



# COVID-19 and waste management in Indian scenario: challenges and possible solutions

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## Abstract

The outbreak of COVID-19 pandemic has created havoc all across the globe causing exponential casualties and tremendous health and economic loss. With increasing COVID-19 cases, the amount of biomedical waste has increased manifolds making more people vulnerable to the pandemic. The developing and underdeveloped countries are already facing the challenges of waste management, and the waste generated during the pandemic scenario has added to the already existing challenges. The improper waste management practices need to be corrected; otherwise, the world will be facing a new disaster that could be termed as ‘waste disaster’. The increase in COVID-19-associated waste (CAW) quantity and their availability in the environment will result in their easy approach to other organisms, which will possibly increase the potential risk of food chain contamination. Some of the countries have already started to make backup plans and are struggling to overcome the ‘waste disaster’. In light of the limited knowledge available on the mutational properties and possible hosts of this newly emerged COVID-19, there is a great demand to have an efficient strategy to prevent the environment from further contamination in India. The necessity of the prevailing time is to create a more efficient, automatic, mechanized, and well-modified waste management system for handling the present situation and delaying the projected waste disaster in the near future in the era of COVID-19. The article aims to address the issues that originated from waste discharges, their potential sources along with possible sustainable solutions.

**Keywords** COVID-19 · Biomedical waste · Sustainable solutions · Environment

## Highlights

- COVID-19 transmission is reduced by use of PPEs Kits, disinfectants and social distancing.
- COVID-19 has led to various socio-economic and environmental challenges.
- Preventive measures taken to mitigate COVID-19 otherwise may lead to a ‘waste disaster’ on the planet.
- A safe & sound waste management techniques for liquid, solid & biomedical waste have been suggested.
- A holistic approach is needed to control the outbreak of COVID-19.
- COVID stimulus package can majorly prompt to control the adverse impact of COVID-19.

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## Introduction

In the last week of December 2019, a bunch of pneumonia cases reported by Wuhan Municipal Health Commission of China was later identified as a coronavirus, i.e. severe acute respiratory syndrome corona virus 2 (SARS-CoV-2). As soon as the know-how of the ongoing health-associated issues were known, severity and human-to-human transmission risks were identified by the World Health Organization (WHO) declaring the epidemic as a public health emergency globally on 30 January 2020. Later, on 13 March 2020, the WHO did an assessment and categorized COVID-19 as a pandemic. Besides the ongoing clinical treatment trials, increasing availability of personal protective equipments (PPEs), and adopting mandate norms like home isolation, social distancing, frequent hand sanitization, and wearing mask, this pandemic is still spreading and taking lives of humans globally by causing infectious respiratory disease and also affecting other vital organs of the human body. Humans are living in an era of development based on overall progress including economic as well as social perspectives. Countries of the world are majorly divided into three groups which are developed, developing, and least developed countries. Among the other developmental indices, socio-economic aspect is found to be the most significant constraint in deciding the vulnerability level of a country towards human health problems (Kawamura 2014; Poirier et al. 2020; Williamson et al. 2020). The human-to-human transmission and higher contagious properties of this pandemic created a major concern among the lower-income countries (least developed and developing). Because of the higher population and proportion of people having below or poor socio-economic conditions, these countries are at major risk of current public health emergency situation.

The physical and biological characteristics of solid waste are dramatically changing with the passing time and also in the current COVID-19 pandemic era. Prior to the COVID-19 pandemic, the sources of biomedical waste were limited to hospitals, nursing homes, biomedical research centres, etc. (Padmapriya 2013), but in the meantime, biomedical waste quantity and sources have increased significantly. Nowadays, on a global scale, every solid waste parcel generated per person contains certain proportions of biomedical wastes that include used masks, air respirators, hand gloves, gowns, aprons, face shields, and other protective gears. The PPEs are proven as essential by governmental organizations all over the globe, for human in their daily use. As PPEs can be used only for a limited cycle, its discarding becomes essential. However, PPEs are more often not discarded properly after their usage. This can create trouble for society (community-level transmission) (Nzediegwu and Chang 2020). According to Das (2020), there is a high proportion of PPE wastes generated in the form of biomedical waste which is not collected and segregated properly in developing

countries (viz. India) and many of other developing countries have high population density. The great burgeoning population in such countries creates more problems in their urban areas (Dutta and Jinsart 2020). An enormous amount of solid waste is dumped asininely without proper treatment in the outskirts of the urban area, along the roadsides in the open areas. This leads to an increased level of vulnerability towards this disease (COVID-19) to people living in those areas, to frontline sanitation workers, to rag-pickers, and to the people living in the nearby slum areas (World Bank, 2020).

Due to the unawareness of people about the hazardous nature of biomedical wastes associated with contagious diseases, wastes are not dumped accordingly and get mixed up with other types of wastes (like municipal solid waste, industrial wastes) indeliberately. This creates a big challenge for the waste management system, as the system is not well planned to manage such type of situations. There is a major but unnoticeable role of rag-pickers in waste management (Joshi and Ahmed 2016; Krishna et al. 2019). Studies have shown that about 60% of rag-pickers are non-native migrant workers that come to the cities for their livelihood (Krishna et al. 2019). Because of the arrival of this pandemic, these non-native rag-pickers have emigrated towards their hometowns (mostly rural). Meanwhile, the carelessness of people regarding the spread of COVID-19 and the throwing of these untreated biomedical wastes in their surroundings have worsened the situation. The unawareness and carelessness by the people and waste management system can lead to dramatic rise in the contagious waste spreading all over the areas (leading to air, water, and soil contamination directly or indirectly) and can enhance the severity of this pandemic. Many studies showed the persistence and infectivity of different human coronaviruses on certain inanimate surfaces like metal, plastic, glass, clothes, and papers, up to 9 days at room temperature (Kampf et al. 2020; Fiorillo et al. 2020). The longer persistence of viruses on wastes' surface and infectivity of virus adhered on such wastes pose a high rise of contamination in the ecosystem, when thrown carelessly. The increase in COVID-19-associated waste (CAW) in the environment might result in their easy approach to other organisms, which will possibly increase the potential risk to contaminate the food chain (in ecosystems like freshwater, marine, terrestrial). Hence, an increase in the quantity of CAW might lead to a waste disaster, when not managed properly. Some of the countries have already started to make back-up plans and are struggling to overcome such type of projected waste disaster (Nzediegwu and Chang 2020).

In light of the limited knowledge available on the mutational properties and possible hosts of this newly emerged COVID-19, there is a great demand to have an efficient strategy to prevent the environment from further contamination. The need of the hour is to create a more efficient, automatic, mechanized, and well-modified waste management system

for handling the present situation and delaying the projected waste disaster in the aftermath of COVID-19. Transmission and persistence of COVID-19 by various mediums, sources (point and non-point) of COVID-19-associated waste generation, impacts of COVID-19-associated waste on components of the biosphere, anticipated waste disaster of COVID-19, possible solutions towards solid and liquid waste managements, and possible innovative solutions of COVID-19-related issues are the main objectives that are illustrated in the present article. Although literature is available on COVID-19-related issues, there is need to address the issues in a holistic approach. The present review article incorporates the issues originated to waste discharges, their potential sources, and the possible sustainable solutions towards environmental sustainability along with on-site strategies.

### Airborne transmission of COVID-19

On 9 July 2020, WHO updated the information on transmission of COVID-19 replacing the scientific brief published on 29 March 2020 (WHO 2020a). The main findings of this updated report included about the airborne transmission of the SARS-CoV-2 virus. It suggests with various evidences that transmission of SARS-CoV-2 can also occur indoors via aerosol-generating procedures. The previous report suggests that direct and indirect contacts are the only way of transmission. But in the updated report, WHO has suggested a new hypothesis in which inhalation and exhalation processes by an infected person result in generation of microscopic aerosols ( $< 5 \mu\text{m}$ ) even while normal breathing and talking. A possible mechanism of airborne transmission is when an infected person exhaled SARS-CoV-2 infectious droplets which have high potential to cause infection in another person. Experiments were performed under controlled laboratory conditions producing aerosol which have infectious viruses through high-powered jet nebulizers. The RNA of SARS-CoV virus in the air viable to infect up to 3 h and another study shows 16 h viable in aerosol which also replication competent (Van Doremalen et al. 2020; Alyssa et al. 2020).

Transmission possibilities of SARS-CoV-2 are profound in aerial medium, and they can be categorised into two ways, i.e. droplet transmission and airborne transmission. However, droplets are settled in close proximity of source and contaminate fomites which can act as secondary transmitters, while airborne transmission extends over a period of time and covers greater distance compared to droplets due to small size and poses a high risk. Settling of expelled respiratory particles is the function of size, time, and evaporation. Jayaweera et al. (2020) illustrated a wide concept of COVID-19 transmission in three confined settings (airplane, passenger car, and healthcare centres) where the chance of infection is high.

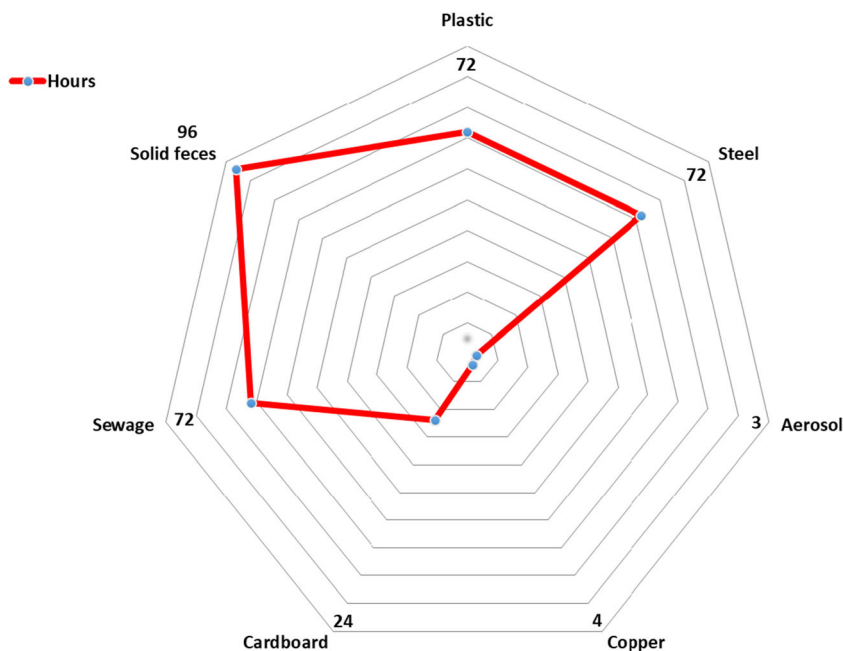
### Persistence of SARS-CoV-2 on different inanimate surfaces

Any substance or material which can carry infection and make peoples susceptible to it is called fomites (contaminated surfaces). Fomites can be any material like clothes, papers, wood, plastics, metals contaminated with infection. During outbreaks, fomites act as a key vehicle for the transmission of infections. Many studies reported that the COVID-19 virus can remain viable and persist in the environment for a few hours to several days (Fig. 1). The persistence of COVID-19 on different surfaces suggests that the CAW fomites, viz. used PPEs (masks, gloves, face shield, gowns/aprons) etc., generated from quarantine centres, isolation wards, and households with suspected COVID-19 persons could be a possible infection transmission source (Nghiem et al. 2020).

### Healthcare materials: raw materials used and their impacts and effects

In the prevailing pandemic, the common people are advised to wear mask before leaving the house and health workers are required to wear full PPE kit to avoid the chances of contamination. According to WHO modelling, it is estimated that 89 million medical masks, 76 million gloves, and 1.6 million medical goggles are required during each month of this pandemic (WHO 2020b). A report by Klemeš et al. (2020) mentioned a dramatic increase in the biomedical waste generation in Wuhan, China, from 40 tonnes/day (normal level) to about a peak of 240 tonnes/day (exceeding the maximum incineration capacity per day, i.e. 49 tonnes/day). In the prevailing time, more concern is given to health as compared to environment and healthcare materials are the most essential part of human life. The healthcare materials like face masks, face shield, head cover, goggles, hand gloves, whole-body aprons, and shoe covers or more specifically, PPE kits (Fig. 2), are made using a variety of raw materials. Patricio et al. (2020) reported that plastics are the most preferred raw material used in several industrial sectors including the healthcare sector owing to its availability, flexibility, and being lightweight. Different types of plastic involved in the manufacturing of PPEs are polyethylene (PE); polyethylene terephthalate (PET); high-, low-, and linear-low-density polyethylene (HDPE, LDPE, and LLDPE); polyvinyl chloride (PVC); polypropylene (PP); and polystyrene (PS) (Klemeš et al. 2020) with their half-lives given in Table 1. The coveralls used are made from non-woven cloth, which feels like a cloth but actually made of PP. Masks are made of non-woven materials incorporating PP and PE. These materials disintegrate into small microplastic pieces. The degradation of these non-woven synthetic textiles has led to formation of microplastic and microfibrils that had been reported to be found in water

**Fig. 1** Persistence of COVID-19 in environment and on certain fomite (Nghiem et al. 2020)



and sediments in Magdalena River in Columbia (Martínez Silva and Nanny 2020). PP and PE are the most common type of thermoplastic found in municipal solid waste (Canopoli et al. 2020). The PP takes many years to decompose in nature and is harmful to environment just like other plastics. Various PPEs end up as ocean plastics debris, and as per estimation, most of the debris reached into ocean as end plastic (Tang et al. 2019). The environmental degradation of plastic is very slow, and remains of plastics on land and in sea take hundreds of years by fragmentation, photo-degradation, thermal degradation, chemical degradation, and biodegradation (Singh and Sharma 2008; Syakti et al. 2017; Ter Halle et al. 2017). Microplastics gets breakdown into 5-mm pieces (Li et al. 2016).

Among the healthcare materials, gloves, mask, coverall/ gowns/aprons, and head and shoe covers are of single use and discarded after use with proper guidelines. The goggles and face shield are also of single use but maybe reused depending upon the raw material quality and disinfection

property (either decontaminated or not). Another PPE, i.e. gloves, also fall in the category of single-use plastics and pose a substantial danger to the environment. The PPE kit used in hospitals and isolation centres during this pandemic should be collected and discarded as per biomedical waste management (BMW) rules as shown in Table 2. These contaminated plastic wastes if not disposed properly can enter into food web and create toxic pollutants for human health risk (Guo and Wang 2019).

### Sources of COVID-19-associated waste (CAW) generation and the possible entrance in the biosphere

Governments of almost every nation released guidelines in order to protect mankind from the pandemic. The use of PPEs and sanitizers is highly recommended in the provided guidelines. These healthcare materials include facemasks,

**Table 1** Half-lives of certain plastic types.

Plastic type	Status of recycling	Half-lives in environment (minimum to maximum; in years)	
		Land (Buried)	Marine environment
PET	Widely recycled	> 2500	-
HDPE	Widely recycled	250 (230 to 280)	58 (23 to > 2500)
PVC	Often not recycled	> 2500	-
LDPE	Rarely recycled	4.6	3.4 (1.4 to > 2500)
PP	Often not recycled	-	53
PS	Rarely recycled	> 2500	-

Source: Chamas et al. (2020); Klemeš et al. (2020)

**Fig. 2** Different PPEs used in this time of pandemic



hand sanitizers, medical gloves, and aprons. Although these healthcare materials are guarding mankind from the pandemic, they may also act as the potential source of infection because of their mismanagement. In the beginning of the pandemic, the use of PPEs was limited to hospitals and laboratories. But, nowadays, every frontline worker (including waste collectors, policemen, and infected person handler) and every citizen are using healthcare materials (Nzediegwu and Chang 2020). The increased number of PPE users has resulted in increased sources of CAW generation. There are numerous sources of CAW generation in the society; for instance, owing to governmental recommendations, millions of facemasks are manufactured and brought into use on daily basis and ultimately end up as a waste capable enough to spread the infection, if not disinfected or managed properly. Figure 3 provides an outlook of the different sources of CAW generation.

### Point sources

These are stationary source of CAW generation which are identifiable in nature and from where the waste can be easily collected for further management. These sources are also called definite sources, which may directly contribute to the origin of contamination if not managed properly. There are certain places which spread the illness often rapidly such as hospitals, laboratories, isolation centres, quarantine wards, households, and offices. Hospitals, laboratories, isolation centres, and quarantine wards are the prime source or considerable epicentres of the CAW generation. Healthcare materials, testing kits, and other laboratory items would become contaminated by infectious droplets or aerosols through direct or indirect contact of infected patients. CAW like used testing kits, swabs, bandages, dressing material, facemasks, gloves, aprons, gowns, and used syringes are generated in large amounts from these places. Households and offices also play

**Table 2** Healthcare materials, their constituents, use, storage, and treatment

Items	Material	Use	Storage	Treatment
Gloves	Nitrile; PVC	Single	Household: double bagged,	Steam sterilization, incineration,
Masks	Plastic sheet and non-woven fabrics	Mostly single	well tied with holding time of 72 h before disposal	chemical disinfection, microwave or radio-wave treatment,
Face shield	PP; polycarbonate; cellulose acetate	Mostly single	Hospital: standard medical waste plastic bag and waste containers	disinfection/encapsulation method, grinding/shredding
Goggles	PP	Mostly single		
Shoe cover	Woven and non-woven (polypropylene) fabrics	Single		
Head cover	Woven and non-woven (polypropylene) fabrics	Single		
Coverall	LDPE; woven and non-woven (polypropylene) fabrics	Single		

Source: Klemeš et al. (2020)

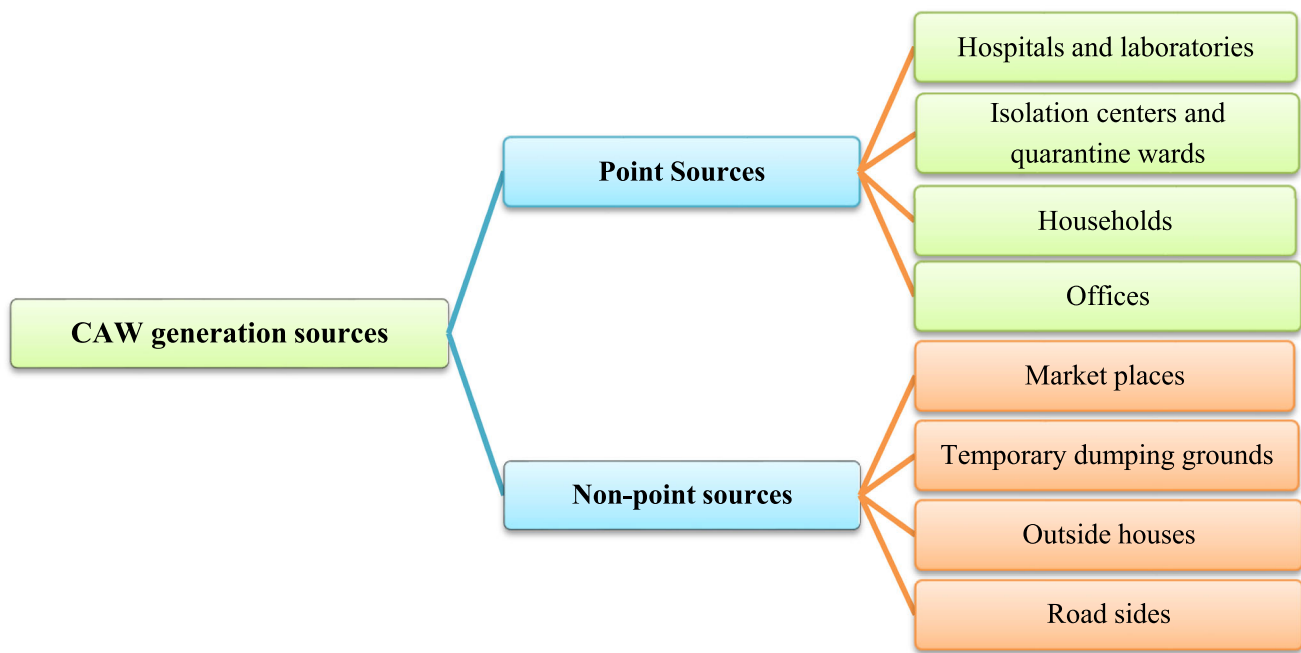


Fig. 3 Different sources of CAW generation

a major role because every person uses PPEs as safety precaution nowadays. The CAW generated from these places is also in a greater amount which should be considered as a major source.

**Non-point sources**

These are the sources which are not easy to identify and the address is also indefinite, belonging to many diffuse sources of generation; market places, temporary dumping grounds, house front yards, and roadsides are the main contributors in the non-point sources for CAW generation. Due to indefinite locations, waste generation sources are not managed properly and are a cause of concern. As these places are not certain in address, wastes may easily spread in other areas through wind and water, therefore a viable source of contamination in the environment (Fig. 4).

Generally, the above sources have sideways dumping areas which are temporary. Such places give rise to multiple types of waste generation like plastics, wrappers, packaging materials, cartons, tetra packs, glass, scraps, bottles, and used PPEs. These wastes can act as CAW fomites, if generated by symptomatic or asymptomatic COVID-19 suspects. Hence, such wastes need to be properly disposed of with more precautions to stop the transmission of COVID-19 from waste fomites to personals.

Infectious solid waste generated at different sources (point and non-point) is often dumped without any disinfection into open or unmanaged landfills where stray animals like dogs, cows, goats, cats, rats, and other animals or birds come in search of food. In this way, humans and other livestock may

get exposed to COVID-19 (Nzediegwu and Chang 2020). Figure 4(D) shows a scenario of stray animals coming in contact with CAW.

**Impacts of COVID-19-associated waste (CAW) on components of biosphere**

Recently, the pandemic COVID-19 has presented all together a very challenging scenario, where not only human health but the overall ecosystem is at stake and facing new challenges. Some reports have suggested that there is an increase in production of PPEs (Klemeš et al. 2020). This will later lead to its higher utilization and, finally, result in colossal generation of wastes all around. As we already know, the waste management system of developing countries like India is not much advanced to tackle any type of projected waste disaster (Srivastava et al. 2015). There is a need to utilize the products in more sensible and sustainable manner to stop further environmental contamination and minimize the risk to mankind (Sharma et al. 2020; Kalina and Tilley 2020; Klemeš et al. 2020). The biosphere components such as air, water, and soil are nowadays greatly influenced by CAW.

**Impact on water**

COVID-19 transmission through wastewater is still being researched. Some studies have shown the presence of SARS-CoV-2 strains in faeces of infected person which may get into wastewater. There are many researches available which have reported about the viable SARS-CoV-2 in

**Fig. 4** A, B, and C CAW (mask, hand gloves, PPE kits) dumped carelessly on roadside; D stray animals coming in contact with discarded CAW on roadside; E discarded mask in temporary open dumping site



wastewater (Ahmed et al. 2020; Medema et al. 2020; Wurtzer et al. 2020). As a precautionary measure, there is an essential need for proper treatment of wastewater, as contaminated wastewater may act as a potential source of transmission. Wastewater generated through various sources like hospitals, laboratories, isolation centres, quarantine wards, households, market places, industries, and offices may lead to further transmission of COVID-19. Waste-based epidemiology method for detection of infection like COVID-19 in untreated wastewater is an important area of research, which shows scale of infection by using sewage as an indicator (Barcelo 2020). Different viruses have different survival rates in sewage as bacteriophage, *Cystoviridae*, can easily activate in the sewage for 3–7 days depending on the temperature (Barcelo 2020). A study conducted by Casanova et al. (2009) about survival of two surrogate coronaviruses show that transmissible gastroenteritis (TGEV) and mouse hepatitis (MHV) survive in water and sewage for days to weeks. COVID-19 virus was identified in the stool samples of infected humans which indicates faecal transmission route in a study done by Zhang et al. (2020). The study on a patient infected with SARS-CoV-2 showed that duration of this virus in stool samples remained for 22 days which was higher than that from respiratory track where the virus persisted for 18 days and in serum samples for 16 days. Ahmed et al. (2020) used reverse transcription-quantitative PCR (RT-qPCR) assay to detect first confirmation of SARS-CoV-2 in untreated wastewater in Australia. Some reports have mentioned about the mishandling patterns of CAW and their drastic end up in the form of waste masses in the water bodies (Kalina and Tilley 2020; Boyle 2020), thereby causing interference in the aquatic ecosystem, thus affecting the entire food chain.

### Impact on soil

If not managed properly, the CAW may lead to soil contamination and may lead to further transmission of the disease. Limited manpower and trash collectors and panic due to seriousness of the disease have resulted in unorganized behaviour in healthcare systems. The non-biodegradable and non-recyclable biomedical waste, if dumped on land without proper decontamination steps, may persist for years and can be transported from one place to another through wind or water movement. The monsoon rains may aggravate this problem. For example, Mumbai is a polluted and populated metropolitan hub and every year this city as well as surrounding regions faces floods during monsoon. In this scenario, contaminated biomedical CAW may lead to serious problems of soil and water contamination in India. CPCB has issued mandatory guidelines for proper handling, storage, and disposal of biomedical CAW generated during the pandemic. Due to ongoing pandemic, there is high spike recorded in the use of PPEs, which surely will increase day by day because of the high

population demand. As the infrastructure and technologies for waste management in India are not much advanced and also the incinerators working these days are found incapable to handle this increased CAW quantity (ABP News Bureau 2020). Predictions can be done about rise in the demand of landfills for collected waste and this will later lead to soil contamination.

### Impact of disinfectants on indoor air and atmospheric chemistry

There are many types of disinfectants like isopropyl alcohol, derivatives of chlorine (liquid chlorine, sodium hypochlorite, and chlorine dioxide), and ozone which are used these days for decontaminating environmental surfaces (animate and inanimate), CAW, and wastewater (Wang et al. 2020). Disinfectants may kill the good micro-flora of environment, and there is also an associated possible health risk to humans (Pechter and Rosenman 2016). Spraying of sodium hypochlorite (NaOCl) solution for disinfecting indoor environments has recently been questioned. The vapours of such disinfectants may cause notable implications on human health as well as on atmospheric chemistry. The droplets of NaOCl react with water vapour to form HOCl, which further photo-dissociates to generate Cl radical. The Cl radical thus results in secondary aerosol formation, removal of tropospheric ozone, and sulphate aerosol production (Chatterjee 2020) thus affecting the atmospheric chemistry.

### Waste disaster: new challenge for biosphere's health with COVID-19

Waste can be defined as any garbage or solid, liquid, or gaseous trashes. Mismanagement of any kind of waste might cause social, environmental, economical, or health implications. Nowadays, huge quantity of infectious waste (healthcare waste) per day generation has emerged as one of the challenging and disastrous impacts of COVID-19 pandemic on human and the environment. Kalina and Tilley (2020) conducted a study revealing that dozens of single-use facemasks were found on the seashore indicating poor waste management practices that often lead to harmful effects to the aquatic life. Secondary microplastics are formed by the degradation of plastic products (used in PPE's). Comprehensive studies have shown the evidences of the presence of microplastics and microfibrils in the water bodies and sediments (Martínez and Nanny, 2020).

### Problems due to solid waste exposure

Poor waste management practices often lead to several environmental and health-related problems in the earth's



ecosystem affecting human life along with other living organisms. Mostly the solid waste generated during the pandemic comprises personal protective equipments like gloves, facemasks, and shielding goggles in huge quantity because these are used and discarded daily. Many of the medical and laboratory trashes including dressing materials, cotton swabs, bandages, used syringes, and pharmaceutical trash have also increased rapidly due to their usage during the COVID-19. Disposing of such kind of infectious solid waste should be done after disinfection treatment as per the recommendations and guidelines given by WHO. Without treatment/decontamination, disposal of such waste would raise several problems as illustrated in Fig. 5.

Open, scattered, and uncontrolled discharge of infectious healthcare waste poses a high risk of disease transmission among humans. Uncontrolled dumping of untreated wastes leads to landscape pollution, reduces aesthetic value, and produces foul smells. Toxic solid waste through landscape contamination could result in various types of environmental pollution, viz. air pollution by releasing harmful gaseous emissions into air, water pollution, or groundwater contamination via contaminant leaching, soil pollution through adding unwanted waste components to soil. Health-related issues among human and other living beings occur due to food chain contamination led by solid waste of landscape pollution.

### Problems due to liquid waste exposures

Liquid wastes are generally comprised of excretory waste, sewage, biomedical waste like blood, wastewater from medical facilities, and other quarantine facilities with potential

threat of spreading contagious diseases. Although there is no confirmation related to spread of COVID-19 through water infection, there is a potential risk involved. From the studies, faecal matter of COVID-19 patients has been found to be a probable transmission source of this pandemic. On being exposed to any infectious liquid waste, it is recommended to maintain hygiene and proper hand sanitization to secure prevention against infectious virus by using 70% ethanol or 0.1% sodium hypochlorite for 1 min (WHO 2020c).

### Waste collection and management system in India

In India, an integrated management system for handling and managing solid waste has been adopted. Integrated management of solid waste is a combined process of activities like waste generation, aggregation or storage, collection, segregation, transportation, energy recovery, processing, and final disposal. These strategies follow a hierarchy system as shown in Fig. 6 that primarily focuses on minimization of waste generation.

Waste reduction at source is the most preferred action in integrated management of biomedical waste. Management systems involve collection of waste generated from all possible sources and then segregate the recyclable items, glass, and metals from the waste. The Central Pollution Control Board (CPCB) has suggested the necessary guidelines, mentioned in the biomedical waste management (BMWM) rules 2016, for segregation of biomedical waste generated during COVID-19 pandemic as shown in Table 3. After segregation, the final waste is stored for shredding and compaction to make smooth and its effective transportation to disinfection or treatment

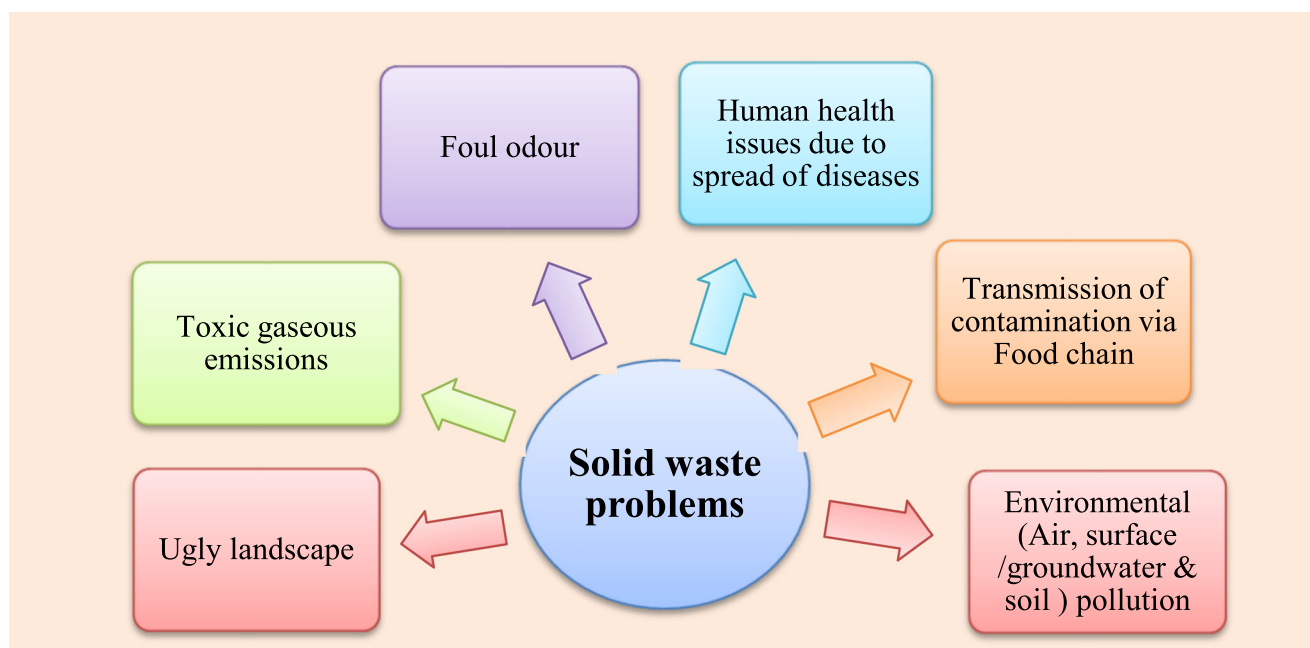
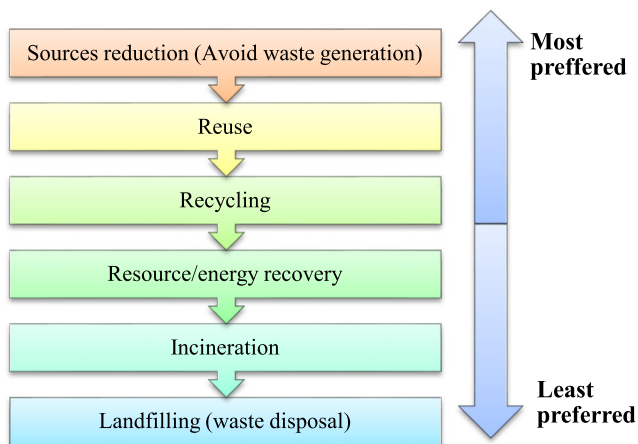


Fig. 5 Issues with solid waste



**Fig. 6** Waste management hierarchy

plants and ultimately the final leftover waste is disposed of into landfills.

### Percentage of waste collected

The enormous demand for disposable medical items, for instance, surgical masks, single-use gloves, and empty IV bags, in the wake of the pandemic has produced a deluge of medical waste. The biomedical waste creation from COVID-19 patients is escalating worldwide including India each day. India is producing approximately 517 tonnes of biomedical waste per day from the medical or healthcare institution and hospital, quarantine wards, OPD, and other departments (Anwer and Faizan 2020). During the current era of COVID-19, hospitals are anticipated to produce about sixfold more medical waste than what was generated before the pandemic (Ranjan et al. 2020). Additional biomedical waste generation in Wuhan City of China has reportedly found to be about 240 tonnes/day, while in Manila, Bangkok, and Jakarta, it is reported to be about 280, 210, and 212 tonnes/day, respectively, as per Asian Development Bank reports (Ranjan et al. 2020).

### Corona warriors: risks and challenges

Corona warriors refer to workers of different fields like volunteers, doctors, nurses, caregivers, waste pickers, housekeeping workers, police, and many more who used to stay in proximity of COVID-19-infected patients. Inadequate personal protection of healthcare personnel and prolonged exposure to diseased prolonged exposure can also increase the risk of infection in healthcare personnel (Wang et al. 2020c). As per the guidelines recommended by WHO, these people should cover themselves with full-body gowns; wear masks, gloves, and goggles; and sanitize their hands with alcohol-based sanitizer from time to time. With the passage of time, the number of infected patients is increasing alarmingly (Saadat

et al. 2020) that also enhances the risk of infection to people who are dealing with them. One major challenge these people are facing is the large amount of medical waste generation that possesses great potential to spread the disease. Surge in solid medical waste puts solid waste collectors, waste pickers, and waste handlers at a higher risk (Kharel 2020). As per the CPCB guidelines on biomedical waste generation during COVID-19, there are some preventive measures or solutions (Fig. 7) that need to be taken to reduce health-related challenges and risks on corona warriors.

- Adequate supply of PPEs, i.e. three-layer sanitized masks, face shield, splash-proof aprons/gowns, boot cover, protective goggles, and gloves, shall be provided to workers at hospitals, quarantine centres, waste management centres, and also waste pickers and transporting workers.
- After every use, sanitization of vehicles should be done with any appropriate chemical disinfectant like sodium hypochlorite solution, 70% ethanol, or other.
- Waste handlers are needed to be trained, via videos and demonstrations in their native languages, on disease prevention measures, use of PPE, hand hygiene, respiratory or sneezing etiquettes (in crossed elbows), social distancing, etc.

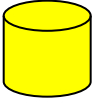
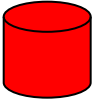
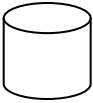

### Possible solutions for waste management of COVID-19

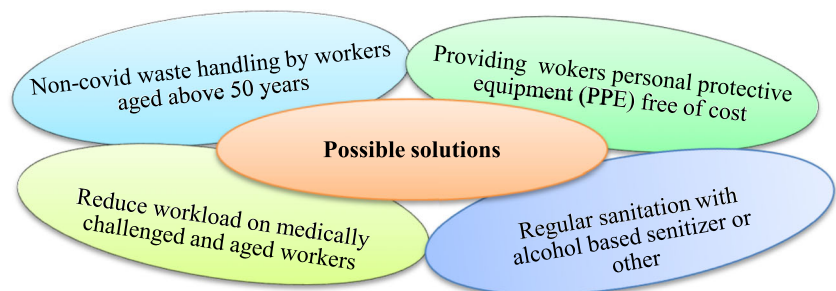
In order to reduce the impact of COVID-19, governments in all countries have set laboratories, isolation wards, sample collection centres, and quarantine centres/camps. These places along with hospitals have generated a lot of medical or healthcare waste with huge potential to spread infection if not managed appropriately. The waste comprised of solid and liquid wastes including dressing materials, N95 facemasks, gloves, used syringes, cotton, blood, anatomical waste, sewage or wastewater from hospitals and quarantine wards, tissue wipes, bandages, and much more. Thus, there is need of an efficient system that can effectively manage such kind of waste. The effective management system requires the need of the already-existing waste management options along with some innovative solutions for on-site management of COVID-19-related waste so as to prevent future waste disaster.

### Solid waste management options

Infectious medical or healthcare solid waste can be treated for disinfection by several thermal treatment processes such as incineration, pyrolysis, steam treatment (autoclaving), microwave treatment (Klemeš et al. 2020), and landfilling.

**Table 3** Colour coding of biomedical waste segregation disposing (source: CPCB)

Bag colour	Types of container/bag used for collection	Category of waste	Final disposal
Yellow 	Non-chlorinated plastic bags Different collection systems leading to effluent treatment	Anatomical waste of human Anatomical waste of animal Solid waste Solid and liquid chemical waste	Incineration of pyrolysis of landfill
Red 	Mainly non-chlorinated plastic bags or containers	Tubing, bottles sets, catheters, urine, vaccutainers and many more.	Autoclaved, shredding followed by recycling
White 	White puncture-proof, leak-proof, tamper-proof containers	Metalic sharp waste like needles, scalpels, blades, syringes with fixed needles	Autoclaving shredding followed by encapsulation of disposal in iron foundries
Blue 	Puncture proof, leak-proof cardboard box or container with blue marking	Metal and glass-based waste	Disinfection than recycling

**Fig. 7** Possible solutions to risks and challenges of COVID-19 on corona warriors (Source: CPCB)

Although these processes can disinfect the COVID-19 waste from the virus, lack of proper handling would lead to spread of the virus from waste to waste handlers and treatment plant workers. Proper handling of waste along with personal protective measures is the minimum requirement for efficient waste management.

**Incineration**

The toxic/infectious solid wastes, e.g. biomedical waste, that should not be disposed of in landfills as well as incapable of recycling and not reusable are often selected for incineration. Incineration takes place at a high temperature greater than 800 °C inside the furnace of incinerator in presence of oxygen as represented in Fig. 8. During incineration, a huge amount of heat energy is also released that further could be used for electricity generation. However, in case of incomplete combustion and improper management, several toxic pollutants like dioxin and furans are also released that need to be prevented from emitting into the environment (Weidemann et al. 2016).

Incineration is a widely used disposal technology in the developing countries because it is simple, safe, and effective for disposal of medical waste. The outlet incinerator working temperature is 800 °C that kill the microorganisms present in the hospital waste and mineralize the organic waste into ash form. This incineration process reduces the volume of hospital waste by approximately 85 to 90% (Wang et al. 2020). China used incineration for disinfection of SARS-contaminated waste in 2003, which was built under military-to-civilian program. China mainly uses three types of incinerators which are pyrolysis, rotator kiln, and plasma, respectively (Ma et al. 2020). The increasing generation of COVID-19 waste necessitates the development of municipal solid waste incinerator for medical waste disposal. It will help to dispose the medical

waste on-site. In spite of various environmental concerns associated with incineration, it can still be the best available technology during this COVID-19 pandemic.

Hospital waste material is burned in the presence of oxygen, and burning of waste creates gaseous emissions. Incomplete burning of hospital waste gives the possibilities of survival to pathogenic microorganisms. Incinerator requires an optimal airflow for the proper combustion of waste materials. Although an excess airflow is a necessity of good combustion process, it reduces the temperature level in the incineration chamber that creates toxic gases like furans and dioxins which are released into the environment. After combustion of hazardous waste materials, a significant amount of bottom ash is produced that could be further disposed by sanitary landfill method (Nema and Ganeshprasad 2002). Radioactive waste from hospitals cannot be dealt with incineration process (Wang et al. 2020). Although toxic emission and bottom ash are the major challenges with incinerator, it is the best available medical waste disposal method that could give on-site solution. The problems associated with incineration can be rectified by incorporating end-of-pipe treatment (bag filters, wet scrubbers, fixed bed adsorption system).

**Pyrolysis**

Pyrolysis is the thermal decomposition of organic waste at high-temperature range from 400 to 700 °C but takes place in the absence of oxygen (Czajczyńska et al. 2017). Although it is most commonly used in industries for charcoal and fuel formation from agricultural waste, biomass, waste rubbers, tyres, and plastics, it can also act as the most reliable disinfection method for biomedical wastes. Disposal of PPEs by pyrolysis is considered valuable as it is suggested that the PPE kits can be repurposed for biofuel production (Jain et al. 2020). The use of PPEs has increased during COVID-19

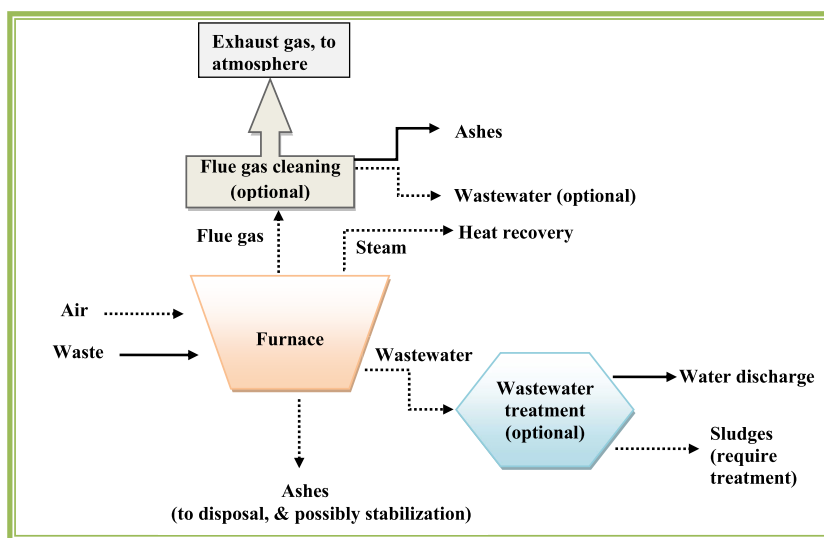


Fig. 8 Incineration treatment for solid waste (source: [https://www.who.int/water\\_sanitation\\_health/medicalwaste/077to112.pdf](https://www.who.int/water_sanitation_health/medicalwaste/077to112.pdf))

pandemic throughout the world that has created solid waste disposal problem as most of the PPE kits are made from plastic materials which is not only a burden for the environment but also creates a contagious vicinity and pose a serious threat for human health.

### Autoclaving

Autoclaving offers the wet sterilization method for decontamination of toxic microorganisms from any reusable instruments especially in hospitals. This sterilization method involves the use of equipment called autoclave where the waste or contaminated material is allowed for full-steam penetration at temperature (minimum) of 121 °C and pressure 100 kPa or 1 bar. For complete disinfection of waste weighing about 5–8 kg, it requires at least 60-min autoclaving cycle. Autoclaving is a low thermal treatment process in which saturated and controlled steam treat the waste materials in a given time. Research laboratories and hospitals commonly use autoclaving as there are several equipments which need to be utilized more than once (Thakur and Katoch 2012). On-site sanitization using autoclaving can reduce the waste load which is further treated in common biomedical waste treatments and disposal facility. Autoclaving is suggested to have a better filtration efficiency and disinfection capacity over 70% ethyl alcohol (Kim et al. 2020).

### Microwave disinfection

The exposure of microwave radiation over infectious solid waste is the main function of microwave disinfection. In this process, electromagnetic radiation creates a thermal effect to inactivate the microbial population. Microbial population destroyed by the intermolecular heating is caused by microwave at 2450-MHz frequency and a wavelength of 12.24 cm (Thakur and Katoch 2012). Microwave disinfection is applied to soft contact lenses, dental instruments, dentures, urinary catheters, etc. This process of sterilization can be applied on metal instruments with certain precautions (Rutala and Weber 2008). Microwave disinfection is reported on various kinds of microorganism (such as fungi, lipophilic or hydrophilic viruses, mycobacteria, and bacteria) (Wang et al. 2020). Microwave disinfection technology can effectively work with other disinfection technologies for biomedical waste management.

### Landfilling

Landfilling is the simplest method of waste disposal after disinfection. Infectious solid wastes like biomedical or healthcare waste from hospitals, testing laboratories, quarantine wards, and other sources are dumped in a secured way into 1–2-m-deep burial pits called as secured or sanitary landfill sites.

Before disposing off the COVID-19-infected healthcare waste into landfill sites, it should be treated and disinfected properly by various wet or heat methods including autoclaving and dry heat treatment like irradiation methods using action of ultraviolet or microwave radiations. Landfills generally are of two kinds: open dumps (uncontrolled and scattered disposal) and sanitary landfills (engineered pits isolated from geological material). For infectious solid waste management, sanitary landfills should be used for disposal of decontaminated or treated waste. Poor waste management practices like open disposal of untreated infectious waste material into water bodies, land surface, or open pits are offering a serious threat to human health and environment.

Landfill is a special kind of engineered facility of land disposal of solid or hazardous wastes. The biological, chemical, and physical processes occur in the landfill and promote degradation of waste. These processes in the landfill produce polluted water in the base of landfill site and various gases (Reinhart and McCreanor 2000). Commonly, incineration ash, sharps, pathological waste, red bags, and hazardous chemical are used for landfill disposal as special waste. There are various types of microorganism found in the landfill leachate. Coliform, faecal coliforms, *Streptococci* are common species in the leachate. However, faecal materials from various sources contaminated with enteric virus in the leachate are pathogenic in nature (Reinhart and McCreanor 2000). Solid waste from hospitals has high number of microorganism than municipal solid waste. These microorganisms may move into the leachate (Klangsin and Harding 1998). Leachate also contains medicine waste and chemicals which can pose serious problem for groundwater table. Although autoclaving of waste before dumping into landfill is a good alternative of solid waste disposal, threat of groundwater contamination is still high. Thus, possibilities of COVID-19 contamination are very high from medical waste.

### Ultraviolet (UV) light

Ultraviolet irradiance refers to electromagnetic wavelength between 200 and 400 nm. There are three types of UV light, i.e. UV-A (315–400 nm), UV-B (280–315 nm), and UV-C (200–280 nm). A 200–300-nm wavelength has characteristics to destruct the structure of DNA and RNA of microorganisms (such as bacteria and viruses) which inhibit the protein synthesis. Thus, UV-C and UV-B are most effective against bacteria and 253.7 nm is considered optimal for ultraviolet disinfectant. The drawback with UV-C is an inadequate penetration in solid and liquid materials. The cost of UV light is low as compared to chemical disinfectant like chlorine (Wang et al. 2020). SARS-CoV virus was reported to be inactivated by UV radiations at 254 nm and heat treatment of 65 °C (Darnell et al. 2004). Riboflavin and UV light reduce blood-borne pathogens and efficacy of riboflavin with UV light increases in reducing

the infectivity of SARS-CoV-2 in human plasma (Ragan et al. 2020; Keil et al. 2020).

### Chemical disinfections

SARS-CoV-2 strains are phylogenetically very close to the bat SARS-related coronaviruses, and 78% nucleotide identity of spike protein shows with human SARS-CoV-1. These similarities may lead to similar sensitivity of disinfectants. Researcher reported that the SARS viruses could be inactivated with 2.19 mg/L residual chlorine dioxide or 0.5 mg/L residual free chlorine for 30 min. at 20 °C. Chlorine dioxide treatment gave best disinfectant results compared with UV irradiation and ozone disinfection (Chen et al. 2006; Wang et al. 2005). Derivatives of chlorine-based disinfectants (such as chlorine dioxide, sodium hypochlorite, and liquid chlorine) are widely adopted as hospital waste disinfection practices. These chlorine derivatives are used for liquid waste disinfection in hospitals for wastewater which come out in the form of drain material and poured into the sewage. Wang et al. (2020d) reported that the 6.5 mg/L residual chlorine is required for septic tank with a 1.5-h longer contact time and faecal coliform colonies less than 100 per litre. UV radiations and heating are also recommended for COVID-19-designated hospitals for ideal performance of disinfection practices. COVID-19-affected patients mainly use respiratory equipments as an external respiratory support system. These equipments should be saturated for 30 min in 75% alcohol. COVID-19-designated hospitals' waste is required to be collected in protective conditions. Wang et al. (2020d) suggested that the hospital wastes and wastewater should be treated with suitable disinfectants so that waste and wastewater must be free from infectious viruses before discharged into sewage. Consistent improvement processes are required for hospital waste management system during the COVID-19 pandemic.

### Liquid waste management options

The liquid waste generally containing wastewater released from toilets in hospitals, quarantine places, laboratories, or any other source suspected of transmitting COVID-19 contamination should be decontaminated or treated in wastewater or effluents treatment plants before being discharged into water bodies. It may include blood, urine, stools, or hospital sewage. Public health policies suggested that the wastewater should be treated in centralized wastewater treatment facilities before discharge. Each stage of treatment along with a standard retention time and dilution reduces a gradual risk. Lagoon pond or oxidative pond is a simple wastewater technology which is a suitable option to kill the pathogens, but their retention time is high (20 days or longer) and if combined with sunlight, elevated pH levels and biochemical activity along with other factors could accelerate pathogens reduction

(WHO 2020d). The final step of wastewater treatment plant is disinfection in which chemicals or disinfectants are used to kill pathogens of water. Bacteria, virus, and algae are the main pathogenic microorganisms.

Faeces of COVID-19-infected patients contain RNA of SARS-CoV-2 which triggers serious concern to disinfect human waste and wastewater of hospitals that are involved in the treatment of COVID-19 in China. RNA of SARS-CoV-2 found in the wastewater discharged from a COVID-19 hospital indicates contamination risk of drainage system is high in China (China Citywater 2020). Transmission of virus is possible through waste of infected patients, and wastewater system may allow airborne transmission of SARS-CoV-2 (Gormley et al. 2020). The disinfection of hospital waste requires high priority since the waste production augments rapidly during the pandemic period and this may increase the risk of contamination for medical staff (Yu et al. 2020).

The transmission routes of COVID-19 are direct contact and respiratory droplets which are risk for close vicinity. Human faeces are also main factor of transmission as approximately 2–27% COVID-19-infected patients have shown signs of diarrhoea. Faeces contain viral RNA fragments (WHO 2020e) which possibly reach into sewage systems. Inhalation and ingestion of dried particles which are contaminated from body fluids and faecal matter form another main way of transmission of norovirus and hantavirus. Transmission of virus by vectors like housefly and cockroaches can also be possible, when they contact with infected body fluids. SARS outbreak was also tested positive in human stool samples in 2002–2003. These indirect transmissions mentioned clearly indicate that various routes may arise in the future with rigorous investigations.

The World Health Organization (2020e) suggested an interim guidance about water, sanitation, hygiene, and waste management. In this interim guidance wash health care and wash practices in homes and communities mentioned and liquid waste management practices broadly suggested in view of preventive measures against COVID-19. Faeces of COVID-19 suspect or known patient requires to collect in diaper or clean bedpan and requires an immediately disposed of into a specific toilets and it considered as biohazard. The used bedpan should be washed with neutral detergent and disinfected with 0.5% chlorine solution. All the equipments and PPEs that are in contact with COVID-19 patients need to be disinfected with 0.5% chlorine solution or market-available disinfectants. The efficacy of disinfectants is not uniform for organic materials. Thus, the prewash with water can give good results before use of disinfectants. A PPE shield is required for individual who are dealing with cleaning process. Bhowmick et al. (2020) mentioned the possibilities of COVID-19 contamination circumstances in the urban and rural water cycles which help to create a comprehensive scene of exposure of COVID-19 (Fig. 9). Impurities of water create favourable conditions

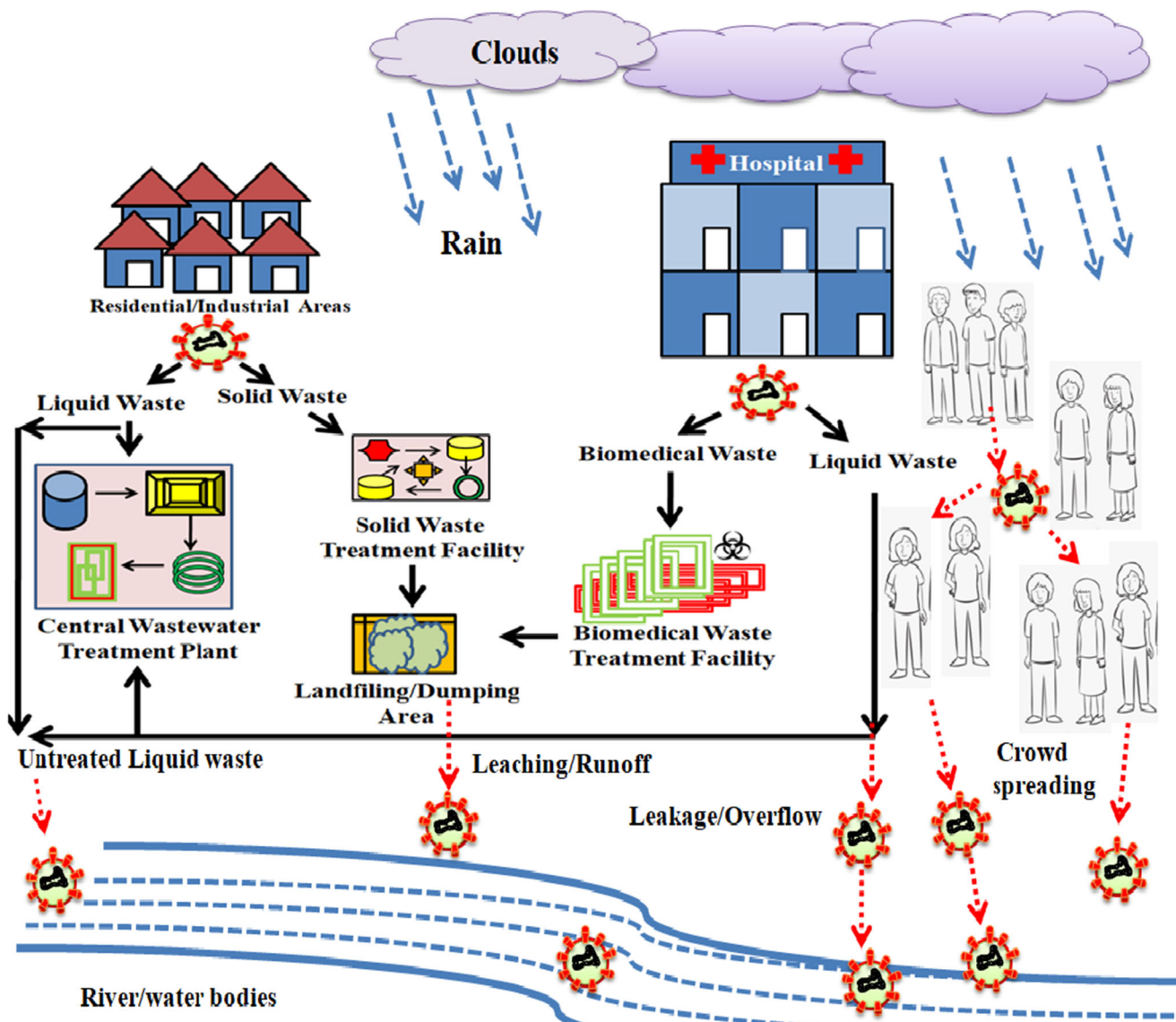


Fig. 9 Spreading possibilities of COVID-19

for various types of microbes. *Escherichia coli*, *faecal streptococci*, and *Clostridium perfringens* are the main bacterial species; *Cryptosporidium* and *Giardia* are well-identified pathogenic protozoan. Similarly, many viruses and microalgae are also found in the wastewater (Reinoso et al. 2008).

Surface water contamination is still a matter of investigation and there is no significant study reported for the same. In view of consistent research about the outbreak of COVID-19, various routes can contaminate the surface water resources. Thus, the chances of risk can be very high as surface water is utilized for drinking, bathing, irrigation, etc. The best way to check the outbreak of COVID-19 is to treat the surface water resources by the best available technologies such as chemicals disinfectants, UV irradiation, ozone exposure, etc. Wastewater treatment facilities require COVID-19 surveillance system so that on-site detection and treatment can be possible.

### Possible innovative solutions

COVID-19 pandemic has severely affected each and every sector throughout the world in various aspects like poor economic development; enhanced health problems; increasing energy crisis; lack of proper, cheap, and convenient strategy for infectious waste management; and many more that would make life difficult in the aftermath of the pandemic (Tahir and Sohaib 2020). Therefore, it is the need of the hour to find some possible innovative solutions for few of issues by means of renewable energy technologies and use of nanotechnology.

It can be easily realized that the “Necessity is the mother of invention” during COVID-19 pandemic which is triggering novel and innovative solutions to control the outbreak of COVID-19. Harris et al. (2020) selected various low-cost innovations responsive to the COVID-19 pandemic in the

world. Although most of the selected frugal innovation have existed, they are re-fabricated and re-purposed in view of pandemic necessity. Hydroxychloroquine is being used against coronavirus which was previously used for malaria prophylaxis. Ventilator multipliers, portable and open-source designs of ventilators, face masks and visors, task shifting in ICUs, and prone self-ventilation are some innovations of pandemic. Distilleries have produced millions of bottles of sanitizers for hand sanitization. China has made a COVID hospital in 10 days with 1000 beds capacity.

Asimov Robotics, a startup based in Kerala, India, has developed robots which distributed hand sanitizers at entrances of office buildings and public places and carry food and medicines in hospital wards which prevent the health worker from being getting into direct contact with COVID-19-infected patients (<https://www.weforum.org/agenda>). Indian railways came forward to combat COVID-19 by making mobile hospital in the trains and converting train coaches into isolation wards to meet the increasing demand for beds and ventilators (<https://www.livemint.com/news/>). Ventilators are the external respiratory support system required by the COVID-19 patient, but their cost is very high. Moreover, there is also shortage of ventilators in the medical facilities. In response to the shortage, AgVa Healthcare, Nocca Robotics, and Aerobiosys Innovations are some companies that are developing affordable, portable, and user-friendly ventilator for the emerging demand of Indian hospitals. Aqoza Technologies and PerSapien claimed that they have developed unique chemical formulations that disinfect public spaces which may meet the requirement of public spaces. PerSapien have developed a machine which dispenses ionized water droplets to oxidize the viral protein. Droom named startup claimed a special kind of anti-microbial coating “Corona Shield” which inhibits the growth of microbes on surfaces of vehicles. Google and Apple technological companies have developed COVID-19 tracking apps. In this series, the Government of India launched a nationwide COVID-19 tracking “Aarogya Setu” app which uses global positioning system and Bluetooth to provide valuable information about coronavirus. Drones are also utilized for monitoring social distancing rules, thermal imaging, and medicine deliveries in the country (<https://scroll.in/article/960783/indian-startups-are-fighting-covid-19-with-innovation>).

Although some positive changes are seen in the environment during lockdown such as reduction of plastic waste and greenhouse emission, pandemic control measurement utilizes plastic products which again create massive plastic waste. The use of plastic as a raw material for healthcare equipments is discussed in the section “Healthcare materials: raw materials used and their impacts and effects”. The cost of materials needs low and biodegradable nature of healthcare materials is beneficial for environment. Banana tree fibre has been utilized for manufacturing of mask. In the Philippines, teabags

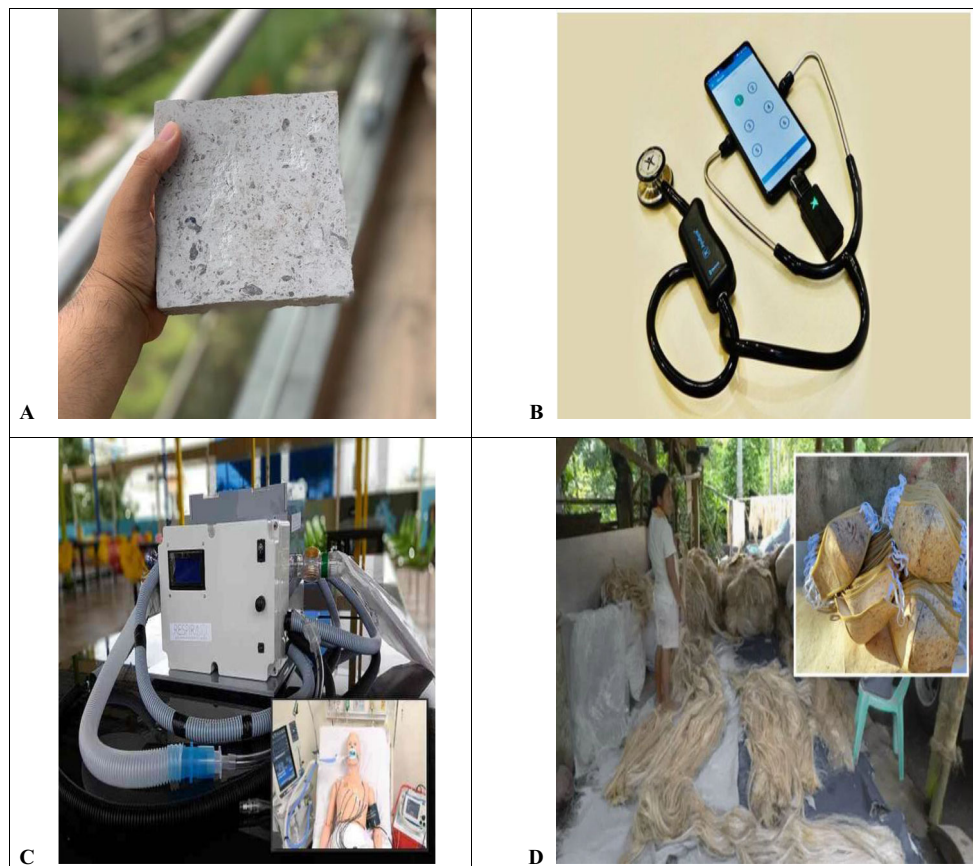
and banknotes are made from abaca (musa textile), and it is used in manufacturing masks during pandemic period. It is as durable as polyester and decomposes within 2 months (<https://theologicalindian.com/sustainability/masks-made-from-banana-tree-species-22702?infinitescroll=1>). Eco Eclectic Technologies make a “Brick 2.0” which is made by recycled PPE face masks. This can solve the problems of waste disposal and provide a value-added product. The formulations of bricks are 52% of shredded PPE materials, 45% paper sludge, and 3% binding agent. It is waterproof, is fire-resistant, and costs 2.8 INR per piece (<https://www.thebetterindia.com/235645/face-mask-recycle-ppe-masks-waste-bricks-gujarat-low-cost-innovation-covid-19-eco-friendly-ros174/>). AyuSynk is a digital stethoscope developed by a startup Ayu Devices which belongs to Society for Innovation and Entrepreneurship (SINE), IIT Bombay. The core advantage of digital stethoscope is that it can be attached to any regular stethoscope and maintains physical distance between the doctor and patient by sending data wirelessly from patients to doctor (<https://indianexpress.com/article/technology/tech-news-technology/an-indian-rethinking-of-stethoscope-suddenly-finds-relevance-in-covid-19-challenges-6354428/>). Defense Research and Development Organization and IIT Roorkee jointly developed 3-D-printed face shields to meet the shortage (<https://www.wionews.com/photos/how-covid-19-is-driving-innovation-in-india-291705#faceshields-291690>). “RespirAID” is a portable breathing support system used for the patients who are at severe risk of lung collapse. It is developed by Biodesign Innovation Labs for shortage of ventilators in hospitals. It is supported by Nidhi Prayas Programme of the Department of Biotechnology, Department of Science and Technology, Government of India. “Emvolio” is a portable temperature-controlled (2–8 °C) device which is utilized for transport of vaccines and biological samples in fields for 12 h. However, about 1100 pre-existing innovations submitted to the Centre for Cellular and Molecular Platforms (C-CAMP) and 18 technologies have been deployed in their respective fields (<https://indiabioscience.org/columns/indian-scenario/innovations-to-make-india-self-reliant-in-tackling-covid-19>). With time, the innovation numbers have increased in various aspects of COVID-19. These innovations can help to tackle the current and future challenges related to COVID-19 (Fig. 10).

### Renewable energy technologies

Energy in the form of electricity and fuel is the major requirement at every place. Households, hospitals, schools, offices, government, and private institutions need electricity for various purposes. Moreover, the use of fuel is necessary to industries, vehicles, and automobiles. Solar energy, wind energy, hydro energy, and biomass energy are main renewable energy technologies that can contribute to electricity generation that



**Fig. 10** **A** Brick made from waste PPE kits; **B** digital stethoscope; **C** RespirAID portable breathing support system; **D** biodegradable masks from banana tree. (sources: A, <https://www.thebetterindia.com/235645/face-mask-recycle-ppe-masks-waste-bricks-gujarat-low-cost-innovation-covid-19-eco-friendly-ros174/>; B, <https://indianexpress.com/article/technology/tech-news-technology/an-indian-rethinking-of-stethoscope-suddenly-finds-relevance-in-covid-19-challenges-6354428/>; C, <https://indiabioscience.org/columns/indian-scenario/innovations-to-make-india-self-reliant-in-tackling-covid-19/>; D, <https://thelogicalindian.com/sustainability/masks-made-from-banana-tree-species-22702?infiniteScroll=1>)



would be economically viable as these energy options are naturally available and environmentally sound. The ongoing COVID-19 pandemic has slowed down the economic growth due to closing of all developmental activities and has also resulted in huge energy crisis. In addition to households and other places utilizing energy, there are hospitals, laboratories, quarantine houses or wards, and many possible places which are in urgent need of additional energy in the form of electricity that could utilize renewable energy sources and meet their energy demands instead of depending upon conventional energy sources. Fuel requirements can be fulfilled by generation of biofuels from biomass. This would help in economic development and reduction in energy crisis.

#### **Nano-based technologies for healthcare materials of COVID-19 for manufacturing and treatment: a way forward**

Nano-based technology or nanotechnology has emerged as an attractive method for waste management. It involves the use of special particles of unique characteristics commonly called as nanomaterials. Nanomaterials refer to materials with nano-scale dimensions, size ranging from 1 to 100 nm. Nanomaterials possess great potential to decontaminate the waste appropriately and efficiently, and it is also expected that nanotechnology would help in waste management at a low-

cost reduction. In addition, energy demand is reported to reduce up to some extent using few selected nanomaterials. Nano-adsorbents like carbon nanotubes (CNTs), metal-based nano-adsorbents, and zeolites adsorb toxic organic compounds from wastewater, leading to its decontamination (Gehrke et al. 2015). Healthcare waste generated from COVID-19 also comprises liquid waste along with medical solid waste. The wastewater contaminated with SARS-CoV-2 can be treated with the nano-adsorbents in order to disinfect it. CNTs primarily act as adsorbent for removal of contaminants like non-polar organic compounds, oil, and heavy metals (Dermatas et al. 2018). The metal-based nanomaterials like silver, zinc, bimetallic, and magnetic nanoparticles are considered to be highly efficient for toxic liquid waste management (Lu et al. 2016).

#### **Contribution of Nanotechnology/nanomaterials to COVID-19**

Nanotechnology and nanomaterials could significantly deal with many clinical and public healthcare challenges that have arisen due to the prevailing COVID-19 pandemic. Chloroquine and hydroxychloroquine have a significant history as safe and inexpensive drugs used for controlling malaria (Andrea et al. 2003). Chloroquine has been widely accepted in the field of nanomedicine for the study of nanoparticle uptake in cells. The synthetic nanoparticles are active at early stage,

before viral replication that is resulted mechanism of chloroquine. Thus, the chloroquine-induced alterations of SARS-CoV-2 cellular uptake can be detected in nanomedicine studies. Recent studies described the various diagnostic methods such as nucleic acid and computed tomography testing and protein, point-of-care testing like new approaches of nanotechnology for diagnosing SARS-CoV-2 (Buddhisha et al. 2020). Silver nanoparticles (AgNPs) are used as inhibitors of viral reproduction, and their viricidal potential depends on the target virus. AgNPs can also inhibit the viral entry in the host cells and HIV-1 virus signifying the interaction of AgNPs with cell receptors (Kerry et al. 2019). AgNP interactions with the viral genome in the case of double-strain RNA (dsRNA) viruses inhibit the viral replication (Di Gianvincenzo et al. 2010). The antimicrobial properties of nanosilver colloids are well established (Aderibigbe 2017). It has been reported that colloidal silver (Ag) of particle size range between 3 and 7 nm is greatly useful to reduce viral mechanisms of infection at IC<sub>50</sub> concentrations at a concentration of about 10 µg/ml. These formulations were found efficient for the avoidance and treatment of respiratory viral infections including SARS-CoV-2 at early stages. The optimal anti-viral effectiveness was found with < 10-nm-sized nanoparticles (Nakamura et al. 2019). The filtration and separation of submicron-sized pollutants are of major concern for modern nanotechnology (Fig. 11) (Barhate et al. 2008). Nano-filters are a robust technology that maintain filtering efficiency and durability, though cost is still a challenge that needs to be reduced for its wide applicability.

### Implication policies for COVID-19: role of CPCB, municipalities, and NGOs

The regulatory body, CPCB (2020), in India on April 19, 2020, has notified a guideline for handling, treatment, and disposal of waste during treatment/diagnosis/quarantine of COVID-19 patients. The salient feature of the guideline is

the use of double-layered bags (i.e. using 2 bags) to ensure that the bags are of enough strength and does not leak. The guideline directs for segregation of the waste arising from the isolation wards as “COVID-19 waste” (constituting of biomedical waste) and “general waste” (without contamination). While the “COVID-19 waste” has to be managed and disposed as per the biomedical waste management rules, 2016, however, the role of CPCB to counter the pandemic has to be widened. Wide-scale awareness by holding webinars, installing banners, and holding at various places in cities and villages could be done. This becomes more important due to the fact that the nature and behaviour of the novel coronavirus (SARS-CoV-2) has been envisaged in the upcoming research findings. In cities and villages of India, blue- and green-coloured bins were installed to dispose of the biodegradable and non-biodegradable waste. Due to lack of medical beds in public and private hospitals, many non-symptomatic patients are suggested to go for home quarantine. Hence, there ought to be generation of virus-contaminated waste. These contaminated wastes will need to be managed and disposed with utmost care. Thus, the role of CPCB, municipalities, and non-government organizations (NGOs) becomes pertinent in the prevailing situation.

The municipality personnel involved in day-to-day collection of municipal solid waste must be trained for the safe collection, handling, storage, and disposal of the municipal waste. They must strictly use the PPE (particularly mask and gloves) and report any symptoms of COVID-19 to the authorities immediately. Further, the municipalities have to come up and play a wide role in the prevailing situation. The municipalities must ensure that pure domestic water supply is provided to each and every household for the requirement of daily chores by each individual of the family. The quality of the domestic water supply becomes more important in the present situation. Hence, proper wastewater treatment followed by disinfection must be ensured by the local authorities. As the water demand is also anticipated to rise due to increase in cleansing activities, viz. washing hands, bathing, washing

**Fig. 11** Nanocoated and uncoated mask



clothes, etc., it must be ensured that sufficient water is made available to each household. The rooftop water harvesting could be widely encouraged and made mandatory for making the freshwater available. This will lessen the additional burden on the municipalities in supplying freshwater in a locality. Electricity demand is also expected to rise as more washing of clothes will be done. Thus, electricity must also be supplied sufficiently and ensured that it reaches to maximum possible household.

The NGOs must be involved in the planning and policymaking by the government bodies. It is expected that more and more personnel at ground level will be needed in days to come. Thus, the government must partner with the NGOs and entrust them with the work as per need and requirements of the locality. This may include taking their services in creating awareness in localities, door-to-door campaigning and seeking the health status at the ground level, moral boosting of the people, and informing people about the schemes and programmes offered by the government. There has been a rise in demand of hand disinfectants. It has been reported that some vendors owing to the high demand have resorted to use methanol, in place of ethanol, to produce disinfectant. Methanol is not only ineffective in killing the novel coronavirus but also highly toxic if it penetrates the body through dermal contact leading to blindness and even death. The US Food and Drug Administration (FDA) has identified 9 hand sanitizers (manufactured in Mexico) to be adulterated with high concentration of methanol. These sanitizers were earlier approved by the FDA (<https://11xi.in/fda-issues-warning-against-9-hand-sanitizers>). NGOs could play a vital role in creating awareness to the common people to avoid using such types of disinfectants.

This pandemic has suspended one of the most essential activities that is the conventional education system that provides classroom mode of teaching. Providing quality education to the target audience is a challenge and has several limitations, particularly in developing economies. Protecting a child's mental health is another challenge that could be taken and addressed by NGOs. The policies need to be designed in such a way that they reach children who are at undeserved locations and need utmost care and attention. The outreach will enhance the mental health of the children and their parents as well. NGOs may also make people aware of future cyber-attack, phishing attack, and other forms of cyber-attack. NGOs, thus, may offer services at various levels and can be an important connecting link between people and government.

## Future prospects

Biomedical waste management is challenging in developing nations like India and COVID-19 has created an extra burden on the biomedical management systems. Sensible use of PPE kit can

reduce waste load. Waste to energy concept application can give beneficial results in the direction of energy generation from waste such as gasification. The use of biodegradable materials in making of PPE kits is a sustainable option for waste management. The on-site waste treatment facilities can easily reduce the risk of contamination which can also help to build a clean environment. More research and development is needed so that innovative solutions can easily tackle out future challenges.

## Conclusion

The COVID-19 pandemic has created havoc and extreme condition for environment and human race worldwide. Waste management practices were not well established to handle such pandemic situation, and now, COVID-19-associated waste (CAW) has become a great challenge in these situations. There are various harmful impacts of CAW on various components of biosphere (air, water, soil). Moreover, waste management and disposal technologies (incineration, pyrolysis, autoclaving, landfilling, microwave disinfection, ultraviolet light, chemical disinfection, nanotechnology, renewable technologies, biodegradable masks, tracking app, etc.) are in the developing stage and their accessibility is also not uniform. Selection of single most effective waste management and disposal method is also a major challenge. In order to safeguard human health, there is much demand to manage the solid waste along with CAW to reduce waste and avoid disease transmission. Major governmental policies and NGOs are working to handle this pandemic situation and provide possible comfort at each level.

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## Declarations

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