase (Patrício Silva et al., 2021a, 2021b, 2021c). Mass production of PPE and household plastic waste have been reported during repeated pandemic lockdowns (UNEP, 2020). The life cycle assessment (LCA) of COVID-19 vaccination drive also revealed that the process is not sustainable and also act as potential source of plastic wastes (Klemeš et al., 2021a, 2021b; Hasija et al., 2022). Even if the threat posed by COVID-19 recedes in coming years, quantitative estimates of persistent plastic waste do not anticipate a dramatic decline (Fig. 1).

Plastic pollution has become a formidable challenge due to improper management of the approximately 12 billion tons of plastics waste predicted to be transferred or discharged into the environment by the year 2050 (Editors, 2021). These predictions are significantly higher than the 4.9 billion tons handled in 2015 (Editors, 2021). Inadequate landfilling and incineration options are also increasing carbon footprints and the emission of hazardous atmospheric pollutants (Aragaw and Mekonnen, 2021). The growing plastic-waste footprint is an imminent challenge that requires significant advances in recycling and upcycling to ensure sustainability and environmental resilience (Sharma et al., 2020). Further, LCA methodology is still inadequate to assess environmental performance of various plastic



**Fig. 1.** Increase in plastic waste volume from 2010 to 2018 and projected or estimated increase in the post-COVID-19 period (i.e., 2019–2050; excluding 2020).

waste management systems like landfilling and incineration (Li et al., 2022; Zhao et al., 2022a, 2022b).

The need for both safe on-site treatment and off-site transfer of hazardous PPE plastic waste to prevent cross-contamination during the COVID-19 pandemic has also been emphasized (WHO, 2020a, 2020b). An adequate strategy for recycling PPE plastics has been proposed to reduce future plastic-waste pollution (ISWA, 2020). Nevertheless, actual PPE waste disposal practices typically do not follow institutional guidelines designed to prevent or reduce environmental and human health risks (UNEP, 2020). Interactions between significant increases in plastic waste volumes and inadequate management practices may counter efforts to improve environmental sustainability (Shekhar et al., 2022).

In only a few of previous studies, efforts were put to address the holistic influences of plastic pollution on environmental quality, health risks, ecotoxicity, energy resilience, climate action, and the UN's Sustainable Development Goals (SDGs) from a balanced perspective (Yuan et al., 2021; Rai et al., 2022a). The significance of biomedical waste pollution and related environmental sustainability issues was largely overlooked when the healthcare sector was prioritized to treat COVID-19 (Ramakrishna and Jose, 2022). Also, the significance of rare diseases such as neurofibromatosis that can affect small heterogeneous group of human population and require specific pathologies or biomedical treatment was not properly considered during COVID-19 (Ardizzone et al., 2022; López-Sánchez et al., 2022). Plastic-waste pollution during the pandemic increased the vulnerability of the recycling sector, macro-economies, and social and political systems due to the linear “take-make-dispose” approach enforced by escalated demand for plastic products for food and consumer safety (Ebner and Iacovidou, 2021a, 2021b). The popularity of the “take-away” approach to packaged food and groceries during the pandemic is also an unsustainable approach to the protecting human health and safety. Unsustainable practices such as take-away food habits are therefore on the rise in COVID-19 which adversely influence plastic lifecycles and increase the linear approach (Klemeš et al., 2021b). Conversely, relatively little attention has been paid to sustainable processes such as thermal gasification and biorefineries which use plastic waste as potential feedstock for conversion into renewable energy or value-added products (Teymourian et al., 2021). These approaches are considered highly valuable and can foster the energy resilience, climate-smart health care, and circular economies in the time of COVID-19.

The challenge presented by plastic-waste management due to changing habits in response to the COVID-19 pandemic was explicitly addressed in the *Circularity Gap Report, 2021*, which estimates the global economy is only 8.6 % circular (Fraser, 2021). Reduced circularity in plastic-waste management may further jeopardize ecosystem health, socio-economic indicators, climate action, progress toward meeting SDGs, and energy resilience (Ramakrishna and Jose, 2022). A bio-economic approach (i.e., one that embraces economic activities that rely on biorefineries and bio-based value chains) can establish a robust and sustainable management framework for the management of plastic waste after the COVID-19 era (Lima and Palme, 2022).

The environmental burden, threats to biota, and occupational (or human health) risks can be categorized as harmful effects of plastic waste. On contrary, the technological innovations for up-cycling of plastic waste and biorefinery applications can be beneficial aspects for the contribution toward sustainable plastic value chain and circular economy (Klemeš et al., 2021b). The present review is novel in the sense that it abridges both positive and negative effects of plastic waste in COVID-19 with future directions for the maintenance of nature's sustainability. As discussed before, the effects on occupational safety and human health risks were lacking in the management efforts of plastic during COVID-19 (Vanapalli et al., 2021). Likewise, an in-depth analysis was made scantily on the potential of plastic waste as feedstock in biorefinery with respect to the circular economy along with the issues covering environmental footprint, human health, and SDGs (Patrício Silva et al., 2021a, 2021b, 2021c). In light of limited knowledge in this research field, this review attempts to fill these

knowledge voids to quest pragmatic technology-based solutions and to set regulatory framework for sustainable management of plastic wastes in COVID-19.

This review emphasizes the strategies required for the sustainable management of plastic products in circular bio-economies, green economies, and biorefineries. It focuses on delineating the opportunities triggered by COVID-19 in plastics management and recycling in an effort to encourage resilience and the development of circular economies. The status of plastic pollution from PPE, grocery products, and their effects on the environment, biota, and human health are briefly discussed. This review also demonstrates why the COVID-19 pandemic offers an opportunity for a paradigm shift in plastic-waste research toward upcycling, green management options, and circular economy. The present discussion also emphasizes the strengthening of LCA methods as sustainable tool for governmental decision-makers and Institutional policy managers to estimate the environmental burden of PPE plastic waste and to formulate concrete measures in relation to health system resilience, improved disaster preparedness, and SDGs (Nabavi-Pelesaraei, 2022). It emphasizes the need for sustainable plastic-waste management strategies to augment energy resilience, circular economies, progress toward meeting SDGs, and climate action (Wang et al., 2022a, 2022b, 2022c). The discussion also addresses the need to revisit the multiple effects of plastic-waste pollution during the pandemic and envision a pathway to meeting SDGs by 2030. These integrated efforts can help fill gaps in our knowledge of the effects of plastic pollution during the pandemic on the environment, energy, and circular bio-economies while making significant contributions to environmental restoration, resilient economic systems, and a sustainable future.

## 2. Plastic-waste pollution and the effects of an increased environmental footprint during the pandemic

The most prominent short-term effect of the COVID-19 pandemic was a significant increase in global trade, demand for and production and supply of plastic products (Patrício Silva et al., 2020) (Table 1). According to Plastics Europe, the global production of plastic waste was estimated to be 299 million tons in 2013 and 311 million tons in 2014 (Duer, 2020). The global production of plastic waste was estimated to be 380 million tons prior to the outbreak of COVID-19 (e.g., in 2018) (Shams et al., 2021). However, considering the rates of disposal of biomedical waste during the pandemic, the quantity of plastic wastes was estimated to double (to 630 million tons) in the year 2020 (Khoo et al., 2021). Fig. 1 depicts the annual generation of plastic waste from 2010 to 2020, with a projection for 2050 taking into consideration the abrupt increase due to COVID-19. The massive generation of plastic waste initiated after the advent of COVID-19 poses imminent danger to both the environment and human health (Morgana et al., 2021). For example, the generation of solid wastes during the pandemic in the city of Wuhan in China reached 240 tons of single-use PPE plastics per day, six times higher than the pre-pandemic average (Adyel, 2020). According to recent estimates, approximately 685 kg of medical waste was generated each day for every 100 confirmed COVID-19 patients (Patrício Silva et al., 2021a, 2021b, 2021c). Another study noted that approximately two-thirds of plastic waste originated in hospitals, with 72 % of the total global discharge occurring in Asian countries (Peng et al., 2021). A meta-analysis of plastics associated with responding to COVID-19 in 193 countries revealed the disposal of  $8.4 \pm 1.4$  million tons of waste as of August 23, 2021 (Peng et al., 2021). Estimated increases in the quantity of household plastic waste of 1 % and 3 % were estimated in the Czech city of Brno and Singapore, respectively, from March to August 2020 (Fan et al., 2021a, 2021b). In contrast, Shanghai reported a 23 % reduction in the midst of the pandemic for the same period, reflecting the effect of stringent lockdowns (Fan et al., 2021a, 2021b). The large differences in the production of plastic waste among countries points to the importance of geographical, sociological, decentralized governmental initiatives, and nation-specific waste management policies. Long-term monitoring is required to confirm such variations across continental landscapes.

**Table 1**

Demand, disposal, and waste generation scenarios for plastic personal protective equipment (PPE) in different landscapes during the COVID-19 pandemic and their environmental/human health impacts.

S. No.	Country/continental landscapes	Demand of PPE/other plastic products during COVID-19	Plastic waste generated during COVID-19	Environmental and health risks of PPE	Reference
1.	China	Production of 116 million of single-use face masks during February 2020, equivalent to a 450 % increase compared with January 2020	In Wuhan, PPE plastic waste generated increased by six times to 240 tons per day, while in Hubei Province, PPE waste generation increased by 370 %	PPE plastic waste are nondegradable and contaminate multiple environmental matrices	Patrício Silva et al. (2020); Klemeš et al. (2020a, 2020b); Parashar and Hait (2021)
2.	US	US company 3 M produced 1 billion N95 masks in 2021 to meet PPE needs; demand for N95 masks increased from 50 million to about 140 million per year	PPE plastic waste disposal caused a 70 % increase in marine litter, whereas the initial 2 months of the pandemic in the US saw a PPE disposal rate equivalent to the annual disposal in preceding year.	PPE plastic waste can exert adverse influence on marine ecosystem and biota	Stankiewicz (2020); Parashar and Hait (2021); Shams et al. (2021)
3.	India	Demand for 2.5 million PPEs and a supply of 4.6 million N95 masks during June 2020	Upsurge in plastic waste pollution.	PPE such as face masks are potential source of MPs and NPs	Shams et al. (2021); Parashar and Hait (2021)
4.	South Korea	Escalated production of PPEs while demand for packaged food items increased by 92.5 % over the pre-pandemic phase	295 tons of plastic waste generated in 2 months (February to March 2020).	Adsorption of hazardous chemicals on weathered PPE can impose biotic and human health risks	Rhee (2020); Vanapalli et al. (2021)
5.	UK	PPE requirement for health workers was 7.5 to 12 million per day in 2020; 10 million PPE distributed in August 2020	Inadequate plastic disposal increased by 300 %.	Imposed occupational and environmental health risks	Duer (2020); Shams et al. (2021)

The massive generation of plastic waste during the COVID-19 pandemic is directly related to the increase in global demand for PPE. An estimated 129 billion face masks and 65 billion gloves were used in 2020 alone (Adyel, 2020). Frontline healthcare workers were estimated to use approximately 89 million face masks, 76 million pairs of gloves, 30 million gowns, and 1.6 million goggles on a monthly basis (Stankiewicz, 2020; WHO, 2020a, 2020b). In addition to PPE, the increased utilization of plastic in grocery take-away or home delivery services also increased the generation of waste (Klemeš et al., 2020b; Yuan et al., 2021). For example, the COVID-19 pandemic in South Korea resulted in a 92.5 % increase in PPE use along with digital (or online) shopping for packaged food items compared with pre-pandemic era (Rhee, 2020; Vanapalli et al., 2021). The demand for groceries packaged in plastic was mainly due to household needs, whereas demand in the biomedical sector was generally confined to healthcare workers. Demand for plastics from packaging industries (40 %) to be used in household groceries was greater than that from the biomedical sector (17 %) (Patrício Silva et al., 2021a, 2021b, 2021c).

### 2.1. Chemical pollution

Recent studies found a two-fold increase in the amount of plastic debris generated globally during the COVID-19 pandemic (Fig. 1) and linked with chemical pollution (Prata et al., 2020). Weathering process of plastic waste can be driven through physical, chemical, photodegradative, thermal degradation, and biodegradative pathways (Rai et al., 2022a, 2022b). Although weathering of plastic waste is inextricably linked to the chemical pollution, it can increase the adsorption of chemical pollutants due to the combined effects of various factors (e.g., increased oxygen-containing functional groups and high specific surface area) (Kumar et al., 2021). Therefore, weathered MPs have high propensity for the adsorption of chemical pollutants with the potential to undergo either bioaccumulation or biomagnification and leach into groundwater, where they pose threats to wildlife, aquatic food webs, and human health (Patrício Silva et al., 2021a, 2021b, 2021c) (Fig. 2).

Weathering can convert disposed plastics wastes into small molecules (such as oligomers and monomers) through the interaction of free radicals and microbes (Duan et al., 2021). In this context, free-radical reaction mechanisms can guide the weathering process through step-wise chain initiation, propagation, and termination (Duan et al., 2021). The disposed PPE plastic waste undergoes microbial degradation and physical weathering, with the latter likely to release microplastics (MPs) and nanoplastics (NPs) into the environment (Rai et al., 2021c). Further, the weathering of plastic waste into microfiber, MPs, and NPs is dependent on the combined effects of their physicochemical properties and ambient environment (Rai et al., 2022a, 2022b). The weathering of plastic waste in the aquatic

ecosystems is usually slower than the terrestrial environment due to lower water temperature (Duan et al., 2021). It should be noted that the information on chemical pollution in terrestrial (e.g., agroecosystem soil) environment due to the weathering of plastic waste is scanty when compared with aquatic systems (Kumar et al., 2020).

As PPE plastic waste undergoes weathering, it is also converted into MPs and NPs that can facilitate the adsorption of chemical pollutants (Kutralam-Muniasamy et al., 2022). Adsorbed inorganic and organic chemical pollutants have the potential to contaminate multiple environmental matrices (Sullivan et al., 2021). For example, used face masks release or desorb heavy metals such as lead, copper, antimony, zinc, titanium, and iron (Amuah et al., 2022). Sorption of pesticides such as carbendazim, Dipterex, diflufenzuron, malathion, and difenoconazole on plastic debris can also contaminate environmental media (Wang et al., 2020a, 2020b). Adsorption of eight mixed-pesticide residues took place efficiently on the surfaces of MPs composed of polyethylene (PE) (Wang et al., 2020a, 2020b). Used and weathered face masks can also adsorb contaminants such as antibiotics (e.g., tetracycline, ciprofloxacin, sulfamethoxazole, and triclosan) through hydrophobic interactions (Lin et al., 2022a, 2022b). In a sorption study by Lin et al. (2022a, 2022b), the distribution coefficient values for tetracycline ( $0.3947 \text{ Lg}^{-1}$ ) and sulfamethoxazole ( $0.0399 \text{ Lg}^{-1}$ ) on weathered face masks were higher than their counterparts on MPs derived from conventional plastic polymers. In addition, the sorption affinity was positively correlated with the octanol-water partition coefficient of the compound (tetracycline > sulfamethoxazole > ciprofloxacin > triclosan) (Lin et al., 2022a, 2022b). Weathered face masks can also adsorb radionuclides such as U-232 and Ra-226 and transport them to the environment (Ioannidis et al., 2021). In summary, weathered PPE can serve as potential vectors of heavy metals, organics, chemical additives, emerging pollutants, and pathogens in aquatic and terrestrial environmental matrices (Rai et al., 2022a, 2022b) (Fig. 2).

#### 2.1.1. Atmospheric pollution and air quality

The incineration of plastic waste can degrade air quality through atmospheric emission of diverse pollutants, including greenhouse gases (GHGs), particulate pollutants, and volatile toxins such as dioxins and furans (Parashar and Hait, 2021). For example, incineration of PPE plastic wastes reportedly generates various air pollutants, including particulate matter (PM) smaller than  $10 \mu\text{m}$  in diameter ( $\text{PM}_{10}$ ), PM smaller than  $2.5 \mu\text{m}$  in diameter ( $\text{PM}_{2.5}$ ), and heavy metals (Rai et al., 2021b). The air pollutants emanating from the incineration of plastic waste can also pose significant human health risks, particularly to patients infected with the coronavirus that causes COVID-19 (Barouki et al., 2021). Airborne PM can also act as transmission media for the coronavirus through “plastic rain” or “plastic smog” (Bank and Hansson, 2019; Liu and Schauer, 2020).

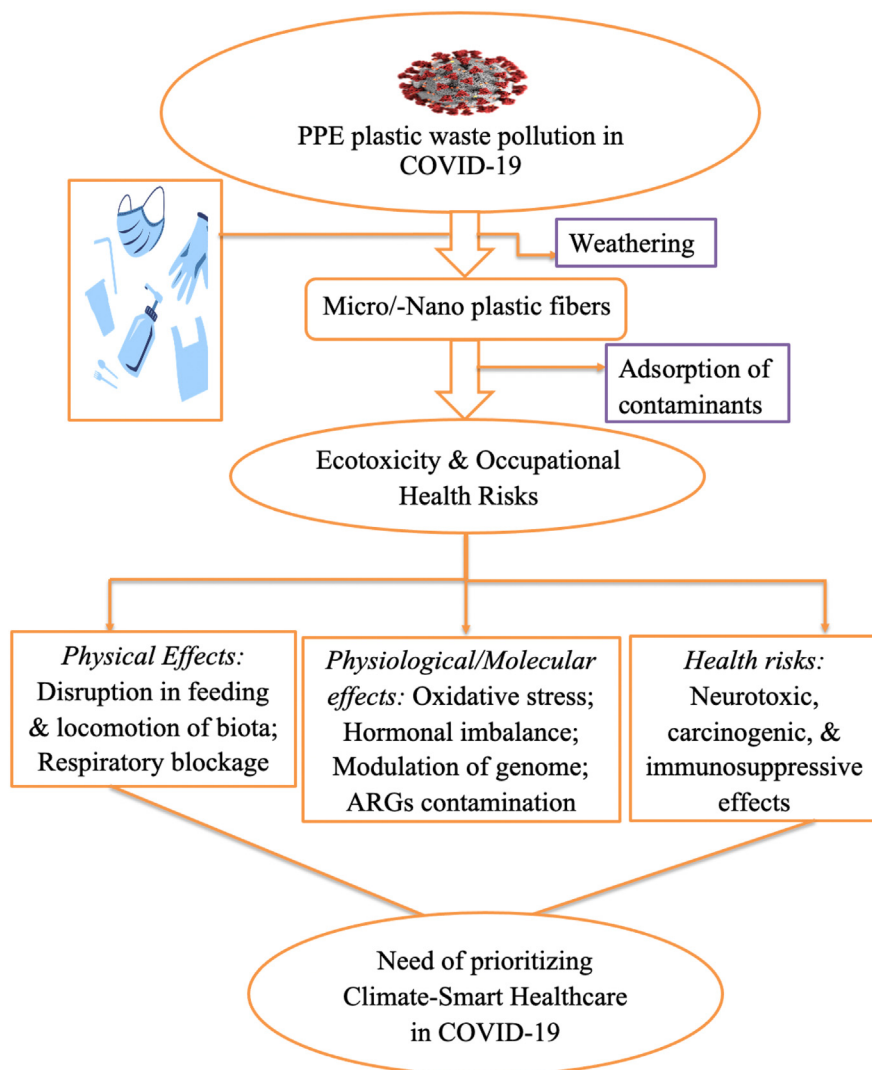


Fig. 2. COVID-19 induced the disposal of plastic products and created multiple types of risks (carcinogenic, neurotoxic, and mutagenic) to living organisms that can be mediated through oxidative stress and hormonal imbalance. Inadequate plastic management techniques such as landfilling and anaerobic digestion produce hazardous leachates and antibiotic-resistance genes can perturb environmental quality.

### 2.1.2. Marine pollution

Recent studies estimated that  $25.9 \pm 3.8$  kt of plastic waste were released into marine ecosystems, accounting for 1.5 % of the total plastic waste generated during the COVID-19 pandemic (Peng et al., 2021). The excessive use of plastics during the pandemic led to a 30 % increase in seashore plastic litter when compared with the pre-pandemic year 2019 (Fadare and Okoffo, 2020). Weathering of PPE products on seashores can generate MPs and NPs that are hazardous to marine ecosystems and biota (Dharmaraj et al., 2021a, 2021b). During the initial COVID-19 phase in 2020, approximately 1.56 billion face masks, equivalent to 5.66 Mt. of waste, were disposed offshore (Yuan et al., 2021). Disposed PPE in marine environments can further undergo weathering into MPs and NPs, the adverse impacts of which are more pronounced in intertidal zones due to dynamic geochemical conditions (Rai et al., 2021a; Wu et al., 2022).

PPEs that include heavy metals (e.g., molybdenum, titanium, zinc, and silver) can disrupt aquatic ecosystem health (De-la-Torre et al., 2022). Plastics particles from disposable face masks near the seashore can be ingested by marine biota (e.g., seabirds, penguins, and turtles), leading to excess mortality rates (Ray et al., 2022). In one study, as much as 77 % of fecal samples from *Aptenodytes patagonicus* (king penguin) were reportedly contaminated with plastic derivatives, such as synthetic polyester and nylon microfibers (LeGuen et al., 2020). These plastic particles, once ingested by marine biota, can exert ecotoxic and cytotoxic effects (Hiemstra et al.,

2021). In addition, MPs from weathered PPE waste can be genotoxic in aquatic organisms through the activation of reactive oxygen species, oxidative stress-induced inflammation in immune responses, and disruption of DNA repair (Tagorti and Kaya, 2022). Adsorbed chemical pollutants in PPE waste can also be released into marine environments through desorption, perturbing ecosystems and marine food webs (Rai et al., 2021a, 2021b, 2021c) (Fig. 2).

### 2.2. Microbial pollution

The formation of “biofilms” as a result of interactions between plastics and microbes can influence the environmental behavior, fate, and ecotoxicity of chemical pollutants (Rai et al., 2021b). Landfilled PPE plastic can be anaerobically digested, releasing antibiotic resistance genes (ARGs) and contaminating groundwater with other metabolic byproducts (Rai et al., 2021a) (Fig. 2). The presence of ARGs in disposed carbon clothes/non-surgical ( $1.29 \times 10^{12}$ ) and surgical face masks ( $1.07 \times 10^{12}$ ) confirms their role in microbial pollution (Zhou et al., 2022). The presence of ARGs in PPE wastes can facilitate the proliferation of other microbial pathogens. Also, as biofilms on plastics serve as active sites for horizontal gene transfer, they can influence microbiomes, biodegradative metabolic pathways, pathogenicity, and human health (Rogers et al., 2020).

### 3. Health hazards in COVID-19

Physical-chemical and biological weathering can convert health-care PPE plastic waste into MPs and NPs that led to increases in the sorption affinity of hazardous pollutants on plastisphere during COVID-19 (Min et al., 2020). In environmental matrices, the stability of NPs can be assessed in terms of aggregation using Derjaguine-Landau-Verwey-Overbeek (DLVO) calculations, which is intimately linked with their behavior, fate, and potential human health risks (Wang et al., 2021). Therefore, the multiple attributes linked with health-care plastic waste such as weathering, chemical composition, molecular weight, sorption mechanisms, stability, and plastic-microbe interactions determine their hazardous effects on human health, especially during COVID-19 (Rai et al., 2021c; Rai et al., 2022a, 2022b). Weathered plastic particles can adsorb various hazardous chemical pollutants that are potentially cytotoxic in human organs through direct or indirect pathways (De-la-Torre et al., 2021). MPs and NPs also provide surfaces for the adsorption of pathogenic microbes that pose potential human health risks (Rai et al., 2021b). Disposed PPE can also act as secondary sources or potential vectors of coronaviruses (Patrício Silva et al., 2020).

The abrupt increase in the health-care waste during COVID-19 can also contaminate the food crops in agroecosystems which may raise serious human health implications (Rai et al., 2022a). Other food stuffs such as honey, beer, commercial salts, and gizzards of chickens can be contaminated with plastic particles to pose human health risks (Carbery et al., 2018). The increased contamination of MPs and NPs, especially in tourism intensive coastal regions can also adversely influence the food chain during COVID-19 (Lee and Kim, 2022). In this respect, the contamination of seafood with MPs and NPs can also increase the propensity of human health risks (Walkinsha et al., 2020). In addition, the escalated consumption and emission of plastic waste in industrial sectors such as food packaging, wastewater or sewage treatment plants, and biomedical appliances during COVID-19 can also be a serious threat to human health (Lee and Kim, 2022).

The influence of COVID-19 on multiple sectors such as agriculture systems and industries also impacted human health, besides PPE plastic waste. The agroecosystem resilience is remarkably jeopardized during COVID-19 which adversely influenced the dietary intake of nutritionally safe or immunity booster crop cultivars (Priyadarshini and Abhilash, 2021). Further, the effects of COVID-19 and climate change are increasingly being realized as twin problems to worsen the agroecosystem/food system resilience, crop yield, food security, and agricultural sustainability (Rasul, 2021; Fan et al., 2021a, 2021b). The COVID-19 associated health risks were tightly regulated by climate change as certified in '26th Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC)', at Glasgow, Scotland, during November 2021 (John, 2022). In this context, UNFCCC emphasized the establishment of 'low-carbon sustainable health systems' to facilitate the climate-smart health-care (WHO, 2021; Ebi, 2022). Henceforth, the escalated PPE plastic waste in concert with the COVID-19 driven influence on agriculture, food sector, and climate change can remarkably impact the human health.

The increasing plastic waste also increased the risks of occupational safety to plastic waste collection workers (PWCW) (Ranjbari et al., 2022; Beckert and Barros, 2022). Further, rare diseases like Behcet, Down, Stoneman, Alice In Wonderland, Hutchinson-Gilford Progeria, Alkaptonuria, and Rasmussen's potentially are reported to interact with COVID-19 to impact COVID-19 disease map circuits. However, inadequate knowledge of such mutual interactions exacerbate the challenges in healthcare sector (Severin and Dan, 2022). In this sense, a meta-analysis of 2518 disease genes responsible for 3854 rare diseases showed that a total of 254 genes exerted direct effect on the COVID-19 dynamics while 207 showed indirect effect (Severin and Dan, 2022). In addition to rare diseases, the COVID-19 pandemic worsened the treatment of neurological disorders such as epilepsy (Abokalawa et al., 2022).

The contamination of MPs and NPs and the pathways involved in human health risks are shown in Fig. 3. During the COVID-19 pandemic, landfilling was proven to be an inadequate means of managing increasing volumes of PPE wastes as face masks tend to remain non-degradable in

subsurface conditions (de Albuquerque et al., 2021). Landfilled facemasks tend to weather into MPs and NPs (and generate ARGs) with the potential to perturb human health (Fig. 2). In addition, the incineration of PPE can generate airborne MPs that are neurotoxic and can attenuate immune responses (Prata et al., 2020). Inadequate management of plastic waste and improper disinfection protocols can also exacerbate human health risks by promoting the transmissibility of coronaviruses (Nzediegwu and Chang, 2020).

Weathering of plastic waste into MPs and NPs presents multiple physical hazards (e.g., abnormal locomotion and feeding behavior in biota) and physiological hazards (e.g., increased oxidative stress) (Morgana et al., 2021) (Fig. 3). Coronaviruses can survive on plastic particles for approximately two to three days, during which time they can infect people in contact with the plastic products (Van Doremalen et al., 2020). The ecotoxic effects of the adsorption of diverse chemicals associated with plastics (e.g., heavy metals, polychlorinated biphenyls [PCBs], polyaromatic hydrocarbons [PAHs], endocrine disrupting chemicals, phthalates, bisphenol A, polybrominated diphenyl ethers, pharmaceuticals, and cosmetics) are also widely documented (Rai et al., 2021b). Oral and dermal exposure to MPs and NPs can exert carcinogenic, mutagenic, and teratogenic risks in humans (Rai et al., 2021b). The term "plastisphere" describes a human-made ecosystem created over the past five decades. It can serve as a potential reservoir of pathogenic microbes characterized by the close interface between plastic litter and microbiomes (Rai et al., 2021b). Plastisphere-microbe interactions are therefore inextricably linked with human health.

The adsorption of hazardous chemicals in plastispheres poses significant threats to biota in light of the dramatic increase in volumes of plastic waste generated during the COVID-19 pandemic (Rai et al., 2022a, 2022b). The incineration of medical and household plastic waste has worsened air quality by releasing diverse hazardous airborne pollutants (HAPs) such as PCBs, PAHs, dioxins, furans, and heavy metals (Patrício Silva et al., 2021a, 2021b, 2021c). The combined effects of the released MPs and NPs and subsequent sorption-desorption cycles of hazardous chemicals and pathogenic microbes can undermine environmental quality (Rai et al., 2021a). Several types of face masks used during the pandemic are sources of deleterious organophosphate esters (Fernández-Arribas et al., 2021). Most PPE products are composed of plastic polymers, which tend to weather into MPs and NPs (Morgana et al., 2021). Single-use face masks contain large amounts of MPs and NPs such as polypropylene (PP), PE, polyurethane, polyacrylonitrile, and polystyrene (Jiang et al., 2021). The LCA of face mask with in-built metal strips revealed severe human health implications in view of high human toxicity potential (HTP) (Kumar et al., 2021).

If the environmental effects of MPs are assessed through holistic LCA approach, MP microfibers/fragments can impose greater eco-toxic effects into several impact categories, when compared with mismanaged plastic waste (Zhao and You, 2022). Effective protection of human health therefore requires diverse approaches to manage plastic pollution, especially with respect to the persistence of weathered plastics (i.e., MPs and NPs) and their ecotoxic effects (Patrício Silva et al., 2021a, 2021b, 2021c). Therefore, ensuring health system resilience in COVID-19 is pertinent for improved human well-being, disaster preparedness, and environmental sustainability.

### 4. Effect of plastic pollution during the COVID-19 pandemic on climate and sustainable development goals

Abrupt increases in plastic waste in the time of COVID-19 can influence the SDGs and climate change. The effects of plastic waste on SDGs can be manifested through their influence on environment, socio-economy, and human well-being, as discussed in previous sections. Further, the coupling of unsustainable management practices and inadequate LCA methods can adversely influence the climatic variables. Therefore, this section is organized to address the effects of plastic waste on both SDGs and climate change.

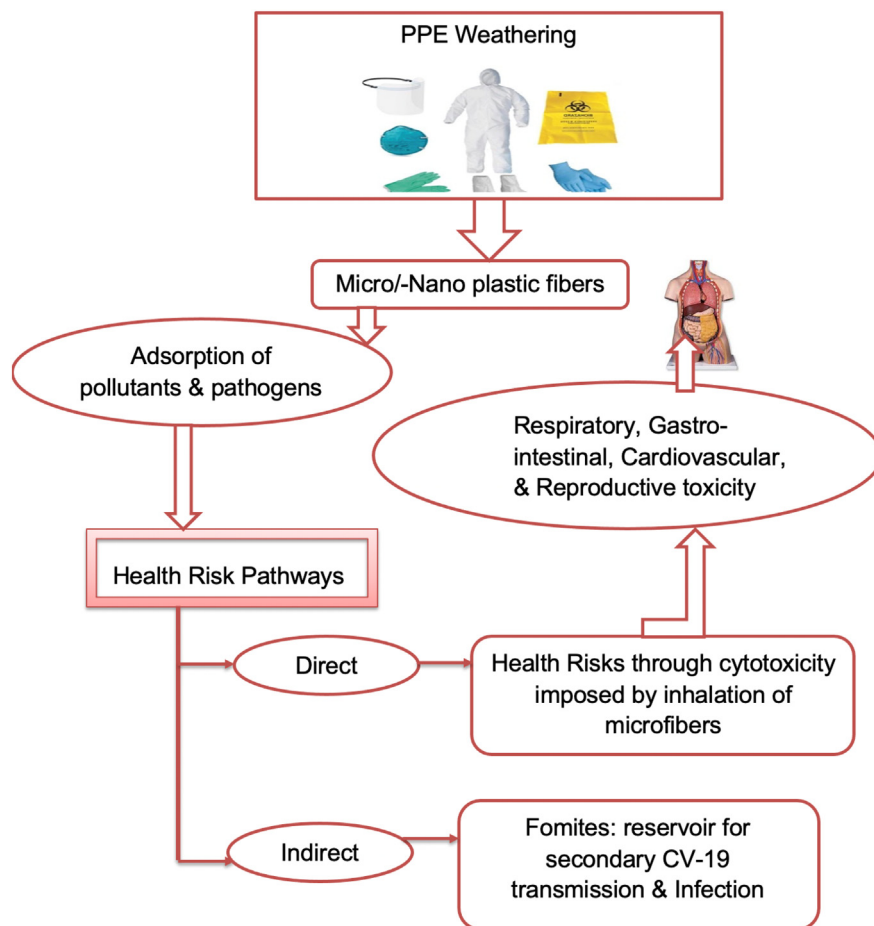


Fig. 3. Direct and indirect pathways of human health risks due to the disposal of personal protective equipment (PPE)-derived microfibers, fomites, and micro- and nanoplastics (MPs/NPs).

#### 4.1. The effects of plastics pollution on SDGs

Plastic product and their unregulated release during the COVID-19 pandemic has influenced several SDGs. Unprecedented levels of the use of plastics have caused MP/NP pollution that impairs the achievement of SDGs#3 and 6 by causing eco-toxicity and blocking sewage treatment plants, respectively (Rai et al., 2021a, 2021b, 2021c). Likewise, the increased disposal of plastic waste during the pandemic has adversely influenced progress toward meeting SDG#12 due to a consumptive and linear “take make dispose/take-away” approach (Jiang et al., 2021). Also, massive generation of MPs and NPs that are toxic to terrestrial and aquatic biota influenced progress toward SDG #14 and 15 (de Sousa, 2021). In addition to environmental quality, the adverse effects of the pandemic on education and economic growth can influence progress toward meeting SDG #4 and #8, respectively (Elavarasan et al., 2022). For timely accomplishment of SDGs by 2030, the year 2020 has been marked as a “Decade of Action.” However, the outbreak of COVID-19 altered several environmental indicators and forced revisions to action plans (Sharma et al., 2021). The pandemic has also adversely influenced plans to meet other SDGs through global economic shocks in the form of a decline in gross domestic product of US \$76.7 billion (Nandy et al., 2022). However, improved management of PPE and household solid wastes may also allow for the resumption of progress toward SDGs with respect to plastic pollution during the COVID-19 pandemic. Application of sustainable polymers, synthesized primarily from renewable as well as biodegradable plastic components, can help achieve SDGs (Tarazona et al., 2022). Therefore, it is necessary to quantify the potential environmental impacts of the escalated PPE plastic waste in COVID-19 through LCA methods for a better understanding on their impacts on SDGs (Nabavi-Pelesarai, 2022). The sustainability paradigm

in plastic-waste management through climate action, energy resilience, and circular bio-economies may help accelerate such progress.

#### 4.2. Plastic pollution in COVID-19 and its implication on climate change

Rising levels of plastic pollution during the COVID-19 pandemic has dramatically increased carbon footprints and emissions of GHGs due to inadequate waste management practices (Shekhar et al., 2022). The increase in carbon footprints jeopardized the attainment of SDGs, nature sustainability, and global environmental justice (UNEP, 2021). Although an 8 % decline in global carbon emissions was reported during COVID-19 lockdowns, their contribution in terms of the long-term effects on climate action was negligible (Werikhe, 2022). In its sixth report, the Intergovernmental Panel on Climate Change (IPCC) suggested revisiting the anthropogenic activities responsible for climate change during the on-going pandemic (IPCC, 2021). Pre-pandemic predictions had already projected an increase in global temperatures due to the annual release of approximately 2.38 Gt of CO<sub>2</sub>-equivalent emissions by 2050 if the quantitative discharge of plastic waste remains at the same pace (Kaza et al., 2018; Sharma et al., 2021). The increased use of PPE during the initial six months of the COVID-19 in UK resulted in 106,478 t of CO<sub>2</sub> emission which worsened the carbon footprint (Rizan et al., 2021). Therefore, the efforts to minimize the plastic footprint can also help address the issue of environmental and carbon footprint.

The escalated disposal and inadequate management of biomedical and household plastic waste during the pandemic adversely influenced the action plans designed to mitigate climate change (EPA, 2020). A LCA of polyethylene terephthalate products in China (2000–2018) indicated that the production of plastics is responsible for the generation of approximately



74.9 % of GHGs (Chu et al., 2022). Another LCA of polyvinyl chloride (PVC), PP, and PE in China estimated that 403 million Mt. of GHGs was associated with the complete plastics cycle in the year 2020 (An et al., 2022). The incineration of landfilled plastic waste also exerted a negative effect on climate, as 67.42 Mt. of CO<sub>2</sub>-eq GHG emissions was observed in the US alone during 2018 which further increased by 15.8 % in a projection of a COVID-19 scenario (EPA, 2020). In this respect, LCA of PPE kits was performed for two types of the management methods (i.e., landfill and incineration) using GaBi version 8.7 (Kumar et al., 2021). Herein, six environmental impact categories (i.e., Global Warming Potential (GWP), Eutrophication Potential (EP), Acidification Potential (AP), Freshwater Aquatic Ecotoxicity Potential (FAETP), HTP, and Photochemical Ozone Depletion Potential (POCP)) were assessed. Accordingly, PPE body-suit incineration and landfill exerted the maximum impact on GWP followed by gloves and goggles. The increased health risk of PPE incineration is already mentioned in previous section with high value of HTP impact category. However, the incineration reduced the impact of remaining four impact categories (Kumar et al., 2021). Accordingly, the incineration of plastic waste appears to exert adverse influences on the climate change and human health.

The comparative LCA studies between single-use surgical and reusable face masks have been carried out to assess their effects on the environmental and climatic variables (Klemeš et al., 2020a, 2020b). Likewise, the LCA of embedded filtration layer (EFL) and single-use surgical face mask was also performed using ReCiPe method with the Hierarchist perspective to assess the nine impact categories (Lee et al., 2021a, 2021b). Accordingly, EFL reusable face mask was favorable to achieve about 30 % reduction in climate change and waste generated relative to single-use surgical face mask (EFL: 0.338 kg CO<sub>2</sub>-eq and 0.0004 kg waste; single-use surgical face mask: 0.580 kg CO<sub>2</sub>-eq; 0.004 kg waste). Both types of facemask were found to exert the ameliorative effects on the other environmental impact categories (e.g., 'water depletion, freshwater eutrophication, marine eutrophication, and human toxicity') although less pronounced than climate change and waste reduction.

Increased plastic-waste footprints due to abrupt increases in PPE disposal and inadequate waste management strategies are therefore hampering efforts to address climate change. In this aspect, the circularity practices such as recycling of PPE plastic waste for obtaining pyrolyzed liquid fuels (or other value added products) and encouraging reusable facemasks gained a momentum for sustainable management of COVID-19 (Boix Rodríguez et al., 2021). In this respect, LCA of plastic waste during COVID-19 also advocated the replacement of single-use PPE plastic waste with recyclable/reusable alternates to minimize the environmental footprint (Klemeš et al., 2020a, 2020b). Therefore, increased plastic waste in COVID-19 paved the way for climate smart health-care waste management and circular economy to attain the hazardous waste management, SDGs, occupational health safety, economic resilience, and environmental sustainability.

## 5. Sustainable management of plastics during the COVID-19 pandemic

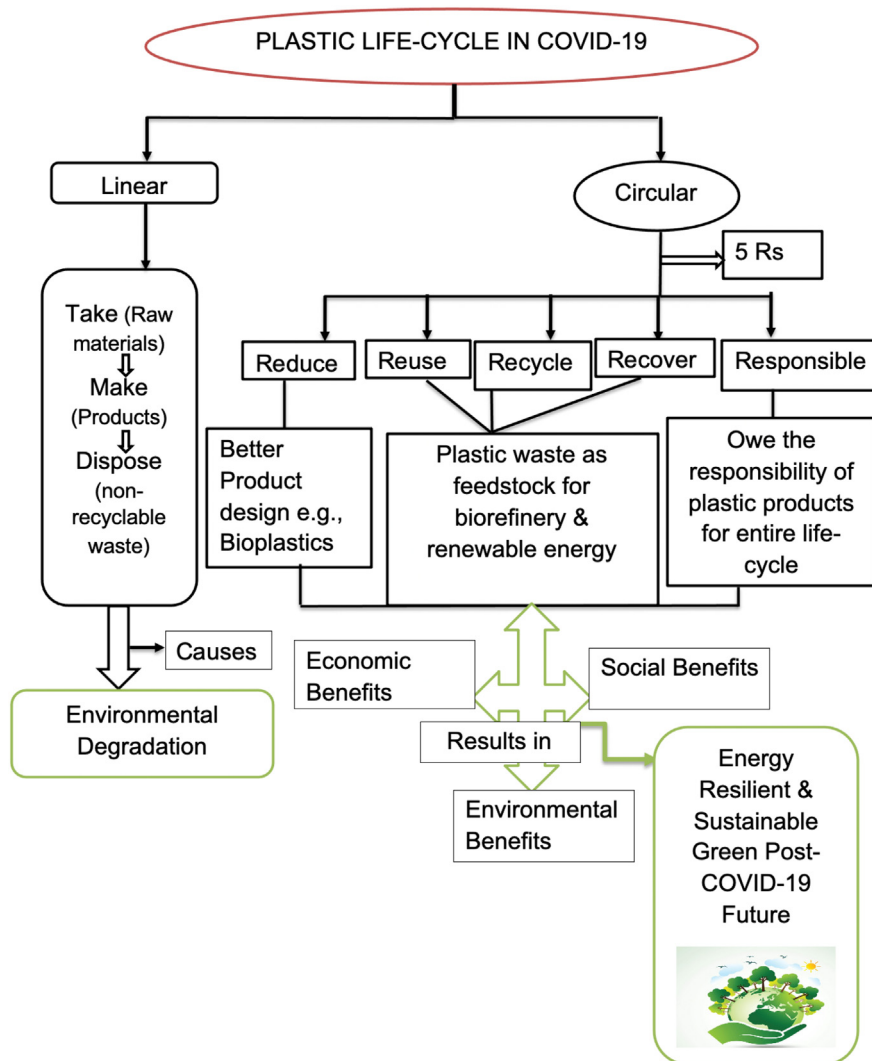
The increase in plastic wastes during the COVID-19 pandemic has raised concerns and challenges. Before the onset of COVID-19, the EU recycled only 29 % and landfilled 31 % of its plastic waste, whereas the US dumped approximately 53 % of its plastic waste into landfills (Paço et al., 2019). In post COVID-19, despite the decreases in other industrial waste (due to global lockdowns), house-hold packaged and PPE plastic waste increased dramatically (Ranjbari et al., 2022). Nevertheless, the increase of plastic and agri-food waste channelized the efforts to enhance circularity practices. In this sense, circular economy, eco-design process of face masks through adequate LCA, and recycling approaches should be augmented to help achieve resilient supply chains and SDGs (Boix Rodríguez et al., 2022). The increased utilization of reusable plastics has shown positive effects on environmental quality as sustainable waste management option (Ahamed et al., 2021; da Silva et al., 2021). Therefore, technological innovations to facilitate the reuse of plastic waste can minimize their effects on environmental footprint (Torres and De-la-Torre, 2022). For example, the use of EFL reusable face mask is more favorable to minimize the environmental

footprint than single-use surgical face mask (Lee et al., 2021a, 2021b). Also, the technological advances in decontamination, reprocessing, and reuse of PPE plastic waste can reduce the environmental burden, while maintaining their supply chain to attain climate-smart healthcare (Rowan and Laffey, 2021).

Face masks can be reused safely 10 times after cyclic disinfection (5 or 10 washes followed by five autoclaving treatments) (Alcaraz et al., 2022). Maceno et al. (2022) also studied LCA between handmade cotton fabric based reusable face masks and conventional surgical face masks by using ISO 14040 and the Material Circularity Indicator (MCI) to assess their comparative effects on the environmental impact categories. Accordingly, the reuse (up to five times) of cotton fabric face masks has a better environmental performance and a higher circularity than the single-use surgical face mask. Likewise, comparative study on LCA of reusable and single use face mask also corroborated the superiority of reusable face mask in terms of their effects on sixteen impact categories (Morone et al., 2022). Also, in another study based on LCA method, reusable face mask reduced 85 % of generated waste with a 3.39 times lower impact on climate change, when compared with single use face mask (DoThi et al., 2021). Further, the application of membrane technology in eco-design of reusable face masks can enhance their effectiveness, environmental performance, and circularity (DoThi et al., 2021). Therefore, encouraging the reuse and recycling of PPE plastic materials with adequate LCA approach from 'cradle-to-grave system' boundary is cost-effective approach to significantly reduce their environmental burden in COVID-19.

As MPs and NPs are potential habitats for coronaviruses, the number of sustainable management options is limited. Selecting ideal sites and formulating efficient management strategies for plastic wastes during a pandemic can be challenging. Landfilling is often not a feasible or sustainable option for plastic waste, which can lead to secondary chemical pollution and microbial contamination through the leakage of ARGs (Patrício Silva et al., 2021a, 2021b, 2021c). Landfilling and incineration can also jeopardize circular economies, climate action plans, progress toward meeting SDGs, and environmental sustainability (You et al., 2020). Nevertheless, coupling of plastic waste incineration with energy recovery can be a wise step to address multiple environmental challenges in COVID-19 (Deepak et al., 2022). Also, application of chemical disinfection and recycling approaches of PPE plastic waste can reduce the environmental/carbon footprint as well as the associated health risks (Nabavi-Pelesaraei, 2022).

Effective waste management approaches are in high demand, given that roughly 3.5 Mt. of plastic PPE waste was disposed in 2020 (Patrício Silva et al., 2021a, 2021b, 2021c). Enormous disposal rates of PPE-derived biomedical plastic waste require their co-incineration in municipal incinerators due to inadequate landfilling capacities (Lan et al., 2022). Corrosion of incineration machinery is followed by the release of heavy metals including barium, chromium, manganese, and nickel, along with flue gas enriched with alkali metals and HCl (Lan et al., 2022). Physical and chemical methods of treating plastic waste, such as chemical disinfection, micro/radio-wave treatment, and steam sterilization are not environmentally sustainable (Khoo et al., 2021). Sustainable management of plastic wastes can be rather approached by embracing the 4Rs (reduce, recycle, reuse, and recover) (Jiang et al., 2021) (Fig. 4). In addition to the 4Rs, the incorporation of the "responsibility" principle can contribute to recycling success (Zuin and Kümmerer, 2022). Technological advances in optimizing the reuse of PPE plastic waste can minimize disposal volumes in environmental matrices. Sustainable technological innovations or processes such hydro-cracking should be encouraged to help reduce carbon emissions, air pollution, and energy consumption during treatment of PPE waste streams (Davidson et al., 2021). In this respect, integrating mechanical and chemical processes into the recycling of plastic waste can address several challenges in the sustainable management of PPE plastic waste and help achieve climate-smart health care. Resetting recycling infrastructure by creating "green" jobs is also linked with several SDGs, such as 1 and 13 (Sharma et al., 2021). Low-environmental-impact chemistry can also be vital to elucidating the fate of chemically diverse plastic polymers and optimizing sustainable plastic management (Tarazona et al., 2022).



**Fig. 4.** The need for a circular (bio) economy approach to a sustainable, energy-resilient, post-COVID-19 future to resolve environmental degradation, carbon-positive economies, and sustainability gaps based on plastic waste lifecycles associated with a linear economy.

The inadequate municipal solid waste management induced the risks of occupational safety and health hazards to PWCW (Penteado and Castro, 2021). Therefore, the governmental initiatives should prioritize the occupational or personnel health safety of PWCW through proper waste handling training with sufficient PPE kits (Beckert and Barros, 2022). Since the occupational safety and health risks of PWCW are intimately related to SDG 3, frequent statistical data collection and policy measures are warranted to help achieve resilient municipal solid waste management sector during the COVID-19 (Ranjbari et al., 2022).

In addition, ecologically sensitive technological innovations that transform plastic into value-added products means a “waste into wealth” approach can contribute to sustainable management of MPs and NPs. For example, the catalytic pyrolysis of disposed face masks can produce value-added products and chemicals such as benzene, toluene, ethylbenzene, and xylene (Lee et al., 2021a, 2021b). Solar energy-driven innovations that reclaim municipal solid waste through renewable hydrogen production (“photoreforming”) is also a promising technology that can help create carbon-neutral economies (Uekert et al., 2021). These approaches to recycling can foster the responsible management of plastic wastes during the COVID-19 pandemic by establishing productive relationships among macroeconomic, political, and other stakeholders (Ebner and Iacovidou, 2021a, 2021b).

The MPs can be remediated through separation technologies such as membrane filtration, coagulation, ultrafiltration, and reverse osmosis

(Patrício Silva et al., 2021a, 2021b, 2021c). Advanced oxidation processes such as the electro-Fenton reaction and biological treatment using enzymatic engineering and constructed wetlands are other options for the removal of MPs from environmental matrices (Rai et al., 2021b). In addition to advances in chemistry, the integration of polymer science with nanotechnologies and 3D fabrication to protect, probe, sense, and control coronaviruses can also strengthen management practices (Mallakpour et al., 2022). A resilient waste management and energy infrastructure is required for the sustainable management of plastic waste during the pandemic.

*5.1. Energy resilience*

Increased volumes of plastic waste during the COVID-19 pandemic can undermine the traditional energy production sector (Klemeš et al., 2020a). Disposed face masks adversely affect anaerobic digestion as PPE wastes can decrease methane production by 18 % (de Albuquerque et al., 2021). However, efforts to convert plastic waste into energy have increased during the pandemic (Zhou et al., 2021). LCA of PPE or biomedical waste revealed that incineration coupled with energy recovery is an eco-sustainable option as the chemical energy content of plastics can be recovered for value added products (Klemeš et al., 2020a, 2020b). Therefore, plastic waste streams can be used as feedstocks to help bolster energy resilience which can boost the socio-economic systems (Li et al., 2022). As thermocycling technologies

can convert PPE waste into energy through pyrolysis, gasification, and torrefaction, they can be considered feasible approaches to energy resilience, carbon neutrality, environmental sustainability, and circular economies (Fig. 5) (Felix et al., 2022). Face masks and gloves made of PP and PVC can be pyrolyzed into renewable energy (Aragaw and Mekonnen, 2021).

Pyrolysis of plastic waste can be driven through thermochemical reactions at high temperatures (400–800 °C), atmospheric pressure, and in the presence of catalysts (Kalargaris et al., 2017). The degradation of plastic waste in pyrolysis is guided through multiple mechanisms such as polymer chain reactions, polymer chain scission, side group, and recombination reactions (Zhao et al., 2022a, 2022b). Several studies on pyrolysis of plastic waste revealed that composition of feedstock, temperature, heating rate, and reaction time can significantly influence the quality of generated bio-oil and other value-added products (Kalargaris et al., 2017; Das and Tiwari, 2018; Zhao et al., 2022a, 2022b). Accordingly, pyrolysis of mixed plastic waste consisting of styrene, butadiene, and polyester was investigated under two varying temperature range (i.e., 700 °C and 900 °C) (Kalargaris et al., 2017). In this study, the pyrolysis of mixed plastic waste resulted in production of high-quality bio-oil, equivalent to the efficiency of diesel. However, the bio-oil produced at 700 °C was more thermally stable and energy efficient with low emission of GHGs, when compared with the bio-oil generated at 900 °C. Likewise, it was also noted that the changes in temperature during plastic waste pyrolysis can influence the quality of generated energy and value-added products (Das and Tiwari, 2018).

In one study, application of pyrolysis converted 75 % of PPE-based plastic waste into bio-crude oil or tar resources (Aragaw and Mekonnen, 2021). The pyrolysis of PPE-based plastic waste can produce energy-efficient products, although further advances are required to improve the conversion efficiency (Dharmaraj et al., 2021a). The pyrolysis of face masks at 973 K (700 °C) can lead to the production of non-condensable hydrocarbons with a relatively high heat value (HHV) of >40 MJ kg<sup>-1</sup> (Park et al., 2021). The co-feeding of face masks with food wastes reportedly resulted in the production of char, with greater H<sub>2</sub> and lower hydrocarbon content. In contrast, the pyrolysis of surgical face masks at temperatures of 456 to 466 °C resulted in the production of a liquid fuel with an HHV of 43.5 MJ kg<sup>-1</sup> (Li et al., 2022). A LCA of the energy produced from face-mask waste indicated the process was sustainable, unlike conventional plastic-waste management methods.

Gasification process with regulated operating conditions is significantly influenced by the physico-chemical characteristics of plastic waste used as feedstock (Zhao et al., 2022a, 2022b). In this respect, the contamination of input plastic waste can result in catalyst deactivation to reduce the efficiency of gasification. The syngas produced from plastic waste gasification can be used as commercial energy product (Bai et al., 2020). However, the side-products of gasification (e.g., tar) can offer constraint to the plastic upcycling process (Zhao et al., 2022a, 2022b). In this respect, plasma- and supercritical water-assisted gasification can be useful options to overcome the limitations of conventional gasification process, although their scale-up is still not cost-effective (Yayalik et al., 2020; Bai et al., 2020).

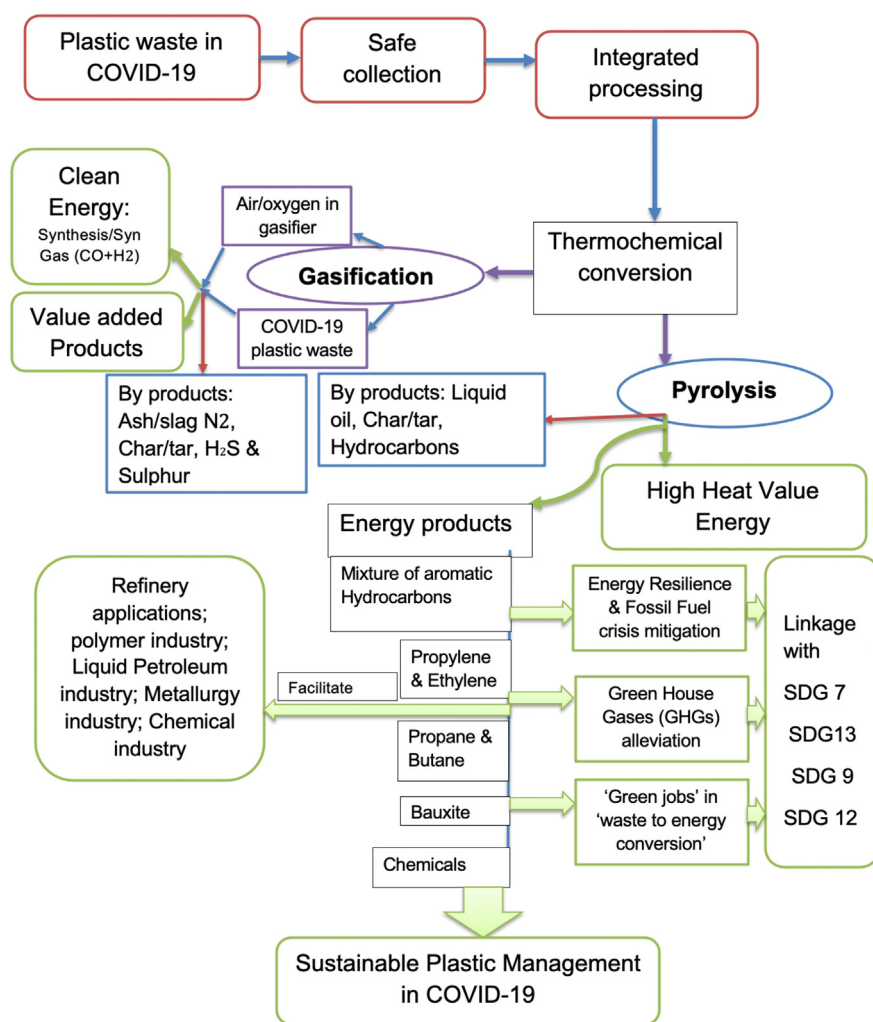


Fig. 5. During the COVID-19 pandemic, the role of “waste to wealth” (i.e., conversion of PPE plastic waste into energy and value-added products through clean thermochemical technologies such as pyrolysis and gasification in managing circular economies and meeting United Nations SDGs.

Technological innovations can help promote the conversion of PPE into renewable fuels or value-added chemicals to augment resilience in energy and climate actions (Zhao et al., 2022a, 2022b). The valorization of disposed face mask waste through gasification on Ni-loaded ZSM-5 type zeolites increased H<sub>2</sub> production while drastically reducing the production of hazardous byproducts such as NO<sub>x</sub> (Farooq et al., 2022). Likewise, co-processing of surgical masks with waste motor oil and biomass was capable of producing HHV hydrocarbons, matching the standards of green fuels with a yield of 89.58 % (Ardila-Suárez et al., 2022). Processing face masks in conjunction with Ca<sub>3</sub>Co<sub>4</sub>O<sub>9.8</sub> resulted in the formation of efficient-energy devices such as solid-state supercapacitors (Mendoza et al., 2022). The solar-driven transformation of plastic waste into renewable energy and hydrogen fuel is therefore expected to make a contribution to carbon-neutral economies (Uekert et al., 2021).

The collection of ecologically feasible recyclable plastics through *Cyclea* containers and selective drawers should efficiently minimize the energy intensive transportation process in dumping solid wastes (Santos et al., 2022). In addition, both the building of renewable energy infrastructure in rural communities and the evolution of “smart sustainable farms” can contribute to energy resilience, economic growth, and meeting SDGs during the pandemic (Pereira et al., 2022). Plastic waste can be converted to high-quality solid biochar through slow pyrolysis, which can help expand the renewable energy sector (Harussani et al., 2022). The pyrolysis of solid or PPE plastic waste as feedstock is therefore a sustainable strategy to minimize plastic footprints, enhance energy resilience, and revitalize the global economy (Fig. 5).

Energy resilience in tandem with the facilitation of sustainable bioeconomy can remarkably facilitate the rebuilding of the economic infrastructure in post COVID-19 phase (Rozakis et al., 2022). Social or community resilience in concert with promotion of green energy can be a sustainable way to revitalize the sustainable economic growth in post COVID-19 world (D'Adamo and Rosa, 2020). The maintenance of the energy resilience can therefore facilitate the multiple sectors such as climate smart health-care and social infrastructures related with sustainable economic recovery during COVID-19 (Heffron et al., 2021).

## 5.2. Circular economy

The upsurge in the generation of plastic pollution during the COVID-19 pandemic has resulted in a paradigm shift in waste management practices (Yuan et al., 2021). Under such conditions, the construction of a “sustainable plastic circular economy” needs to be pursued using integrated upcycling technologies with the participation of scientists, policy-makers, and government and industry representatives (Yuan et al., 2021; Shekhar et al., 2022). Circular economies can be the main pillar of various environmentally friendly interventions such as a “green deal” in Europe to recycle plastic waste during the pandemic (Kahlert and Bening, 2020). Circular economies rely on biological and biorefinery facets that can provide “nature-based solutions” to plastic waste pollution during a pandemic (Rai et al., 2022a, 2022b). In addition to the 4Rs, a sense of responsibility and a recognition of the wisdom of considering the entire lifecycle of plastics products. This approach to responsible consumption can significantly reduce the environmental footprint of plastic waste and make contributions to circular bio-economies (Fig. 4). Technological innovations in bio-economies such as bioplastics, biorefineries, and bioenergy fuels that can close the linear loop can make significant contributions to the sustainable management of plastics (Galanakis et al., 2022). The disinfection of plastic biomedical wastes through plasma gasification can generate value-added biorefinery byproducts (Kaushal et al., 2022). Furthermore, green approaches such as biorefining and valorization or co-gasification and co-incineration of plastic wastes into renewable energy can increase circularity during the pandemic. In this respect, biotechnological advances in enzymatic recycling can significantly enhance biorefinery approaches and bioplastics production (Rai et al., 2021b).

Biorefining in conjunction with a bioeconomy nexus can convert plastic waste into either energy or other value-added products, which can give a

strong impetus to develop circular bio-economies for sustainable plastic wastes management. For example, biochar derived from agriculture waste can be employed in the catalytic pyrolysis of face masks while simultaneously producing hydrocarbons (e.g., xylene and ethyl benzene) and H<sub>2</sub> (Wang et al., 2022a, 2022b, 2022c). Wang et al. (2022a, 2022b, 2022c) observed that biochar potentially adsorbs chemicals such as dyes emanating from pyrolyzed face masks during waste upcycling processes. The use of renewable lignocellulosic biomass as a feedstock for biodegradable plastics or bioplastics such as polyhydroxyalkanoates, polybutylene succinate, and polylactic acid (PLA) minimizes plastic pollution while strengthening the circular bioeconomy (Raj et al., 2022). Such sustainable solid waste management approaches can help minimize the plastic waste footprint in post COVID-19 world by offering nature-based solutions to global energy/environment footprint (Klemeš et al., 2020b). Further, reusable PPE with proper design standard, material selection, and disinfection technique can also help minimize the energy and environmental footprint (Klemeš et al., 2020a). The replacement of fossil fuel-based plastics with bioplastics can enhance the circular approach, although the cost-minimization efforts are insufficient (Singh et al., 2022). In this respect, PLA-based biodegradable face masks can be an alternative to fossil fuel-derived PPE (Soo, 2022). The biodegradation of PLA-based face masks completely mineralized non-woven face masks into CO<sub>2</sub> without converting them into MPs or NPs (Soo, 2022). Advancements in bioplastics are therefore required to curb PPE-related plastic pollution during the COVID-19 pandemic.

The wise application of polymers such as expanded polystyrene plastics can enhance the circularity of plastics with concomitant amelioration in environmental quality (Hidalgo-Crespo et al., 2022). In a study by Hidalgo-Crespo et al. (2022), the reduction in degradation factors (e.g., land use [−31 %], ozone depletion [−28 %], acidification [−24 %], and terrestrial and marine eutrophication [−21 %]) was noted from an environmental perspective. Sustainable polymer materials that are renewable and biodegradable in nature and incorporate environmental chemistry and engineering principles can therefore enhance the circularity in plastics manufacturing and management sectors (Tarazona et al., 2022). Use of renewable polymers (e.g., cellulose, gellan, and pectin) for the fabrication of surgical facemasks and replacement of conventional polypropylene based plastics with bioplastics in vaccine packaging can help successfully minimize the plastic waste footprint during COVID-19 (Hasija et al., 2022). Nevertheless, biodegradable plastics like PLA can also persist in environmental matrices for 2 years. Therefore, establishment of bioplastic waste management infrastructure is required before advocating their large-scale use in the COVID-19 (Vanapalli et al., 2021).

The circular bioeconomy approach to waste management can be regarded as a promising technology of wide public acceptance to be used for potentially valorize rural livelihood to increase the social participation in mitigating COVID-19 effects in a sustainability framework (Lima and Palme, 2022). Also, co-incineration of municipal solid waste and PPE plastic waste can minimize the environmental footprint with co-benefits of power generation and value-added products (Li et al., 2022; Zhao et al., 2022a, 2022b). Importantly, SDGs also bear remarkable analogies with circular bio-economies (Sharma et al., 2021) (Fig. 6). Circular bioeconomy can enhance the attainment of sustainability paradigm in waste management, SDGs, and carbon-neutral post pandemic future (Klemeš et al., 2021b; Muktadir et al., 2022). Circular bio-economies and the perception of communities of consumers or stakeholders can be combined to control plastic wastes during the pandemic (Grodzińska-Jurczak et al., 2022). The incorporation of circular economy approaches in supply chain management system can facilitate the sustainable production and consumption in post COVID-19 phase (Theeraworawit et al., 2022). Adoption of circular economy in decentralized government and corporate approaches can augment the sustainable supply chain management in terms of waste reduction and recycling (Theeraworawit et al., 2022). For sustainable plastic waste management in post COVID-19, decentralization of solid waste management practices with a bottom-to-top approach needs to be formulated for policy-makers (Sharma et al., 2021). Further, the Governmental initiatives on sustainable plastic waste management can be accelerated through the

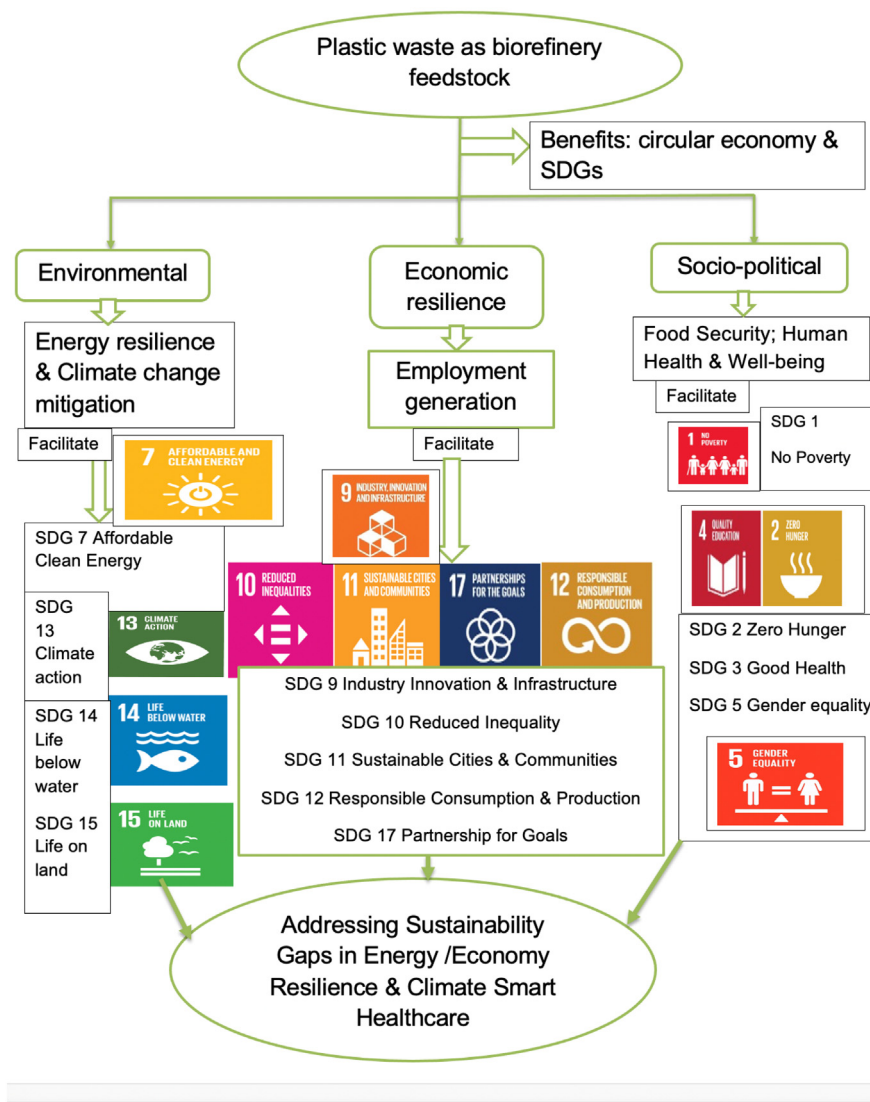


Fig. 6. A circular bioeconomy approach to plastic waste management during the COVID-19 pandemic is inextricably linked with adequate progress toward SDGs, climate action, energy resilience, and climate-smart health care.

involvement and cooperation of local communities (Ranjbari et al., 2022). Therefore, advances in circular bio-economics should present the potential to manage plastic pollution during the pandemic and lay the groundwork for climate-smart health care with a resilient economic system for sustainable post-pandemic future (Nandy et al., 2022).

### 6. Challenges and prospects

COVID-19 response and recovery may warrant holistic cross-cutting efforts to address multiple challenges such as environmental impacts, occupational health safety of solid waste workers or personnel, climate-smart health care, energy resilience, and circular economy (John, 2022). Accordingly, global emphasis on the implementation of safe health-care waste management services may help eventually mitigate the COVID-19 effects on environment, agriculture, food systems, socio-economy, and planetary public health (Rasul, 2021; Fan et al., 2021a, 2021b). The adequate environmental footprints quantification with a holistic plastic LCA approach is warranted to decide the pros and cons of plastic waste during the pandemic (Klemeš et al., 2021b). Although bioplastics generally display sustainable commercial plastic life cycles in view of using renewable biopolymers and carbon-neutral energy, their LCA also reveal several types of environmental risks (Rosenboom et al., 2022). Therefore, LCA is required prior to large-

scale bioplastics production. Also, bioplastics industry needs technological innovations with respect to recycling, advances in microbial gene editing, and biorefinery to efficiently promote the circular economy (Hossain et al., 2022; Rosenboom et al., 2022).

In relation to plastic-based circular economy, the majority of LCA methods emphasized end of life (EOL) assessment. Nonetheless, initial or early stages of supply chain should not be overlooked for sustainable plastic waste management (King and Locock, 2022). Consequently, plastics value chain should ensure holistic LCA approaches in terms of circular design, production, use, and waste management to facilitate the transition toward circular economy (Johansen et al., 2022). In this context, the technological advances in plastic recycling methods such as depolymerisation and pyrolysis can remarkably contribute to circular economy (King and Locock, 2022).

Catalytic cracking and microwave-assisted pyrolysis are emerging technologies to help upgrade the efficiency of conventional plastic waste pyrolysis. However, such advanced pyrolysis tools require further studies to scale-up the plastic conversion processes (Zhao et al., 2022a, 2022b). Future studies of plastics-based feedstocks for biorefinery and renewable energy should gradually lead to the evolution of the circular bioeconomy approach (Galanakis et al., 2022). It should be noted that the reduction and recycling are widely addressed for the plastic management, although the importance of its reuse has scantily been investigated (Klemeš et al.,

2021b). Henceforth, the future researches should prioritize studies on reuse of plastic waste for holistic transition to circular economy. Also, future advances in plastic upcycling technologies (e.g., modifications in polymer design and photo-reforming) can help efficiently transform plastic waste into energy and high-value added products (Zhao et al., 2022a, 2022b). The advances in nano-catalyzed upcycling of the plastic waste with the incorporation of coordination chemistry aspects can also remarkably contribute to circular economy (Wang et al., 2022a, 2022b, 2022c). Focused future studies on 'hybrid machine learning approach' and 'Pinch Analysis framework' can pave the way to maximize the plastic waste recycling to up-scale the circular economy in the time of COVID-19 (Chin et al., 2022).

## 7. Conclusions

Plastic waste footprints grew significantly during the COVID-19 pandemic through extensive trade and disposal of PPEs plastic waste to pose multiple hazards and risks to ecosystem health and environment. The weathering of disposed PPE plastics and the generation of MPs and NPs influences their environmental fate and behavior in multiple environmental matrices such as agroecosystems. MPs and NPs can adsorb hazardous chemical and pathogenic microbes to exacerbate human health risks. Increased demand for and disposal of biomedical plastics products during the pandemic exacerbated the challenges associated with sustainable waste management. Adequate LCA methods revealed that anaerobic digestion, landfilling, and incineration are not sustainable approaches and could contaminate multiple environmental matrices with chemicals, microbes, and ARGs. As such, traditional and linear approaches in plastics manufacturing and management adversely influenced progress toward meeting SDGs, renewable energy, economic resilience, and climate action. At the same time, thermochemical conversion (through pyrolysis and/or gasification) of plastic waste into energy and value-added products can help close resource loops through by enhancing circularity and energy resilience. Likewise, explicit analysis of the lifecycle stages or LCA of PPE plastic waste and associated energy-conversion technologies can identify the measures necessary to reduce GHGs emissions and support action on building climate-smart health care. The coming transition from linear to circular economies, along with a nexus approach to bio-economies can make positive contributions to sustainability issues during the COVID-19 pandemic.

## CRedit authorship contribution statement

**Prabhat Kumar Rai:** Investigation, Methodology, Data curation, Formal analysis, Writing – review & editing. **C. Sonne:** Conceptualization, Formal analysis, Writing – review & editing. **H. Song:** Conceptualization, Formal analysis, Writing – review & editing. **Ki-Hyun Kim:** Conceptualization, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing.

## Data availability

Data will be made available on request.

## 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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