



Minimising the present and future plastic waste, energy and environmental footprints related to COVID-19

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ABSTRACT

The COVID-19 pandemic has had growing environmental consequences related to plastic use and follow-up waste, but more urgent health issues have far overshadowed the potential impacts. This paper gives a prospective outlook on how the disruption caused by COVID-19 can act as a catalyst for short-term and long-term changes in plastic waste management practices throughout the world. The impact of the pandemic and epidemic following through the life cycles of various plastic products, particularly those needed for personal protection and healthcare, is assessed. The energy and environmental footprints of these product systems have increased rapidly in response to the surge in the number of COVID-19 cases worldwide, while critical hazardous waste management issues are emerging due to the need to ensure destruction of residual pathogens in household and medical waste. The concept of Plastic Waste Footprint (PWF) is proposed to capture the environmental footprint of a plastic product throughout its entire life cycle. Emerging challenges in waste management during and after the pandemic are discussed from the perspective of novel research and environmental policies. The sudden shift in waste composition and quantity highlights the need for a dynamically responsive waste management system. Six future research directions are suggested to mitigate the potential impacts of the pandemic on waste management systems.

1. Introduction

The current COVID-19 pandemic has been progressing rapidly [1], as shown by the reported statistics [2]. One of the acute environmental effects of the pandemic is the sudden surge in the demand for and use of plastic products to protect the general public, patients, health and services workers. The widespread use of protective gear throughout the world as the pandemic creates massive upstream supply chain disruptions and downstream waste disposal problems. The demand trend is expected to match the global pandemic curve for various plastic products, as personal protective equipment (PPE) such as gloves and masks for health workers, disposable plastic components for life support equipment, respirators, and general plastic supplies including syringes. Used plastic products are frequently pathogen-contaminated, and ought to be handled as hazardous waste. Even before the start of the COVID-19 pandemic, the management of plastic waste was considered to be a major environmental issue due to growing concerns about pollution in

terrestrial and marine ecosystems [3]. Worldwide waste management systems have already been unable to deal with existing plastic waste satisfactorily, the impending surge in the volume of waste from the COVID-19 pandemic threatens to overwhelm existing waste management systems as does healthcare capacity.

Medical waste from hospitals is particularly problematic due to the need to destroy any residual pathogens [4]. Treatment facilities are typically designed to handle steady-state conditions where the medical waste is handled at a predictable average flowrate and composition. Various treatment technology options are based on thermal processes as incineration, steam treatment (autoclaving), plasma treatment, and microwave treatment. The choice of treatment is dictated by multiple economic, technical, environmental, and social acceptability [5]. Rapid scale-up of waste volume likely upsets systems that are designed for steady-state conditions. Experience in Wuhan shows that optimisation models can be used to provide decision support for the reverse supply chain problem of hospital waste management [6]. A related problem is a

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decision where new facilities should be built to handle the increased waste volume. The relevant aspects include economics, emissions, safety, regulatory issues, and public acceptance. However, at the onset of the pandemic, it is too late for those thoughts.

Fig. 1 illustrates the matching of the supply of and demand for medical waste treatment during the pandemic. The expected amount of waste far exceeds the available capacity for treatment of hazardous medical waste since these systems were designed for waste quantities generated during normal operations. If suppressions measure alone is not sufficient, new facilities can be built, or mobile units used [7] to ramp up capacity. A Pinch Point occurs where this expanded capacity meets the peak of the suppressed curve and ensuring that hazards from pathogen-contaminated wastes are managed. It can be seen that a large surplus is treatment capacity would be left in place after the pandemic subsides. It is unlikely that these treatment facilities are to be incinerators with heat recovery, and that they can be repurposed for municipal solid waste.

Given the technology options available for medical waste treatment, life cycle assessment (LCA) and related approaches can provide essential guidance for identifying the most environmentally preferable alternative. Incineration of medical waste coupled with waste heat recovery is an option that allows the chemical energy content of plastics to be recovered for useful purposes. An early LCA [8] with sensitivity analysis of heat recovery efficiency confirms that environmental impacts are minimised by maximising energy recovery. This is confirmed by more recent LCA, even when non-thermal options as chemical disinfection are considered [9]. However, there are obstacles to the widespread use of incineration with heat recovery. Public concerns about trace emissions of dioxins and furans can become problematic [10].

Social acceptability issues may not loom as large in the current pandemic since fears of contagion are likely to be greater than any concerns about environmental footprints, including GHG and pollutants. A problematic issue is a mismatch between the supply of and demand for the recovered heat. It can be both temporal and spatial. Some experts [11] expect the pandemic may peak in the second quarter of 2020 when the demand for heat in most of the Northern Hemisphere declines due to warmer weather. Waste-to-energy facilities may not be conveniently located for energy recovery since priority is inevitably put on safe disposal of contaminated waste. Xu et al. [12] show perspectives on balancing heat supply and demand to handle spatial and temporal imbalances. However, it remains uncertain if systems to be built on short notice or bring the mobile units to handle rapidly escalating volumes of medical waste can be engineered for optimal energy recovery.

Sustainability of plastics has been under scrutiny even before the COVID-19 pandemic. This paper gives a prospective outlook on how the disruption caused by COVID-19 can act as a catalyst for short-term and

long-term changes in plastic waste management practices throughout the world. The concept of Plastic Footprint (PF) [13] is introduced and then extended to Plastic Waste Footprint (PWF) [14] as a metric for environmental burdens. The current pandemic introduced disruptive changes in production systems. The disruptions through a "butterfly effect" can lead to negative and positive shifts that becoming more permanent features of post-COVID-19 economies.

2. The impact of the pandemic on plastic waste

The pandemic has led to major challenges in the handling of municipal solid waste (MSW) and hazardous medical waste. China has the most data on this issue. According to the 11 March press releases of the State Council's Joint Prevention and Control Mechanism in China [15], the amount of MSW in large and medium cities was reduced by 30% during the disease outbreak. However, the generation of medical waste increased sharply (+370%) in Hubei Province, with a high proportion of plastics. From 20 January to 31 March, the accumulated medical waste in all of China was estimated as 207 kt. In Wuhan, medical waste increased from the normal level of 40 t/d to about a peak of 240 t/d, exceeding the maximum incineration capacity of 49 t/d [16]. The incineration cost of hazardous medical waste in China is estimated at 281.7–422.6 USD/t as compared to 14.1 USD/t for MSW [16]. Fig. 2 shows the trends in waste flow compared to treatment capacity. Treatment systems designed for waste quality and quantity under normal conditions have to cope with dramatic changes that force abnormal operations. Engineering analysis is essential to ensure that these systems are able to cope with the dynamic and evolving nature of the pandemic. Another complication is that much remains unknown about the virus itself, as it is still unclear what products and processes would be needed to manage the pandemic.

The COVID-19 crisis is highlighting the essential role of plastic in daily life. Management of the virus requires single-use plastic [17], even if disposability is largely seen as an environmental liability in most other applications. An effective assessment tool can summarise the key environmental footprints of plastic products. Fig. 3 shows the plastic demand by segment. Demand for medical products and packaging is increasing sharply during the COVID-19 pandemic.

Various mitigation or suppression measures being implemented in different countries are changing both the quantity and quality of plastic waste. Single-use plastics are seen by consumers as a safe alternative for many applications. Van Doremalen et al. [21], studied the survival of the virus on different surfaces, including plastics. Kampf et al. [22] corroborated these results. Although plastics were shown to be no better than other materials in terms of virus retention, disposability is regarded as an important advantage by consumers prioritising hygiene. This has led to an increase in the use and disposal of plastic products, even for non-medical applications. On the other hand, the plastic demand in the

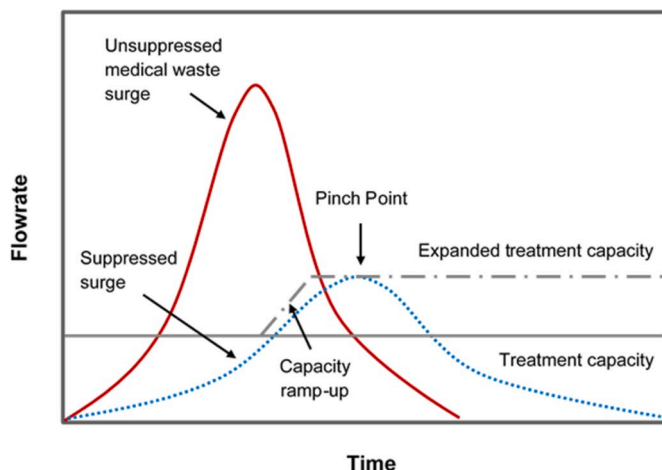


Fig. 1. Flattening the COVID-19 pandemic medical waste curve.

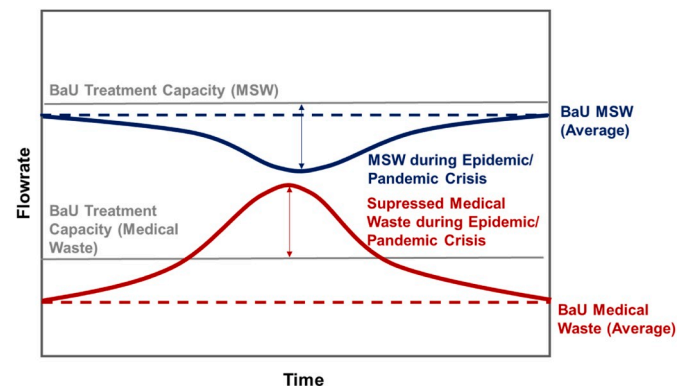


Fig. 2. The expected trend of medical and MSW waste flow along with the epidemic/pandemic crisis.

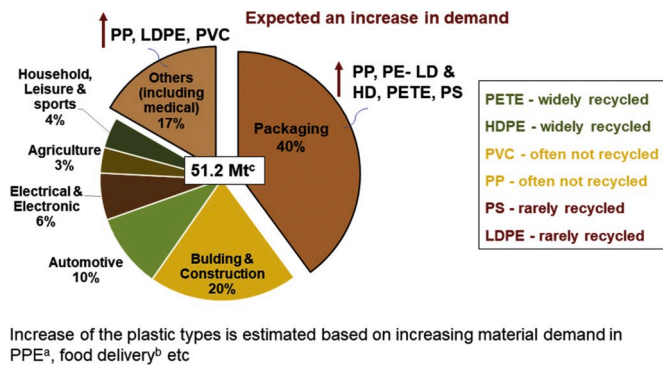


Fig. 3. Plastic demand by segment [18] and the expected increasing trend in medical and packaging. However, the net plastic demand is yet to be assessed. The plastic demand in the medical sector to help in combating the COVID-19 including the face shield (PP), gown (LDPE), vinyl gloves (PVC), disposable bag, tube, masks (plastic sheet and non-woven fabric) etc. [19]^a. The vast demand for food delivery or take out as well as grocery delivery [20]^b increase PP, LDPE, HDPE, PETE and PS, which are the common packaging materials.

other sectors (e.g., automotive and aviation applications) is dropping in the likely global economic recession. Lockdown measures have also led to an increase in the amount of packaging used for the delivery of food and groceries to residences. These shifts may exacerbate environmental issues with plastics, which already existed even before the pandemic occurred. Although this increase is unavoidable, environmental protection efforts should be sustained. In particular, metrics to facilitate system design and comparison of alternatives, footprints, should be developed and fully utilised.

3. New challenges in waste management

During the outbreak, many types of additional medical and hazardous waste are generated, including infected masks, gloves and other protective equipment, together with a higher volume of non-infected items of the same nature. Recent reports of airborne transmission [23] have led to recommendations to use masks in public environments. Sound management of this waste can minimise unforeseen effects on human health or the environment. Effective management of biomedical and healthcare waste requires appropriate identification, collection, separation, storage, transportation, treatment and disposal, as well as important associated aspects including disinfection, personnel protection and training.

Fig. 4 summarises the waste treatment approaches during the outbreak. The source of contaminated waste is not limited to hospitals.

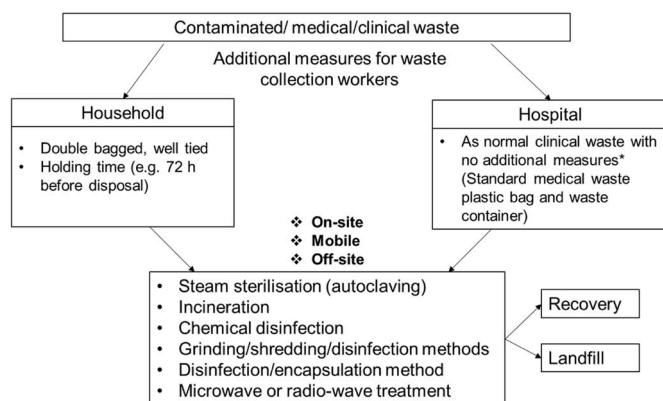


Fig. 4. The main waste handling approaches for contaminated waste during COVID-19. Double bagged [24], Holding time [25], treatment methods [26], on-site, off-site and mobile facilities [27].

Even advanced healthcare facilities have become insufficient for coping with the rapidly increasing number of infected. Patients with mild symptoms self-isolated at home generate contaminated MSW. This requires a substantial structural change in waste management, from the sorting rules, collection, waste treatment to the safety protocol of the waste collection workers. Various safety precautions can be found in ACR+ [24]. In the EU, waste masks, gloves, tissues and other contaminated waste are required to be double-bagged. In Germany, food containers which would normally be classified as recyclable waste. Now they have to be treated as hazardous waste if there is a risk of contamination with pathogens [24]. Households with positive or suspected COVID-19 cases are suggested to limit the use of separate waste collection systems [24]. These practices serve as precautions; however, it stimulates the use of plastic and the generation of mixed waste. They create logistical challenges for waste management systems, and other economic and environmental issues take a back seat in the coronavirus crisis.

Incineration and steam sterilisation (90 min, 120 °C) are the common pathways for thermal treatment of hazardous medical waste. The residue of these processes can be safely handled after the adequate decontamination cycle in accordance with non-hazardous solid waste regulation [26]. In Germany, incineration temperature is required a strict procedure, to be at 1000 °C to ensure safe destruction [24]. Recommendation by the WHO for healthcare waste is between 900 and 1200 °C [28]. The main challenge is that COVID-19 is creating a waste surge that can exceed treatment capacity by a large margin. Whether to utilise the MSW incineration capacity for medical waste in this critical situation remains an open question. In Spain, it is stated that if necessary, cement plants can co-incinerate waste upon request [24]. Norway allows a temporary change in landfill permits and permits to carry waste elsewhere to cope with the medical waste surge [24], if necessary. One of the current debates dealing with this unexpected crisis is to have on-site, mobile or off-site treatment [29]. In China, on-site and mobile treatment is considered to be preferable due to its flexibility in responding to shifting demands. They have always been advantages and drawbacks and are subject to context-specific constraints.

Plastics have calorific values comparable to conventional fuels (Table 1). The calorific value of 25% in MSW is estimated to be the plastics portion [30]. The assumptions (e.g. the incentives, taxes, oversimplification on exact the plastic composition, collection system) made during the planning of waste management systems are suddenly no longer fully valid. They were justified by the need to achieve levels of collection, recycling and recovery defined at the political level, has led to under-sizing of recovery and disposal facilities, favouring recycling even when it was neither possible nor sustainable, as in the case of the current pandemic. Fig. 5 shows the environmental and economic performance of different plastic waste management approaches. Pyrolysis and gasification are in development, stimulated by the request of more sustainable waste treatment options [31]. An economic assessment proposes the present scenario is sustained by tipping fee that is

Table 1

The calorific value of plastic and the exhaust gas released by incinerating MSW, hazardous waste and sewage sludge.

Type of Plastics	LHV (MJ/kg) [30] ^a , [33] ^b
PE	42–45 ^a
PVC	15–25 ^a
PA	36.76 ^b
PET	21.81 ^b
PP	30.90–45 ^a
PS	38.97–40 ^a
Fines (12 mm mesh)	15 ^a
Type	Exhaust gas release (m ³ /kt) [30]
MSW	5.5
Hazardous waste	7.0
Sewage sludge	8.0

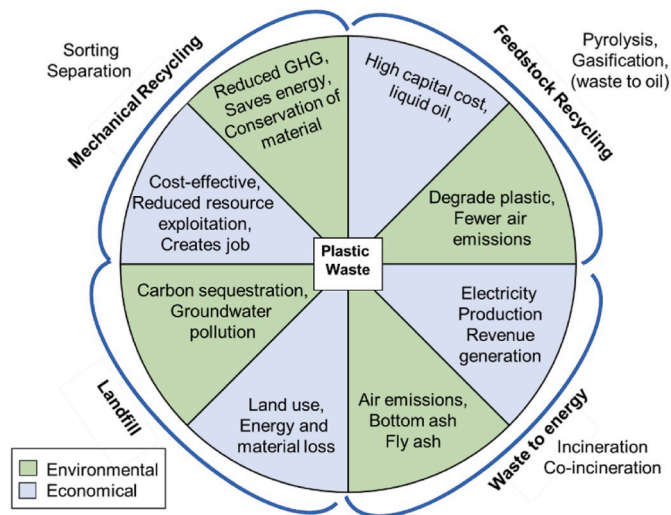


Fig. 5. Environmental and Economic Performance of Various Plastic Waste Management approaches. Adapted from Vanapali et al. [31].

continuously rising due to the high costs of transportation towards the treatment processes, both those for recovery as well as those for disposal [32].

Many countries have restricted the use of plastic bags. In the EU, even if the food packaging is plastic, the carrying bag is made of paper. However, the environmental footprint advantage of paper bags is questionable, especially since they have limited potential for reuse. Fig. 6 shows the material share for packaging. The typical paper bag (2.62 MJ/bag) has a higher energy footprint than a typical plastic bag (0.76 MJ/bag), which is much lighter. This reduced weight also incurs reduced footprints elsewhere in the supply chain. A study by the UK Royal Society of Chemistry [34] reports that paper has a higher Water Footprint and generates more air pollutants throughout its life cycle. This figure indicates that plastics can have superior environmental sustainability if properly used and disposed of. The concept of Plastic Waste Footprint (PWF) was introduced [14] to quantify such aspects. It is defined as the total mass of plastic waste used for a process, product or service minus amount of plastic avoided + reused + recycled + reprocessed, as expressed in Eq (1).

$$MPt - Mev - Mreu - Mrec - Mrep \quad (1)$$

The energy embodied in plastic waste can be recovered if adequately managed. Fig. 7 shows the typical life cycle energy consumption of plastic products. The embodied energy in the plastic can be recovered through primary and mechanical recycling, energy recovery and possibly chemical recycling (depolymerisation). The energy required for

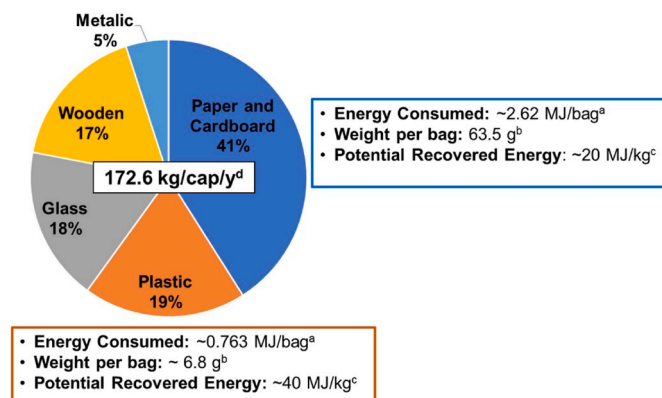


Fig. 6. Packaging alternatives. [35]^a, [36]^b, [34]^c, [37]^d.

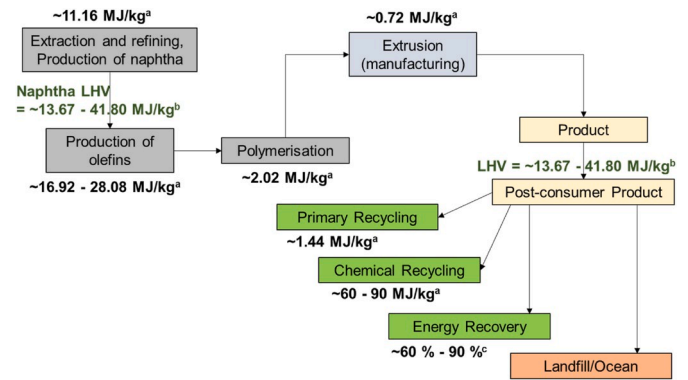


Fig. 7. The embodied energy and value chain of plastic without considering the supply chain (transporting). The % of energy recovery^c is estimated by the efficiency of waste to energy. [40]^a [33]^b.

extraction, refining, production of naphtha and olefins as well as polymerisation can be avoided. This energy is lost when the material ends up in landfills or as a solid plastic pollutant in the environment (against the Circular Economy concept [38]). The net GHG footprint of each recovery/disposal pathway can be estimated based on the energy consumption in Fig. 7, in line with the concept of Plastic Waste Footprint Eq (1). Plastic Waste Footprint highlights the importance of downstream processes in defining sustainability.

Plastic recycling is an alternative but has some drawbacks. Some recycling technologies are highly sensitive to purity. Zheng and Suh [39] stated that replacing fossil-based energy with renewables can reduce the environmental footprint of plastic significantly, especially GHGs. Plastics have characteristics that are important for applications related to the management of COVID-19. However, prior to this crisis, public perception and government regulations have sought to minimise plastic use. It is important to note that many of their environmental impacts (e.g., microplastics pollution) are not inherent properties of the materials but are consequences of behavioural patterns of consumers (e.g., improper disposal).

4. Future outlook

Public health is being prioritised over all other considerations during each pandemic. Recovery plans and economic stimulus packages are being developed. IEA [41] is calling for putting clean energy at the heart of stimulus plans for the coronavirus crisis. Economic and environmental impacts of the plastic surge have not yet been fully analysed. The amount of waste threatens to overwhelm existing treatment and disposal facilities, posing the risk of secondary contagion from improper waste management. As highlighted by Barry [42], the impacts induced by pandemic should be used as a foundation/lesson to build a better and different future society. An important concern is how the emergency measures put in place to deal with the surge will translate into long-term waste management options after the pandemic. Fig. 8 summarises the discussion covered by this article.

The current problem stems from the failure to anticipate the occurrence of a pandemic of this scale. It is also important to consider other scenarios for the future:

- Disaster waste management: Current disaster waste management planning is mainly focused on debris (e.g. earthquake). Optimisation and decision-making tools are needed to support waste management planning: treatment approaches, infrastructure, capacity (scalability), mobilised/automated (e.g. remote-controlled robots) treatment and collection design, logistics, safety, and regulatory aspects link to the bio disaster response.

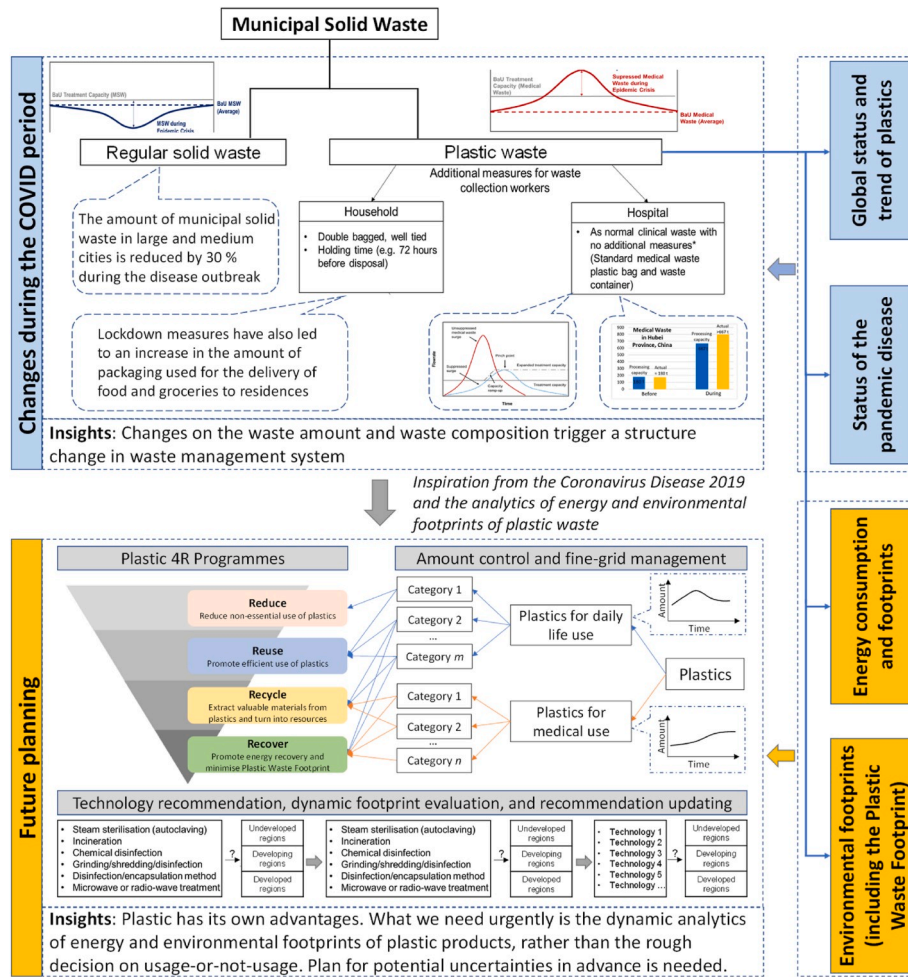


Fig. 8. Summary of the discussion and the outcomes in this article.

- Further, optimise disaster waste management planning (complementing each other): The planning can be on the regional scale (e. g., EU-neighbouring countries) instead of limiting to the local level.
- Rethinking the strategies on minimising the impact of plastic yet make use of its merits: The focus should not be targeted on plastics (as being fundamentally bad) but society (appropriate utilisation) and post-consumer plastic treatments. PWF can be used as a medium to assess sustainability compared to the alternatives (e.g. paper), by considering GHG emissions and energy consumption. A dynamic LCA approach is preferable.
- Incorporation of social factors and uncertainties: Although sustainability consists of three pillars, social factor is neglected in most of the optimisation studies or assessment (e.g. techno-economic assessment). For future planning, either the sustainability of plastic or any other environmental footprint assessment, it is important to include the social factors as well as understanding the potential impacts to a selection.
- Amount control and fine-grid management: Although the surge in the short term seems to be unavoidable [43], waste prevention should be at the highest priority of waste management. With the inspiration from the pandemic disease and the analytics of energy and environmental footprints, better trade-offs between medical/healthcare plastics and regular single-use plastics need to be performed to control the total amount and elevate the flexibility for future uncertainties. All categories of plastics can be managed in a fine-grid manner according to the newly proposed Plastic 4R programmes in Fig. 8 and circular economy strategies.

- Expanded development of advanced engineering and management tools. As an example, these problems can be dealt with by new developments of Pinch Analysis [44].

5. Conclusion

Among the many adverse consequences of the COVID-19 pandemic is the sudden surge in the volume of plastic waste, particularly for products used for personal protection and healthcare purposes. The environmental issues are related to the life cycles of products and are measurable via metrics such as footprints (PF and PWF) highlighted in this paper. The crucial priority is placed on the destruction of residual pathogens for the safe disposal of that waste. It is too early for comprehensive conclusions. However, there are some issues which can influence future environmental footprints: Would after the crises be money and energy (oil and gas) cheaper, would developed countries realise that 'outsourcing' to lower-cost bases is not always reliable, safe and or sustainable in the long-term? The collapse in crude oil prices to negative values was reported in the USA recently. However, it is uncertain if this price level will persist during the post-pandemic recovery period. The impact on the price, the demand for plastics, waste treatment and 6R initiatives have to be assessed. Although there have been studies suggesting the reduction in environmental impacts (e.g. NO_x emissions) related to COVID 19, it is too early to gauge the long term net environmental effects. There is uncertainty over the economic recovery path, and there may be changes in consumer habits. Some issues have been highlighted as priorities in this contribution both for scientific research and for environmental policies. The emergency rush to rapidly

build up capacities to cope with the crisis carries the risk that long-term sustainability aspects may be less considered unless they are highlighted. The risks can be averted by bearing several key points in mind:

- i. The disruption of the COVID-19 pandemic can lead to large and persistent changes in economic structures; in a sense, the outbreak presents a rare chance to shift modern product systems towards a more sustainable future trajectory.
- ii. Metrics such as PF and PWF can become effective tools for decision-making, policy creation, and public engagement. They provide an effective means of communicating abstract environmental burdens in numerical form for use by non-specialists.
- iii. Contingency plans to target the future of plastic and its waste management under various critical situations should be continuously developed and adjusted.

This 'Expert Insights' contribution is an attempt to raise awareness about some issues, which would influence the future of environmental concerns development. To work towards a safer and greener planet, every single step considering the complexity of various issues becomes an imperative goal of humankind. Future work should be directed by post-pandemic development and extend the concepts discussed in this contribution subject to country-specific conditions that may occur.

Declaration of competing interests

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

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