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Challenges and strategies for effective plastic waste management during and post COVID-19 pandemic



Kumar Raja Vanapalli^a, Hari Bhakta Sharma^b, Ved Prakash Ranjan^b, Biswajit Samal^a, Jayanta Bhattacharya^{a,c,*}, Brajesh K. Dubey^{a,b}, Sudha Goel^b

^a School of Environmental Science and Engineering, Indian Institute of Technology, Kharagpur 721302, West Bengal, India

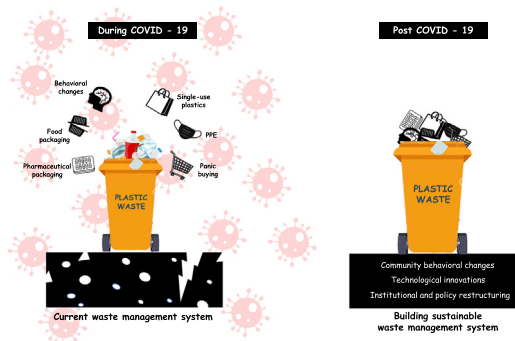
^b Department of Civil Engineering, Indian Institute of Technology, Kharagpur 721302, West Bengal, India

^c Department of Mining Engineering, Indian Institute of Technology, Kharagpur 721302, West Bengal, India

HIGHLIGHTS

- COVID-19 has increased our reliance on plastics for safety and hygienic purposes.
- Increase in plastic waste generation adds up to the woes of our management system.
- Temporary relaxation on use of single-use plastic could alter consumer's behavior.
- Innovation in existing products and technologies could help achieve sustainability.
- Social responsibility, corporate action, and government policy are vital for change.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:

Received 17 June 2020

Received in revised form 20 July 2020

Accepted 3 August 2020

Available online 4 August 2020

Editor: Dr. Damia Barcelo

Keywords:

Plastic waste

Personal protective equipment

COVID-19

Waste management

ABSTRACT

The advent of the COVID-19 pandemic has enhanced the complexities of plastic waste management. Our improved, hyper-hygienic way of life in the fear of transmission has conveniently shifted our behavioral patterns like the use of PPE (Personal protective equipment), increased demand for plastic-packaged food and groceries, and the use of disposable utensils. The inadequacies and inefficiencies of our current waste management system to deal with the increased dependence on plastic could aggravate its mismanagement and leakage into the environment, thus triggering a new environmental crisis. Mandating scientific sterilization and the use of sealed bags for safe disposal of contaminated plastic wastes should be an immediate priority to reduce the risk of transmission to sanitation workers. Investments in circular technologies like feedstock recycling, improving the infrastructure and environmental viability of existing techniques could be the key to dealing with the plastic waste fluxes during such a crisis. Transition towards environmentally friendly materials like bioplastics and harboring new sustainable technologies would be crucial to fighting future pandemics. Although the rollbacks and relaxation of single-use plastic bans may be temporary, their likely implications on the consumer perception could hinder our long-term goals of transitioning towards a circular economy. Likewise, any delay in building international willingness and participation to curb any form of pollution through summits and agendas may also delay its implementation. Reduction in plastic pollution and at the same time promoting sustainable plastic waste management technologies can be achieved by prioritizing our policies to instill individual behavioral as well as social, institutional changes. Incentivizing measures that encourage circularity and sustainable practices, and public-private investments in research, infrastructure and marketing would help in bringing the aforementioned changes. Individual responsibility, corporate action, and government policy are all necessary to keep us from transitioning from one disaster to another.

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* Corresponding author at: School of Environmental Science and Engineering, Indian Institute of Technology, Kharagpur 721302, West Bengal, India.
E-mail address: jayantab@mining.iitkgp.ernet.in (J. Bhattacharya).

1. Introduction

The perils of plastic pollution have mobilized global governments, business corporations, and local communities to combat against its proliferation in the environment (Schnurr et al., 2018). Social, technological, and institutional amendments like nationwide phasing out of single-use plastics, resolutions by businesses and corporations to reduce their plastic footprint, initiatives by non-profit organizations to clean up beaches and ocean, behavioral changes in public to reduce consumption and littering of single-use plastics have raised hope of positive changes in the recent past (Heidbreder et al., 2019; Moore, 2015; Xanthos and Walker, 2017). Moreover, the amendment of the Basel Convention on the Control of Transboundary Movements of Hazardous Waste and their Disposal to include plastic waste in a legally-binding framework in 2019 which was ratified by more than 180 countries has promised improved regulation of plastic waste trade (UNEP, 2019). The announcement of plastic pollution as a worldwide crisis by the United Nations in 2017 (UNEP, 2017) has made several businesses establishments to adjust their corporate strategies, preparing for an accelerated transition to a circular economy.

The advent of the COVID-19 pandemic has however, enhanced the complexities of plastic waste management. Alarming cases of infection have exerted personal protective equipment (PPE) (containing a substantial proportion of plastic) as the most reliable and affordable defense against infection and transmission of the virus (Herron et al., 2020). The increased demand for single-use PPE by doctors and other health care workers and mandated usage of masks for the public (to contain the spread of the disease) has transformed the dynamics of plastic waste generation. The perception of hygienic superiority of single-use plastics over other alternatives has shifted the consumer choice in favor of plastic packaging and single-use plastic bags (Scaraboto et al., 2019). Moreover, national lockdowns and home quarantine orders have stimulated an increased reliance on online delivery of food and other essential groceries which has induced a plausible increase in plastic packaging waste generation (Scaraboto et al., 2019; Singh, 2020; Staub, 2020). Although this new paradigm has underscored the public value of plastic, it has also highlighted our vulnerabilities to pollution. Fig. 1 shows how the mismanagement of masks and PPE kits has become a new nuisance to the already existing worst marine litter (NGO Oceans Asia, 2020).

First of all, as opposed to the general perception of plastic as evil, its sheer mismanagement and underutilization of the resource make it harmful to the environment (Borg, 2020). However, due to their flexibility, durability, water resistance, and affordability, plastics have fuelled scientific and technological innovations in every sector possible (UNCTAD, 2018). Their utility is evident in the protection of health and safety of the frontline health workers of the pandemic and the public. Plastics are one of the significant components of medical equipment and protective gear in use. However, mixed plastics like that of single-use masks with layers of plastics combined with other materials also pose a great threat to the environment due to their low recyclability (Tenenbaum, 2020). The inadequacies and discrepancies in the existing waste management systems like shortage of staff, capacity constraints of treatment facilities, disruptions in mechanical recycling facilities due to the pandemic, could lead to improper disposal of wastes polluting the environment (B.I.R., 2020). Furthermore, several infectious waste plastics like masks, gloves and face shields could also cause greater havoc of viral transmission without proper sterilization (Shah et al., 2020). As the world starts to move ahead of this pandemic, we might realize that our increased dependence on plastics at the expense of our environment has resulted in a new plague of plastic waste which we were struggling to come in terms with.

Unique to the current crises, this article presents a prospective outlook on the disruption caused by COVID-19 on plastic waste management throughout the world. The objective of this review article is to highlight the implications of COVID-19 on plastic waste generation. The article also sheds light on the challenges brought upon by the pandemic on the current waste management systems. While presenting the potential technological strategies for the post-pandemic world, the article also reviews the status of laws, regulations, and policies which have been compromised/affected during the current crisis of COVID-19 pandemic. Future direction and recommendations to bring personal behavioral and social institutional changes for inclusive and sustainable plastic waste management have also been discussed in detail.

2. Implications of COVID-19 on plastic waste generation

It is important to acknowledge that we live in a new and unfamiliar reality after the outbreak of the COVID-19 pandemic. With the temporary closure of restaurants and shops during lockdowns and “stay-at-



Fig. 1. (a–d). Littering of PPE kits has become a new nuisance to already existing worst marine litter (Masks found washed up on the beach during the pandemic at Soko Islands, Hong Kong during an environmental survey carried out by Marine conservationist NGO group- Oceans Asia; Photo credits: Naomi Brannan) (NGO Oceans Asia, 2020).

home” directives imposed by governments, the current situation has altered our living and consumption habits, creating uncertainty in our waste generation patterns (Bengali, 2020). Even, our fixation for hygiene in the face of fear of transmission has conveniently shifted our behavioral patterns like the use of PPE, extensive demand for plastic-packaged food and groceries, and the use of disposable utensils, both for convenience and reassurance (Tenenbaum, 2020).

A temporary relaxation on single-use plastic bag bans in several states of the U.S (United States) like New York, Massachusetts and New Hampshire (Patrício Silva et al., 2020; Prata et al., 2020) is likely to have long-term consequences on consumer behavior (Tabuchi, 2020). The rollback of such policies restricting the use of single-use plastic bags can cause increased generation of waste plastic bags and re-induce use and throw away culture in the consumers, causing a shift in their sustainable lifestyle. Despite the lack of any conclusive evidence of reduced risk of viral transmission from these single-use bags, such a stance taken by governments may integrate people’s belief of plastic as hygienic. The ability of coronavirus to survive on plastic surfaces for up to three days as compared to paper (3 h), cardboard (1 day), cloth (2 days) also contradicts this view (van Doremalen et al., 2020).

Moreover, corona virus-induced paranoia has led to irrational stockpiling of groceries and other household essentials, causing undesirable demand for packaged products with long life in several countries (Sharma et al., 2020). Especially, proactive health-minded and reactive health management are two of the key consumer behavior thresholds linked to the pandemic panic shopping. Despite persistent challenges, in light of the pandemic, online purchases and e-commerce have become de facto fall-back solutions (WTO, 2020). In spite of high operational costs, hiring new staff, and additional costs on safety measures, Amazon e-commerce services recorded a 26% increase in their year-on-year sales in the first quarter of 2020 (Amazon Press Release, 2020).

There was a reported increase in online food purchases and daily necessities by 92.5% and 44.5%, respectively in South Korea relative to last year due to the COVID-19 pandemic (Hyun, 2020). The study also reported a surge in online shopping by 12–57% in countries like Vietnam, India, China, Italy, and Germany during the same period. A market research firm, Rakuten Intelligence has reported a 50% more growth than the annual 20% growth in online shopping in the U.S. from March to mid-April (Rattner, 2020). The dominance of single-use plastic packaging in e-commerce would lead to accretion of plastic

waste comprising of thin films, foam, and multi-layered plastic, which have low recyclability (UNEP, 2018).

The tremendous increase in the use of PPE – like gloves, face masks, and gowns, by healthcare workers, fuelled by the outbreak are disposable after single use generating an enormous amount of plastic waste (WHO, 2016). Besides, the protective equipment used by the healthcare staff and infected patients inside an ambulance including hoods, masks, gloves, gowns, during their transfer to healthcare facilities, are generally disposed of post transport (Higginson et al., 2020). Moreover, the increased biomedical waste generation from laboratory studies and testing which includes a considerable proportion of plastics also contributes to the problem. The inadequacies of the existing waste management system to deal with the fluxes of this momentum could result in its sheer mismanagement. According to a WWF report, “if just 1 % of the masks were disposed of incorrectly and dispersed in nature, this would result in as many as 10 million masks per month polluting the environment” (Italy WWF, 2020). Experts say that face masks imported from China are made of multiple layers of different polymers, making them much harder to recycle (Monella, 2020). During the COVID-19 outbreak in Hubei Province, the People’s Republic of China (PRC), infectious medical waste (having a substantial proportion of plastic) observed an increase by 340% from 40 tons per day to 240 tons per day (Klemeš et al., 2020).

Moreover, the increased usage of medication by patients, self-medication with over-the-counter medicines (non-prescription drugs), surge in demand for popular immunity booster medicines can increase the generation of pharmaceutical packaging waste like blister packs, bottles, etc. from hospitals and households. It is understood here these infectious plastic waste generated from hospitals and at homecare facilities should be collected, treated, and disposed of as per the biomedical waste management rules, which is often country-specific (WHO, 2020a). The infected plastic waste should not be a part of the municipal solid waste (MSW) recycling stream as the chances of viral transmission to the people involved would be very high (Sharma et al., 2020).

The demand for plastic in other sectors (automobiles, aviation, construction) has, however, drastically reduced in the likely economic crisis due to the COVID-19 pandemic (Klemeš et al., 2020). The public paranoia about hygiene and health safety has altered their perception of re-usable cups, bags, etc. as a disease threat. The coronavirus crisis reality



Fig. 2. Implications of COVID – 19 on plastic waste generation.

check has hampered with the global ambition of reducing plastic waste generation. The loss of people's faith in products without packaging could risk the return of the throw-away culture and cause the resurgence of usage of single-use plastics.

So, apart from the waste generated through increased use of personal protective equipment, the rise in demand for plastic packaged products including pharmaceuticals, online delivery services of food, and groceries can be considered as major sources of plastic waste during the pandemic. Also, the consumer behavioral changes could fuel an increase in the use and disposal of single-use plastics contributing to the global plastic waste problem (Klemeš et al., 2020). Fig. 2 shows the implications of COVID-19 on plastic waste management in brief.

3. Challenges for the current waste management systems

The most extensively used techniques of plastic waste management across the globe are mechanical recycling, incineration, and landfilling. Ellen McArthur Foundation estimates the global mechanical recycling rates of waste plastics at 16%. In comparison, the remaining waste plastics were either incinerated (25%), sanitary/unsanitary landfilled (40%), or gets leaked into the environment due to mismanagement (19%) as shown in Fig. 3 (Ellen MacArthur Foundation, 2017). However, these techniques are far from perfect in containing the whole problem of plastic waste; let alone, with increased waste generation during the COVID-19 crisis, the woes only became much worse.

Polymer cross-contamination, presence of additives, inorganic impurities, irregular or inadequate segregation at source or during collection, and partial polymer degradation have always been the major constraints for mechanical recycling of waste plastics (Hopewell et al., 2009). It has been a successful endeavor for the recycling industry to recycle some of the single-stream plastics with minimal impurities like Polyethylene Terephthalate (PET) bottles with almost 80% recycling rates in countries like India (Abraham, 2019). However, the success could not be replicated with all the types of plastics, especially with single-use plastics (especially, film and foam) and multi-layered plastics that have low reward to effort ratio in their collection, high pre-processing costs, technological constraints, and weak integral structure (UNEP, 2018). Moreover, the plummeting of oil prices during COVID-19

caused a dramatic decrease in the value of virgin plastics affecting the competitiveness of recycled plastics in the market (Bell, 2016; Walker, 2020). Furthermore, shortage of staff due to the fear of viral transmission during the collection and handling of waste plastics and restricted transportation have crashed the plastic recycling industry (B.I.R, 2020). The unorganized recycling sector, which is predominant in the developing countries, has suffered the most with frequent cash crunches due to low collection efficiency and unavailability of the market for recycled plastics (Sharma et al., 2020). These disruptions in the recycling industry, causing an inability to utilize its full potential, along with an increased generation of plastic waste could result in mismanagement leading to their leakage into the environment. The shift of production, use, and recycling markets from North America and Europe to Asian countries with weak waste management systems and infrastructures is also proving to be another problem contributing to low plastic recycling rates (National Academies of Sciences, Engineering, 2020).

Although mechanical recycling is considered relatively environmentally friendly in comparison, the added advantage of treating waste irrespective of segregation, cross-contamination, additives, and impurities make incineration much efficient in dealing with diverse and non-recyclable plastic wastes. Incineration is popular in northern Europe for handling MSW (including plastic waste) for its ability to recover energy complementing the energy needs of the market. Some of the developed nations like Sweden, Denmark, and Poland have adopted advanced and improved technology for air pollution control in their 'waste to energy' technology for treating waste (Malinauskaite et al., 2017). Sweden is a very good example in terms of energy output (23%) recovery from both municipal and industrial waste incineration (Ericsson and Werner, 2016). However, Sweden is obliged to follow the waste hierarchy and achieve specified targets of achieving plastic packaging recycling of 55% by 2030 set by the European Union and so to reduce its dependence on waste to energy (Milios et al., 2018). So, although incineration can be treated as an immediate solution amidst the COVID crises, for a long and ideal scenario, waste hierarchy dominated by the concept of reduce, reuse and recycle is always recommended to be followed.

The World Health Organisation (WHO) has mandated incineration of PPE and other infectious/hazardous waste, especially made from

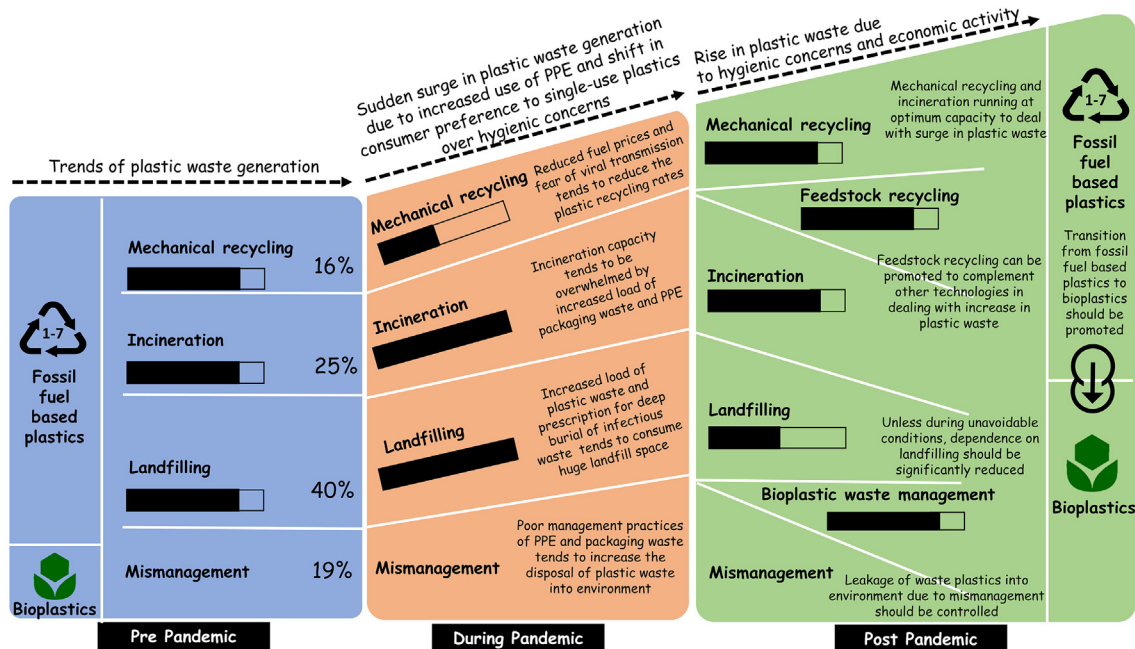


Fig. 3. Trends of plastic waste generation and implications of COVID-19 on existing waste management systems and probable solutions for the challenges in waste management systems post-pandemic (data obtained from Ellen MacArthur Foundation, 2017).

plastic; the directive has increased the load on the incineration facilities (WHO, 2017). The existing incineration infrastructure could not complement the tremendous rise in the plastic waste generation. The estimated accumulated medical waste 240 t/d in Wuhan, China has overwhelmed the maximum incineration capacity of the province (49 t/d) (Klemeš et al., 2020). Moreover, the serious concern about the release of hazardous gases like dioxins and furans during the process always exists with inefficient and under-maintained systems having nominal air pollution control equipment (Batterman, 2004). Plastic waste managed by incineration alone had contributed equivalent to 5.9 million metric tons of CO₂ by emission in the U.S. and globally 16 million metric tons of greenhouse gases in the year 2015 (Azoulay et al., 2019). According to the world energy council, greenhouse gas emission was predicted to increase to 49 million metric tons and 91 million metric tons by 2030 and 2050, respectively, as per previous estimates of the production of plastic and incineration (World Energy Council, 2019). But with COVID-19, the WHO has called for an increase in the production of plastics by 40% to meet the rising global demand (WHO, 2020b), which ultimately ends up in the waste stream. Discrepancies in the recycling industry could lead the waste to incineration, which could promote greenhouse gas emissions into the environment than the expected, ultimately fueling global warming.

Although at the bottom of the scientific disposal pyramid, landfilling is one of the prominent ways of plastic waste management, especially in the developing world. Although some of the metropolitan cities might have scattered scientific landfills, unsanitary landfill, or dumping of waste is predominant in many of these places (Vanapalli et al., 2019). Although incineration is recommended for its energy recovery from the material, landfilling is often considered to be more prevalent strictly from a waste management perspective (Hopewell et al., 2009). A CO₂ assessment study based on non-recyclable plastics revealed that landfilling causes less CO₂ emissions (253 g per kg) compared to incineration (673–4605 g per kg). However, since most of the developing and underdeveloped world still follow unsanitary dumping of waste, it leads to tremendous space constraints, leaching of harmful chemicals, and can also result in open surface fires in dumps, often resulting in the release of harmful air pollutants like dioxins and furans (Azoulay et al., 2019). Moreover, the rise in plastic waste generation, disrupted recycling markets, capacity constraints experienced by incineration during the COVID-19 crisis are causing increased load on waste dumps, and landfills overwhelming their capacity. Further, with inefficiencies and inadequacies of the existing waste management systems and lack of proper implementation of environmental regulations in the wake of the pandemic, there is a tremendous rise in the mismanagement of plastic waste causing serious environmental implications.

4. Potential technological strategies for the post-pandemic world

With limited available solutions, there is a substantial need for innovations which should involve addressing key challenges in plastic waste collection and integrating new technologies in segregation and treatment into the existing waste management system. While improving the capacity and efficiency of the old processes and technologies, these new advancements can complement their capability in sustaining the upcoming surges in the waste generation.

Scientific sterilization of infectious waste at on-site treatment facilities of healthcare centers like steam-sterilization (autoclaving), energy-based treatments (microwave, radiowave), incineration, chemical disinfection would guarantee the reduced risk of viral transmission from contaminated PPE and other plastic waste (Rutala and Weber, 2015). The WHO has recommended high-temperature burn incineration as a preferred technique for the treatment of infectious waste (WHO, 2020a). It was further advised that in case of emergencies with no access to such technologies, deep burial should be preferably practiced (Chartier et al., 2014; Sharma et al., 2020). Moreover, while considering the transfer of waste to a centralized biomedical waste treatment and

disposal facility, safe collection and storage practices should be ensured at medical facilities to prevent infections from the mismanagement of contaminated disposable waste (WHO, 2005). Equipping sanitation staff involved with the collection and conveyance of waste with adequate safety equipment and gear would also minimize the risks (Di Maria et al., 2020). Moreover, a shift to automated systems with integrated artificial intelligence for segregation of the waste would reduce the risk to the health and safety of labor involved. The introduction of artificial intelligence-enabled automated systems for segregation could improve the efficiency and speed of recycling and enhance the quality and so the value of recycled products (Chidepatil et al., 2020). Although automation might eliminate the need for manual labor, the improved waste valorization could generate employment in the fields associated with the gainful utilization of these by-products. So, this should be viewed as redefining the jobs and development of skilled labor, rather than merely eliminating them.

As depicted in Fig. 3, the plastic waste generation is expected to rise post-pandemic due to the hygienic concerns and bounce back of the economic activity. With an increased capacity to handle the post-pandemic waste surges, the up-gradation of existing systems should be ensured. Effective mechanical recycling of plastics requires functional improvement from all the sectors across the plastic value chain. Mandated resin coding on every plastic packaging would improve the recyclability of single-use plastics (Leissner and Ryan-Fogarty, 2019). Restrictions should be laid on multi-layered and other complex forms of plastic packaging which often end up in landfills or prone to leach into the environment due to their low recyclable value (Dilkes-Hoffman et al., 2018). After the pandemic, the existing load on incineration plants is expected to come down to normal optimum levels due to the revival of recycling industry and reduction in infectious waste. However, the design of incineration plants should be modified to incorporate the fluxes in the characteristics and the quantum of wastes for any probable future crisis. Moreover, they should be upgraded with highly advanced emission control technologies that provide clean energy and thereby reduce climate impacts and pollution (Damgaard et al., 2010). Since landfills and waste dumps promote material and energy loss (Vanapalli et al., 2019), efforts should be taken to significantly reduce their usage.

Feedstock recycling can be an effective technology to complement mechanical recycling in the management of plastic waste as a way to “close the loop” by recovering materials and thereby reduce the need for virgin materials (Ellen MacArthur Foundation, 2016a). Feedstock recycling can also work better even if the waste is sparsely contaminated with organics so that it can be a more sustainable solution than incineration or landfill of plastic waste (Hopewell et al., 2009). According to a life cycle assessment (LCA) study, it was found that feedstock recycling of mixed plastic waste emits 50% less CO₂ than the incineration and has similar emissions as of mechanical recycling of mixed plastic waste (BASF, 2020). The study also revealed that fuels obtained through feedstock recycling of plastics cause significantly lower CO₂ emissions than those produced from primary fossil resources. Research suggests that the quality of liquid oil obtained from the same was relatively similar to that of crude oil (Wong et al., 2017). However, for effective and functional feedstock recycling, associated waste processing costs, quality of the products, availability of markets, and economic sustainability of the process should be looked after. Also, the environmental viability of the process should be ensured with flexibility for current and future regulations that could affect the volume and cost of feedstock. Investment in improving the efficiency of the process, if encouraged, could make it more economically viable and can produce competitive products that have the potential to satisfy multiple market needs (Chandrasekaran et al., 2015).

The recyclability and environmental viability of bioplastics are heavily dependent on its base design and the choice of raw materials (Ahimbisibwe et al., 2019; Emadian et al., 2016). Although most of the bioplastics claim to be biodegradable, their complete degradability is

restricted by a set of limitations. For example, some of the bioplastics such as Polylactic acid (PLA) require an industrial scale composting to be biodegradable (van den Oever et al., 2017). So, while promoting the use of bioplastics, development of necessary infrastructure should also be encouraged for effective bioplastic waste management (Bezirhan and Bilgen, 2015; Lorber et al., 2015). The development of diversified waste management strategies as depicted in the post-pandemic section of Fig. 3 would ensure the readiness for any kind of future crisis, as one technology or product could complement another in dealing with the variability of problems associated with it.

A shift to circular base materials could only be possible with the support and push from the producers and consumers alike. The rise in demand itself creates value, which will drive investment to promote such products that will grow environmental and economic sustainability (Confente et al., 2020; OECD, 2013). A shift towards the circular economy will help in making economic benefit of equivalent to 624 billion U.S. dollars and also help in reducing carbon emission by 44% in 2050 as compared to the current development path (Ellen MacArthur Foundation, 2016b). A push in that direction could balance the convenience, cost, and serviceability of the products while reducing the carbon footprint.

5. Status of laws, regulations, and policies with respect to plastics during COVID-19 pandemic

One of the major ramifications of the COVID-19 crisis has been the reduction in the mechanical recycling of waste plastics in some major cities of the world. For example, some major cities in the U.S. have temporarily suspended recycling programs fearing the risks of contaminated waste in recycling centers (Kaufman and Chasan, 2020). The recycling industry in the U.S. which is already stressed out by the Chinese sword policy of 2017, is facing numerous challenges due to the ongoing pandemic (Trentmann, 2020). While smaller municipalities were dropping their collection services (Kaufman and Chasan, 2020), few cities were continuing with their curbside pickup programs. The Organisation for Economic Co-operation and Development (OECD) (OECD, 2020) has ensured that all cities will guarantee waste collection however they have also proposed the closure of some of its recycling centers as the cases of COVID-19 spikes.

The U.S. has been at the forefront in retracting several laws and policies regarding single-use plastics. States like New York, Massachusetts, Maine, New Hampshire, and Oregon have temporarily postponed or rolled back their policies of plastic bag bans and restricted the use of reusable shopping bags fearing the spread of the virus (Bomey, 2020; Chang, 2020). While, San Francisco, the first U.S. city to outlaw disposable plastic bags in 2007, has restricted its businesses from "permitting customers to bring their own bags, mugs, or other reusable items from home" (Department of Public Health, San Francisco, 2020), the state of California has waived the charge of 10 cents (0.1 USD) per bag collected from grocery and retail stores and temporarily suspended the restrictions on the use of thinner single-use plastic bags (Ronayne, 2020). The United Kingdom has also suspended its mandated plastic bag charge for online deliveries, while Scotland delayed its anticipated packaging deposit-return scheme (Department for Environment Food and Rural Affairs, 2020). South Australian government has also decided to pushback its ban on some single-use plastics allowing restaurants and cafes to use disposable items to improve hygiene amid the coronavirus pandemic (Dayman, 2020). Even, some of the fast food and retail chains, including Starbucks, have banned the use of reusable cups and food containers and temporarily shifted to disposables (Johnson, 2020).

Plastic lobbyists in the U.S. are trying to seize the crisis arguing for single-use plastics as an ultimate option for maintaining hygiene and longer shelf life for fresh produce (Plastic Industry Association, 2020). Plastic manufacturers in countries like Turkey, Germany, and Italy were also trying to exert pressure on their respective governments (Lerner, 2020). However, most of the world's jurisdictions with notable

bans or fees on single-use plastic packaging have maintained their policies. For example, although the United Kingdom has postponed its ban on the use of some of the plastics till October, the European Union legislation is still persistent to its single-use plastic directive deadline of 2021, despite pressure from the industry to postpone (Southe, 2020). Some of the African countries including Kenya, Burundi, Rwanda, Tanzania, Uganda are still pursuing their policies like bans and tipping fees for containment of plastic pollution (Lerner, 2020). Vancouver, Canada is still on track with its plan to ban plastic shopping bags by January 2021, although enforcement of some of the bylaws is on hold until further notice (Patrício Silva et al., 2020; Robinson, 2020). The Chinese Ministry of Ecology and Environment announced in mid-March 2020 that it would temporarily suspend environmental standards for small businesses to accelerate economic recovery (Xu and Goh, 2020).

Likewise, major international environment summits like: Ocean Biodiversity Beyond National Jurisdiction postponed, UNFCCC Climate Conference in Glasgow, World Conservation Congress, UN Convention on Biodiversity, UN SDG Conference have been postponed. Delays of these summits could divert many countries to shift the agenda towards COVID-19 health and economic recovery policies, and away from environmental priorities. Any delay in building international willingness and participation to curb any form of pollution through summits and agendas may likewise delay its implementation (Dinneen, 2020; Farand, 2020; McKie, 2020; United Nations, 2020).

After the pandemic, when the world tries to bounce back on its economic growth rampage, failure to inculcate low carbon development strategies and policies in the economic stimulus packages by policymakers would undo all of the environmental development achieved through global consensus over the last few decades (Myllyviritys, 2020). Conversely, the rollback of existing climate policies in response to the upcoming economic crisis, emissions could rebound and even overshoot previously projected levels by 2030, despite lower economic growth (Climate Action Tracker, 2020). There emerges a need for a universal action plan, rather than some scattered environmental policies by a handful of countries in this grim reality (Konov, 2020). Some of the major world economies like the European Union, South Korea, Indonesia have taken positive steps in this regard. While European Union promised 25% of its economic stimulus package of coronavirus crisis to climate-friendly measures (European Commission, 2020), the South Korean government has pledged to reduce greenhouse gas emissions to net-zero by 2050 (Jaeger, 2020). COVID-19 recovery presents both opportunities and threats to enhance our resilience to climate change and environmental pollution caused by solid waste/plastic waste (Sharma et al., 2020).

6. Future direction and recommendations to bring personal behavioral and social institutional changes for inclusive and sustainable plastic waste management

6.1. Future direction

As lockdowns and other restrictions are gradually lifted, we may find our reliance on plastic has increased. Resumption of economic activity and movement of people would result in increased use of PPE and single-use plastics which would cause a surge in waste generation. Managing the surge in single-use plastic waste will be an enormous challenge for governments, even more so in many developing nations. Without proper planning and necessary policy intervention, aggravated mismanagement of waste would result in its leakage into the environment, thus triggering a new public health crisis.

Solving the COVID-19 crisis cannot come at the expense of solving the longer-term issue facing humanity: the climate crisis (Climate Action Tracker, 2020). Unless technological advances introduce better alternatives, we may need a systems-level approach from companies and governments on a global scale to address the issue of plastic and

protect our environment (Konov, 2020). Corporations and governments around the world should allocate more funds to educate people on how the circular economy works and why they should reuse and recycle (Sharma et al., 2020). Complementary public and private investments in physical infrastructure as well as greater regulatory incentives for people and companies to recycle and reuse worldwide (Konov, 2020). Research has found that merely providing information through awareness campaigns is unlikely to change behavior. For instance, media attention and campaigning about the disposal of PPE like masks and gloves in a sealed garbage bag can increase the public visibility of the safety of the sanitation workers (Prata et al., 2020). This can indirectly influence our behavior by making us more open to other interventions and by signaling social norms – the unwritten rules of acceptable behavior (Huang, 2016). Once we are aware of an issue, we may need a little help to move from intention to action. Voice prompt intervention induced context change and promotes pro-environmental behaviors as a recent study shows (Ohtomo and Ohnuma, 2014). A prompt is a visual or auditory cue that reminds people to carry out a target behavior. The effect of a prompt is not to persuade people to change their behavior but to recall people's consciousness towards an action that they intended to perform (McKenzie-Mohr, 2011). Our dependence on single-use plastic products can be successfully phased out by changing the norms. The more we talk about the problem and the solutions, the more businesses would seek out and offer alternatives, and the more likely we are to mobilize together (Borg, 2020).

In every current plastic pollution discourse, the talk about potential plastic replacement by bioplastic is prominent. However, a recent study revealed that biodegradable and oxo-biodegradable plastic formulations persisted and remained functional in the soil and marine environments even after three years. In the case of the compostable bag, although it completely disappeared in the marine environment in 3 months, the product remained intact in soil (Napper and Thompson,

2019). It is therefore not clear that the biodegradable formulations provide sufficiently advanced rates of deterioration to be advantageous in the context of reducing marine litter, compared to conventional bags (Katz, 2019). Other studies even indicated the potential of these bioplastics to undergo disintegration and degradation into micro and nano plastics which could act as a threat to the marine, air, and soil environments (Balestri et al., 2017; Shruti and Muniyasamy, 2019; Sintim et al., 2020). The accumulation of microplastics in the environment from the fragmentation of bioplastics poses a greater threat to the environment than the original intact litter (Napper and Thompson, 2019). Therefore, taking the current crisis in mind even if PPE would be made from such (bioplastic) materials it would not be a silver bullet as biodegradable plastic solutions on their own are not the answer to reducing marine litter. The most essential element is that PPE and all waste needs to be disposed of and managed properly, according to the guidelines placed by the competent authorities. Integrated solutions inclusive of efficient technologies, sustainable products, awareness for litter prevention, and regulation of illegal dumping activities by law will be successful in reducing the problem of plastic waste (Willis et al., 2018). Pro-environmental actions from every stakeholder including scientists, policymakers, industry, and the general public are needed to avoid any shift of responsibility (Heidbreder et al., 2019).

6.2. Recommendations

To overhaul the plastic waste management sector we need to induce the necessary personal behavioral and social institutional changes. Building an appropriate institutional framework along with policy-level directions will help facilitate the required change. The necessary inclusive and sustainable plastic waste management can be achieved when both personal behavioral and social institutional changes take place gradually and simultaneously (as shown in Fig. 4). Few short-term and long-term

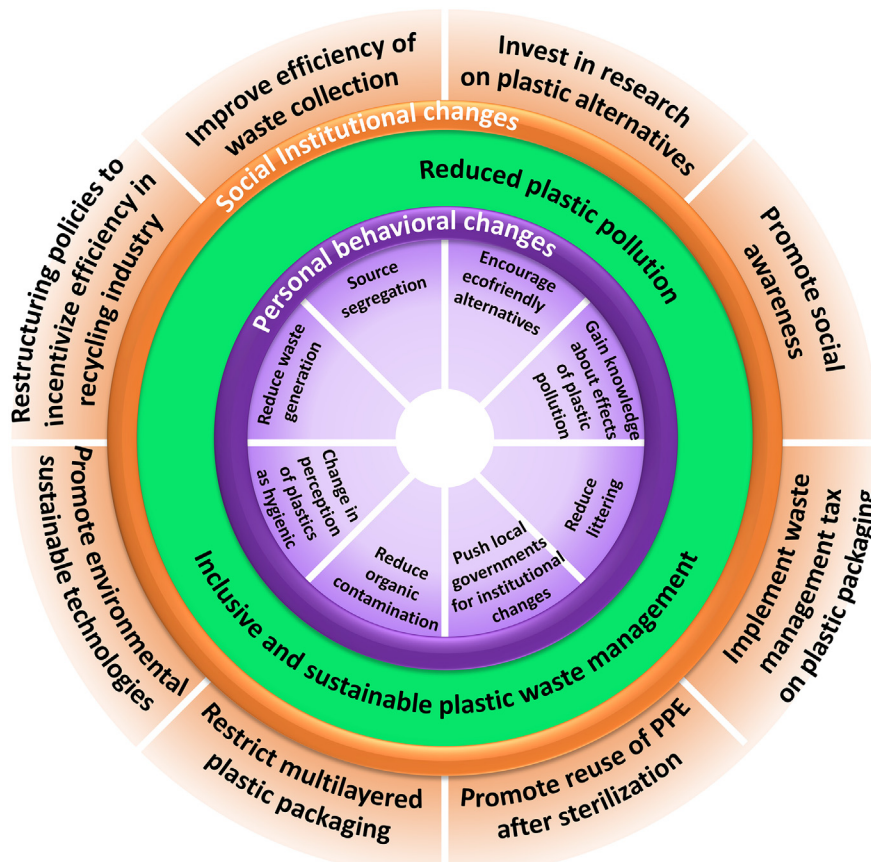


Fig. 4. Illustration depicting an approach to reduce plastic pollution and to bring more inclusive and sustainable plastic waste management.

recommendations based on the detailed study are listed below for policymakers to bring out necessary changes to combat the inevitable rise in the use and disposal of single-use plastics, post-pandemic.

1. Design of policies addressing the psychological and behavioral barriers, including mistrust over hygienics of reused and recycled products and creating awareness among the public against the perception of single-use plastic as protection rather than a problem.
2. Specific colored bags might be provided by the local authority to households to dispose of PPE kits (mask, gloves) in sealed bags, which makes them easy for separation and treatment along with biomedical wastes. Specific colored bins might be provided in community places to improve the collection of such wastes.
3. Encouraging investments in the development of circular products designed for both hygiene and recycling. This can ignite innovations in the existing design of products to make them fit for multiple uses after washing or disinfection.
4. Stimulating research into the development of new and sustainable technologies to recycle mixed and other complex forms of plastic packaging which tend to grow due to hygienic concerns. Investments in emerging technologies such as chemical recycling promise to deliver high-quality resins and chemicals even from mixed plastic waste.
5. As discussed, bioplastic is not a silver bullet solution. Therefore, vigorous testing for recyclability or degradability of bio-plastics before entering into the market, and facilitating infrastructure for effective bioplastic waste management should also be ensured. Incentive policy for the needed investments should be brought in to encourage research and production of eco-friendly and reusable PPE.
6. As a long-term strategy to fight plastic pollution and to create socially and environmentally conscious citizens, development of the school curriculum as a part of environmental science education with a focus on plastic pollution and its environmental consequences is a must.
7. Local production and consumption (one of the principles of the circular economy) will help a reduced generation of plastic packaging waste. The demand for creating local consumption practices can be done by stimulatory measures like tax cuts for locally made products and providing fiscal security at the time of global crises.
8. It is necessary to restructure the policies to incentivizing efficiency in the recycling industry which also includes incentivizing sustainable technologies. Recognizing and rewarding efficiently functioning recycling plants and highlighting it in media to inspire others is necessary.
9. Adopting efficient business models for the collection and sorting of waste. Moreover, encouragement of source separation of waste through monetary incentives in taxation, individual or community recognition (in media/newspaper) for their contributions can help in obtaining clean and homogenous plastic waste streams for recyclers.
10. As a long-term strategy to improve plastic waste recycling efficiency, policies need to be formulated to reduce multi-layer packaging and promote homogenous plastic packaging materials that are easier to be recycled. A separate waste management tax on plastic packaging with low recyclability (for multilayer packaging) can be imposed to discourage such multi-layer packaging.
11. To promote entrepreneurial avenue in plastic waste management and to incubate startup in the waste management sector, the companies should be encouraged to fund them. By doing so, the fund and resource allocated by the companies should be counted as part of extended producer responsibility (EPR).

7. Conclusion

Our increased reliance on plastics during the COVID-19 pandemic may be temporary or likely to change our long-term goals of

transitioning towards a circular economy. Our existing plastic waste management system and infrastructure are restricted by inadequacies and inefficiencies to deal with the fluxes of waste generation. There is a need for innovations in existing products and technologies which would inspire economic and environmental efficiency. Moreover, the integration of new sustainable technologies into the current waste management system would envisage a future in which all plastics are either reused or recycled. Restructuring our policies around psychological and behavioral aspects of social awareness, incentivizing sustainable products and processes through tax cuts, discouraging low recyclable plastic products, encouraging public-private investments in research and infrastructure would help in achieving inclusive and sustainable plastic waste management. Our strategies and action should reflect our readiness for any future crises so that we should not have to choose one crisis over another.

CRedit authorship contribution statement

Kumar Raja Vanapalli: Conceptualization, Methodology, Visualization, Formal analysis, Writing - original draft. **Hari Bhakta Sharma:** Resources, Visualization, Formal analysis, Writing - review & editing. **Ved Prakash Ranjan:** Resources, Visualization, Formal analysis, Writing - review & editing. **Biswajit Samal:** Resources, Visualization, Formal analysis, Writing - review & editing. **Jayanta Bhattacharya:** Resources, Formal analysis, Writing - review & editing, Supervision. **Brajesh K. Dubey:** Resources, Formal analysis, Writing - review & editing, Supervision. **Sudha Goel:** Resources, Formal analysis, Writing - review & editing, Supervision.

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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