Chapter 11
Sludge Hygienisation—A Novel Technology for Urban Areas to Deal with Incursion of COVID-19 Viral Particles in Wastewater

Rudrodip Majumdar

Abstract  The ongoing pandemic of viral infections due to the novel coronavirus disease (COVID-19) is known to have affected about 8,240,000 people globally and approximately 3,67,000 people in India as of June 19, 2020. The pandemic being quite persistent in nature, timely planning for novel and adaptive interventions are required for dealing with it, with a view to detecting the early signs of infection, as well as, controlling the spread of the outbreak towards the uninfected population residing at comparatively safer zones. In general, the coronaviruses belong to a group of RNA viruses that are known to infect a wide range of hosts including humans, other mammals and birds, with the clinical courses in the infected hosts ranging from being asymptomatic to showing acute symptoms in the respiratory, digestive and genital organs. Although the SARS-CoV-2 (COVID-19) is reported to spread primarily through inter-personal physical contacts rather than the faecal-oral route, evidence of gastrointestinal symptoms caused by SARS-CoV-2 infections accompanied by the detection of viral RNA in the faeces of infected individuals, with high probability of their presence in wastewater samples, makes an important case for the thorough characterization and quantification of the pathogenic materials present in the municipal sludge generated in urban centres. This becomes even more important in the case of the metro cities and dense urban centres, where the chance of the medical wastes from the COVID hospital facilities coming into the municipal sewage stream is highly likely. However, the pathogens in the municipal sewage stream become concentrated in the sludge, providing an opportunity to treat the separated sludge from the wastewater stream using a technology of irradiation called ‘sludge hygienisation’ to curb the outbreak of the virus. The present work provides an assessment of the sludge hygienisation technology for its suitability as an option to eradicate the viral particles accumulated in the sludge samples from urban environments that are presumably infected through the faecal deposition, as well as, due to uncurbed release of untreated biomedical wastes. Such an intervention will provide suitable means to control rapid viral outbreak that might be attributed to the high volumetric flow rate of the municipal sewage. Investment in such novel interventions, given the

R. Majumdar (✉)
National Institute of Advanced Studies, Bengaluru 560012, India
e-mail: rudrodip@nias.res.in

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2021
C. Chakraborty et al. (eds.), The Impact of the COVID-19 Pandemic on Green Societies,
https://doi.org/10.1007/978-3-030-66490-9_11
current circumstances, will be important to contain present and future outbreaks, ensuring that the community healthcare systems are saved from being pushed to the limits owing to the increasing pressure on the infrastructure that arises from the rapidly growing number of infected individuals.

**Keywords** COVID-19 infection · Biomedical waste · Municipal sewage sludge · Sludge hygienisation · Irradiation treatment

### 11.1 Introduction

Need for efficient management of urban wastewater poses a significant challenge in many countries, especially the ones that are witnessing rapid urbanization and subsequent formation of dense urban clusters. The primary bottleneck in managing the urban wastewater (UWW) arises from the lack of adequate infrastructure, as well as, the archaic regulations that have not been updated keeping in mind the population growth and complex socio-environmental attributes of urbanization [1–3]. By 2030, the world is projected to have 43 megacities with more than 10 million inhabitants, and many of the fastest-growing urban agglomerations are located in developing regions, viz. Asia and Africa [4]. In a further futuristic estimate, the global urban population is expected to reach the 6.3 billion mark by 2050 [5]. It is noteworthy that ever increasing energy costs accompanied by the acute shortage of potable water have prompted the global urban community to be cognizant of the scarcity of resources and the need to improve the water efficiency with a view to facilitating discreet consumption [6, 7]. The increasing environmental, financial and social costs associated with water quality and availability, has forced the practitioners, policymakers, researchers, as well as, the civic bodies to assign a high priority towards understanding the wastewater management scenario and the necessary remedial actions [7]. However, owing to the lack of well-organized sewer systems outside the central areas at many growing urban centres [8, 9] vast quantities of untreated wastewater flows directly into the environment. It is reported that in Asia about 90% of the wastewater is allowed either to get discharged into the open water bodies; or to leach into the soil, thereby increasing the potential risk of contaminating the groundwater aquifers [3]. In some cases, septic tanks are also found to be directly connected to the open drains, and such an arrangement significantly deters the reduction of the solid waste load from the wastewater stream, resulting in a higher load of sludge and scum in the municipal wastewater stream [10]. The abundance of sanitation waste, which is a prime constituent of the raw urban wastewater, imparts a detrimental impact on the health, dignity and overall development of the urban community [10]. Considering the ongoing pandemic of COVID-19 and its potential to spread fast within an urban community, it is of prime importance to inspect the possibility of incursion of SARS-CoV-2 viral particulates in the urban wastewater and their sustained presence in the municipal sewage sludge. This also necessitates the primary feasibility assessment of the potential indigenous technological options aimed at hygienising the sludge, in
order to ensure that the sewage sludge from the dense urban centres in India is free from contagious and hazardous pathogens.

Urban wastewater (UWW) typically comprises of domestic, agricultural, commercial and industrial components, as well as, the faecal sludge [3]. In addition to the abovementioned components, another pivotal, as well as, critical component of UWW is the wastewater released from the healthcare establishments in the urban centres [11]. The criticality of the individual components in determining the overall quality of the municipal wastewater stream depends on the constituents and the success of the strategies aimed at controlling the discharge of pollutants in the wastewater streams is largely dependent on the identification and quantification of the sources [12].

Typically, the domestic wastewater (DWW) comprises of simple elements, mainly carbon (C), nitrogen (N) and phosphorus (P), as well as, biodegradable macromolecules coming from fat, oil, starch and grease (e.g. amino acids, proteins and polysaccharides) [13], accompanied by other organic materials (e.g. creatinine, urea, etc.), detergents, pesticides, toxic metals (e.g. Hg, Pb, Cd, Cr, Cu, Ni) and microorganisms such as pathogenic bacteria, virus and worm eggs [14]. The principal source of metals in the DWW stream is the faecal matter and every kilogram of faecal matter typically adds about 250 mg of Zn, 70 mg of Cu, 10 mg of Pb, 5 mg of Ni and 2 mg of Cd to the DWW in the form dissolved solids [12]. In the areas where the running water possesses higher extent of hardness, more than 50% of Cu load in DWW comes from the plumbing work that is done especially for the hot water installations, and in the areas with extensive Pb pipework, typically 25% of the total Pb load is attributed to the pipes used for water conveyance [12]. The other identified sources of metals in the DWW include body-care products, pharmaceuticals, cleaning products and liquid wastes. DWW potentially contains four main groups of pathogens, viz. bacteria, viruses, protozoa and helminths, and they are known to enter the wastewater stream through the human excreta (faecal sludge). Although the faeces of an average human being contain a very large number of bacteria (>10^{10}/g), in case of a healthy person most of these bacteria are not pathogenic (e.g. *E. Coli*). Pathogenic or potentially pathogenic bacteria occurs in large numbers in the intestinal track only when an infection occurs and those are passed on to the faeces, thereby increasing the risk of spreading the infection to the adjacent communities. Bacteria population responsible for diarrhoea, cholera, typhoid, paratyphoid and other Salmonella type diseases occur frequently in the human faeces, and hence, there is a substantial chance of their presence in the DWW as well [15]. Numerous viruses are known to infect humans and the typical viral load in the faeces of an infected person is more than 10^{9}/g. In the human excreta, five group of viruses, viz. human adenoviruses (e.g. HAdV-C (relative abundance 78%) and HAdV-B (relative abundance 20%)) [16], enteroviruses (e.g. polioviruses), diarrhoea-causing viruses (e.g. rotavirus), hepatitis-A virus and reoviruses have been predominantly observed. Hence, their presence is also possible in the DWW streams. Additionally, three species of pathogenic protozoa that cause diarrhoea and dysentery, viz. Balantidium coli, Entamoeba histolytica and *Giardia lamblia*; and also the eggs or larval forms belonging to two groups of helminths (parasitic worms), viz. roundworm and flatworm are found in the human faeces,
which have the potential to be transmitted via the flow of DWW and cause pandemic [15, 17].

Agriculture, which accounts for 70% of water consumption worldwide, plays a major role in polluting the natural flows of water and the agricultural run-off is termed as a non-point or diffuse source of pollution. Agricultural wastewater (AWW) typically comprises of organic matter, nutrients (N, P and K), inorganic matter (dissolved minerals), toxic chemicals coming from fertilizers, herbicides, and pesticides and also pathogens [18]. The quest for the growth of crop production to ensure upliftment in the rural livelihood has led to extensive use of chemical fertilizers and pesticides in the agricultural lands [18]. In a number of growing economies, AWW has already overtaken the contamination due to the domestic and industrial activities, and has become a leading factor in the degradation (e.g. eutrophication) of inland freshwater, as well as, the coastal waters [9]. As per the World Water Development Report (WWDR) 2014 of the United Nations, the nitrate ion from the agricultural run-offs has emerged as the most common chemical contaminant worldwide in the groundwater aquifers [19]. Furthermore, compounds present in the pesticides and the herbicides, such as the triazine group (e.g. Atrazine), the phenyl urea group (e.g. chlorotoluron, diuron and isoproturon), the phenoxy acid group (e.g. Mecoprop and 2, 4-D) can also be found in the AWW [12]. Organic matter present in AWW is largely attributed to the excreta of the farm-grown livestock, unconsumed animal feed, mismanaged crop residues and leftover from the animal-processing industries. The untreated organic wastes discharged from the fisheries and aquaculture also contribute to the organic load in the AWW [18]. Over the past three decades, there has been a conscious effort towards reusing treated municipal wastewater for agricultural purposes [20–23]. The conventional primary and secondary wastewater treatment facilities tend to recover most of the organic matter, dissolved solid, as well as, the suspended solid particulates in the form of sludge [23]. However, the microbial load remains unfazed by the conventional wastewater treatment processes and the pathogenic microorganisms continue to survive both in the treated wastewater and the concentrated sludge. The sludge recovered from the municipal sewage water is rich in nutrients (e.g. nitrate and phosphate) and hence, upon drying the sludge often it is used in the agricultural land for improving productivity [24]. Therefore, the pathogenic microorganisms may enter the agricultural field via the treated municipal wastewater, as well as, the dried municipal sludge. Subsequently, the pathogenic load of AWW will be very similar to that observed in case of DWW samples. Additionally, pathogens from the vegetable waste, viz. bacteria (e.g. Pseudomonas lacrimans, Xanthomonas campestris etc.) and viruses (e.g. Potato virus X, Potato virus Y, beetroot and onionmosaic viruses etc.) [25], can also enter the AWW streams. In the agricultural lands, the plants may take up the pathogenic bacteria and subsequently, it may enter the food chain. Therefore, the nutrient-rich bio-solids recovered from the sewage sludge need to be hygienised before being used for fertilizing soil [26]. For the municipal water to be reused in food crop production, EPA Guidelines for Water Reuse recommend a minimum of secondary treatment accompanied by disinfection [27]. However, for the municipal sludge no such guideline is available, and therefore, there is a need for regulatory framework for proper sludge hygienisation and management.
The industrial wastewater (IWW) encompasses contaminated stormwater, washdown waters from mechanical plants and vehicles, cooling water from the energy production industries and process waters from several plant units dedicated to food processing, mineral processing, fertilizer production, textile processing, manufacturing chemicals, petrochemical works, etc. [28]. Several IWW streams contain both heavy metals and the organic compounds as the pollutants [29], and studies indicate the emergence of IWW as a major source through which anthropogenic organic chemicals (e.g. acrylonitrile, styrene, ethylbenzene, dimethyl-benzene, chlorinated organics and other functional chemicals) enter the environment [30, 31]. In the stormwater run-offs, the Pb load is largely attributed to the abrasion of paved surfaces due to the friction between the vehicle tyre and the road, as well as, the wearing of the brake lining [12]. Wearing of brake lining can also lead to the release of other metals, such as Cd, Cu, Sb and Zn into the urban run-offs [32]. Additionally, Pb and Zn being washed down from the roofing materials in the housing complexes serve as the localized sources of these elements in the stormwater [12], especially during the periods of heavy monsoon. The organic load in IWW occurs in the form of various organic substances [12], of which the non-polar organic compounds (NPOC) that are lighter than water (e.g. phthalate esters, alkanes, polycyclic aromatic hydrocarbons (PAHs), etc.) tend to form a prohibitive layer [33], essentially blocking the flow of oxygen into the wastewater stream, whereas, a few polar substances [34, 35] (e.g. pharmaceuticals, viz. 1 H-Benzotriazole, Clofibric acid, Sulfamethoxazole etc.) that are soluble in water have been toxic to the aquatic fauna and have been found to even trigger the eutrophication upon being discharged into the urban waterbodies, thereby disrupting the equilibrium in the biotope [36]. From the viewpoint of treatment of IWW, a critical problem arises due to the fact that the wastewater stream contains a combination of organics. It is comparatively easier to deal with the organic compounds when a particular compound (e.g. Lindane, a common insecticide) is alone in the IWW, using specialized disposal techniques such as high-temperature incineration. However, for the wastewater containing different combinations of organic wastes, no single treatment technique is found to be fully amenable.

The wastewater streams from the healthcare establishments or the medical wastewater (MWW) usually exhibit a physico-chemical quality akin to urban wastewater; however, the presence of various potentially hazardous components, viz. high concentration of enteric pathogens (including bacteria, viruses and helminths), hazardous chemicals used in cleaning and disinfection, pharmaceuticals (including antibiotics and genotoxic drugs), radioactive isotopes from oncology departments, make the MWW a high-risk flow stream [11]; and adherence to biomedical waste guidelines is a must for ensuring safe discharge of healthcare waste in to the sewer. Particularly, the healthcare waste contaminated with pathogens and infectious particles poses serious concern for the people dealing with it at each stage starting from the waste generation to ultimate disposal. The biomedical waste generated while treating the patients in the care units is taken away by the hospital staffs and practitioners, and thereafter, it is handed over to the disposal staff. As the infected waste passes through several hands, there is a finite chance that the infectious particles would spread, which may at times assume the form of a pandemic if not intervened
at the right moment. Infectious diseases are propagated from the healthcare wastes through several different pathways, such as—(a) through the exposure of an uninfected individual to the infected droplets that might be present in the medical swabs, absorbent gauze clothes and other surgical disposable products (e.g. needles and syringes, scalpel blades, lancets, blood spill clean-up materials, disposable suture sets and biopsy forceps); (b) through the exposure to the body-fluid specimens (e.g. blood, saliva and nasal secretions) of an infected vector [37]; (c) through the exposure of an uninfected host to the urine, faeces and vomitus (containing fluid blood) from the infected vector; and in some cases, (d) through the exposure to the carcasses that are suspected of being contaminated with infectious agents [38].

The safe and sustainable management of biomedical waste (BMW) is a major social and legal responsibility of the community as a whole, and it revolves around two main principles, (a) reduction in the volume of biomedical waste generation and (b) recovery and recycling of the waste to the maximum extent possible [39]. Furthermore, it is also important to contain and segregate the biomedical waste separately from other waste at the point of generation. As per the ‘Biomedical Waste Guidelines’ it is mandatory to place the solid biomedical waste in securely tied red bags, and to place the loaded bags in well maintained secondary containers that are rigid, leak resistant, clean and fitted with tight covers [38]. However, owing to the lack of cautious monitoring from the governing bodies, such as the pollution control board (PCB) [40], as well as, the inadequacies of the healthcare facilities (HCF) in terms of the manpower and infrastructure [41], biomedical waste is often disposed in an improper fashion leading to multiple environmental and health hazards [42]. During the times of overland flash floods, the dormant as well as active infectious particulates from the inappropriately disposed biomedical waste can enter into the stormwater run-offs, which may eventually end up in the urban waterbodies. Additionally, while flowing through the large canals and open drains, the infected wastewater may transmit serious illness to any population that may form direct contact with the stream. In case of contagious diseases, such a transmission would be a matter of grave concern, as it has the potential to trigger a community spread through interpersonal contacts. Moreover, the sewers of the healthcare establishments, where the patients suffering from highly contagious diseases, such as cholera and typhoid are treated, are bound to receive contaminated wastewater. Such infected wastewater streams can trigger a massive outbreak of disease within the urban communities, if it is allowed to get discharged into the regular UWW streams without proper disinfection and necessary precautions [11].

It is worth highlighting that the concentrated sewage sludge, largely composed of organic matter and nutrient-laden organic solids [23], being an end product of municipal wastewater treatment process contains the pathogenic microorganisms that are the critical constituents to remain active in the sludge. Among these microorganisms, a number of pathogenic bacteria are both human pathogenic and zoonotic, i.e. they can potentially infect both humans, as well as, animals. Additionally, these organisms have been found to exhibit strong adaptability to suit their survival in the changing environment [43]. Modified bacterial strains can be quite stubborn and relatively resistant to commonly employed sludge stabilization techniques, making
them even more hazardous in the context of both human and environmental health [44]. Figure 11.1 schematically shows the possible pathways in which the COVID-19 particulates can get transmitted to the urban population through UWW and the associated sewage sludge.

During the recent pandemic caused by the COVID-19 RNA virus, scientifically identified as Severe Acute Respiratory Syndrome Coronavirus SARS-CoV-2 [45], the primary mode of transmission of the infection has been inter-personal physical contacts. However, have emerged showing the gastrointestinal symptoms caused by SARS-CoV-2 infections [46–48]. In a recently published research letter, a group of scientists claimed to have isolated live COVID-19 virus from the faeces of patients who supposedly died from acute SARS-CoV-2 infection [49]. Another group of researchers claimed to have detected RNA fragments of SARS-CoV-2 from the surfaces of the hotel rooms where pre-symptomatic individuals had been quarantined [50]. Surface samples collected from the duvet cover, pillow cover and towel tested positive for SARS-CoV-2 RNA and it indicates that the used items from the quarantine facilities, especially the clothes, should not be taken to the washeries or any centralized public facilities. Upon the detection of viral RNA in the faeces of infected individuals [51], the presence of the infectious particles in the wastewater becomes highly probable. The probability becomes even higher for the wastewater samples coming from healthcare facilities dedicated towards treating the COVID-19 patients, popularly termed as COVID hospitals, and also the wastewater streams generating from the households where asymptomatic individuals, as well as, those with mild symptoms have been home quarantined. Published studies indicate that about 20% of the healthcare facilities in the world are devoid of the essential WASH

---

**Fig. 11.1** A schematic for possible pathways of incursion of SARS-CoV-2 particulates into urban wastewater and transmission of the infection
(Water, Sanitation and Hygiene) services, which deters the overall ability to control
the spread of COVID-19, as well as, to recuperate from the pandemic quickly [52].

Such a scenario necessitates a thorough evaluation of the sludge samples using
demographic information, epidemiological and clinical characteristics, followed by
characterization and quantification of the pathogenic materials present in the munic-
ipal sludge generated in urban centres. Moreover, it is also of importance to identify
suitable sludge hygienisation techniques, looking at the adaptive and resilient nature
of the virus strain.

This chapter aims to look at the nature of interaction between the environment
and SARS-CoV-2 viral strains, with a view towards having an insight into the trans-
mision pathways of the pandemic. It also aims to establish the potential connection
between the infected urban wastewater and the spread of the pandemic. Finally,
the chapter also addresses a suitable sludge hygienisation technique and discusses
the key features associated with the implementation. The novel contribution of this
present analysis encompasses the detailed cost analysis of proposed intervention and
the long-term beneficial impacts. Such an intervention would help in releasing the
tremendous pressure that has been put on the healthcare facilities worldwide by this
novel pandemic, in terms of resources, as well as, the treatment regimen.

11.2 Interaction Between COVID-19 Virus Particles
and the Surrounding (the Host and the Environment)

Most of the human coronaviruses belong to the genera Alpha-coronavirus and Beta-
coronavirus and are usually responsible for mild respiratory illness. However, the two
Beta-coronaviruses, viz. SARS-CoV and MERS-CoV have been found to be highly
pathogenic, and especially the novel coronavirus SARS-CoV-2 has been known to
invoke a wide range of symptoms among the patients, ranging from regular symptoms
such as fever, dry cough, loss of taste, smell and tiredness, to the severe symptoms,
viz. difficulty in breathing, acute chest pain and even loss of speech or movement
[53]. However, acute and severe syndromes have been found in only about 5% of
the COVID-19 patients. Therefore, the interaction between the SARS-CoV-2 virus
particulates and its surrounding, which includes both the host and the environment,
becomes essential in order to break this chain of aggressive pandemic.

The interaction of critical pathogens (responsible for several water-borne, as well
as, other diseases) present in the fecal sludge and municipal wastewater, viz. viruses,
bacteria, protists and helminths, with environment is very complex in nature. It
is noteworthy that majority of the bacteria, protists and helminths are zoonotic
pathogens. Although several parasitic zoonotic pathogens that are transmitted via
the fecal–oral route are known to cross the species barrier and spread infection
among a sizeable human population; the pathways through which the pathogens
emerge from the host (animal reservoir) and the mechanism behind their subsequent
persistence within the human population are some of the key issues that are not
still well understood and need continued scientific exploration [54, 55]. The bats are thought to be the most likely ecological reservoirs for SARS-CoV-2. However, it is believed that the virus got transmitted to the humans via another intermediate animal host. While the possibilities include domestic food animals, wild animals, as well as, domesticated wild animals; the identity of the intermediate animal host has not been ascertained yet [56].

The human-to-human transmission of pathogens can be effectively traced through a deeper understanding about the manifestation of a pathogen inside the carrier (host), the transmission through the fecal–oral route, and the sustenance of the pathogens in the environment. For example, pathogens responsible for enteric diseases can get transmitted from one human host to another in two different ways, viz. (a) via the direct contact (fecal–oral route) and (b) via indirect contact (e.g. through contaminated fluids, such as surface water; food, currency notes and fomites, such as clothes, utensils and furniture, that are likely to contain infectious particulates because of daily usage by an infected host (human) [55].

It is to be noted that most of the pathogens that are transmitted via the fecal–oral route are likely to be very stable and can even sustain under reasonably hostile conditions. This ability is exhibited by the success passage of live infectious particles through the varying pH conditions of the gastrointestinal tract that includes acidic ambience of stomach and alkaline or mildly acidic ambience of the intestine the hostile conditions [55].

Furthermore, researchers have found that viruses, helminths and the protozoan cysts and oocysts (a cyst that contains a zygote formed by a parasitic protozoan) exhibit longer sustenance (ranging from a few days to several months) in the environment as compared to the vegetative bacteria [17, 54]. Therefore, the discovery of live COVID virus and the SARS-CoV-2 RNA fragments in the human faeces as mentioned before, elevates the danger of community spread. Further, it is reported that COVID 19, with its high transmissibility, can result in the spread of the virus to at least 2–2.5 uninfected individuals from each infected individual on an average, if the precautionary measures, such as social distancing, are not strictly abided by [57].

The human-to-human transmission of a typical enteric pathogen via the fecal–oral route is largely dependent on the three distinct phases of transmission amplification, viz. (a) Amplification within the donor (host): The amplification within the host depends on a few key factors, such as the gut microbiome (the genome of all the microorganisms, symbiotic and pathogenic, living in the intestine) of the donor, pathogenicity (ability to cause diarrhea) of the microorganism, niche adaptation of the pathogen within the intestinal tract of the host (persistence) and the extent of shedding in the faeces; (b) Amplification in the Environment (during the transmission): The amplification of pathogenicity in the environment primarily depends on the environmental stability of the particular pathogen, habits and practices of a human community in connection with food and hygiene (agriculture, food processing, food storage and transport, etc.) and also on the environmental microbiome; (c) Amplification within the receptor: The amplification within the receptor is akin to that in the donor, and largely depends on the receptor gut microbiome,
niche adaptations of the pathogen within the receptor’s intestinal tract and the expression of the organism within the receptor’s intestinal tract (e.g. tissue distribution, multiplication, etc., depending on the nature of the pathogen).

In addition to the amplification mechanisms that have been discussed above in the context of an enteric pathogen, some other amplification attributes exhibited by SARS-CoV-2 include infection in the upper respiratory tract, followed by inflammation in the alveoli and filling of alveoli with fluid and pus, eventually leading to pneumonia [58]; intra-host genomic variability (several low to higher-frequency single nucleotide variations (SNVs) across the viral genome has been reported, with 7 out of 10 protein-coding viral genes being affected and the density of genome modification has been found to be variable) [59]; and immune evasion during cytokine storm caused by systemic immune over-activation in the hosts with severe infection [60].

Most of the current evidences indicate that the human-to-human transmission of COVID-19 virus primarily occurs via the respiratory droplets and contact routes. More specifically, COVID-19 respiratory infections are transmitted through (a) larger respiratory droplets of diameter >5–10 μm (they travel over short distances, L < 1 m), as well as, (b) virus-laden aerosolized droplets or droplet nuclei (droplets with diameter smaller than 5 μm) (they travel over distances >1 m). Droplet transmission from the infected individual to the uninfected people may occur due to coughing and sneezing while being in close contact. In such cases, upon getting exposed to the infective respiratory droplets, the mucosae of mouth and nose, as well as, the conjunctiva of the eyes may facilitate the entry of virus particulates into the body of an uninfected individual [51]. The COVID 19 virus has also been reported to be active and alive for substantial period on the surfaces of the fomites, thereby enhancing the possibility of transmission via the contact route. Figure 11.2 depicts

![Fig. 11.2 Schematic representation of manifestation of SARS-CoV-2 in the host, sustenance of virus particulate in the environment and transmission into the receptor](image-url)
schematically the possible interaction mechanism between the SARS-CoV-2 partic-
ulates and its surrounding, that includes both the host, as well as, the environment.
It encompasses the manifestation in the host, sustenance in the environment and
subsequent transmission into the receptor.

Overall, from the samples analysed at different geographical locations, it has
emerged that the SARS-CoV-2 particles emerging from the infected individuals via
the respiratory droplets and through the faeces cause a definite level of contami-
nation in the environment [61], and it is likely that both the mediums serve as the
potential pathways towards large-scale transmission of the disease, which may even-
tually lead to community spread. Consequently, the hygienisation becomes an issue
of prime importance. Therefore, apart from thorough sanitization of the spaces of
mass gathering, and maintenance of the hand hygiene at the individual level; it is
also of importance to employ a suitable technology towards hygienising the munic-
ipal sewage sludge of the densely populated urban centres, as the sludges serve as
the breeding ground for a lot of pathogens that can be transmitted to the commu-
nity during the time of handling or through accidental indirect contact with the
contaminated wastewater flowing through the urban canals. International experts
have opined and advised that the countries should adopt the waste treatment path-
ways that are environmentally sound, following the guidelines provided by UNEP
(United Nations Environment Programme) regarding Sustainability Assessment of
Technologies (SAT) pertinent to Best Available Technology and Best Environmental
Practices (BAT/BEP) [62].

11.3 Overview of Sludge Hygienisation Techniques—Focus
on the Irradiation Treatment Technology

Since early years of 1980s, some of the European countries have been directing
substantial research effort towards innovating effective sludge hygienisation tech-
nology. In Switzerland, a 2-stage biological procedure emerged in 1983, which
encompassed partial aerobic thermophilic fermentation in the first stage followed
by anaerobic sludge digestion in the second stage. Researchers associated with this
development had claimed to have achieved effective hygienisation of sludge, along
with improved sludge thickening and reduced digestion time. The innovators also
claimed that the abovementioned process facilitated lesser energy consumption and
enhanced process stability [63]. Serious research work went on for about a decade
with a view to optimizing the procedure and a few pilot plants had been installed
at the wastewater treatment plants (WWTP) in and around the city of Altenrhein.
During those times, it was pointed out that processes like sludge drying and sludge
composting might not be capable of entirely preventing the regrowth of pathogenic
microorganisms. Keller pointed out that liquid sludge irradiation could be an effective
pathway towards disinfecting the sewage sludge [63].
In a research article published in 1983, Breer mentioned that the application of gamma rays or accelerated electrons could be a better alternative as compared to the thermal processes, such as the aerobic-thermophilic fermentation of liquid sludge and the drying of sewage sludge [64]. The advantage with the gamma rays is that they exhibit adequate penetration into the water and the concentrated liquid sludges. The half-value thicknesses of 1.33 meV $\gamma$-rays from Co-60 source, for water and the normal liquid sludge are about 28 cm and 25 cm, respectively [65], and such penetration depths ensure effective delivery of intended irradiation dose across the thick layers of slurry, into the interior parts of liquid sludge.

Although during 1990s the future prospects of irradiation-based sludge hygienisation facilities looked quite promising, with several facilities being in various stages of planning and some under construction; many of those plants were shut down later on. However, most of them did not cite any particular operational difficulties [66]. The most common $\gamma$-ray sources used in the industrial-scale radiation facilities are Co-60 (Cobalt-60) and Cs-137 (Caesium-137). Co-60 is produced by exposing non-radioactive Co-59 to a neutron flux in a nuclear reactor, whereas, Cs-137 can be obtained as a by-product of the spent-fuel reprocessing cycle in the form of CsCl (Caesium Chloride). However, as Co-60 has a lesser half-life (~5.3 years) as compared to Cs-137 (half-life ~30.17 years), and the $\gamma$-photons emitted by the Co-60 (1.17 and 1.33 meV) are more energetic as compared to that emitted by Cs-137 (0.662 meV); therefore, Co-60 has emerged as a preferred $\gamma$-radiation source in the high activity irradiation facilities, such as the sludge hygienisation plant [65]. Disintegration of $^{60}$Co atoms produces two photons with isotopic yield of 100% and the cumulative energy released by the two gamma photons is 2.5 meV. Another advantage of using Co-60 is that it cannot make artificial radiation, which means it does not produce any radiation on being bombarded with high speed (i.e. high energy) particles [67]. On the other hand, CsCl is soluble in water and therefore, it poses great risk of widespread radioactive contamination in case of a leakage from the sludge hygienisation facility [65].

In order to promote the use of $\gamma$-radiation for hygienising municipal sewage sludge, an indigenous Sludge Hygienization Research Irradiator (SHRI) was set up in 1992 at Baroda (now Vadodara) in the State of Gujarat, by the Department of Atomic Energy (DAE) in India. It was a collaborative program between Bhabha Atomic Research Center (BARC) at Mumbai, Vadodara City Municipal Corporation, and the Government of Gujarat, India. The installed irradiator had a provision for a Co-60 source with radiation strength of 18.5 PBq (1 PBq = $10^{15}$ Bq) to disinfect the digested sludge. As reported in a more recent study, the strength of Co-60 source in the SHRI facility was about 220 kCi in 2005, which was provided by 13 pairs of Co-60 pencils housed in horizontally placed pencil slots to impart irradiation into the stainless-steel vessel [68]. The main objective of SHRI project was to treat about 110 m$^3$ sewage-sludge output per day, so that the hygienised sludge can be used as safe fertilizer on agricultural farmland [69]. Over an operational period of about six months, it was found from the results obtained from SHRI facility that 3 kGy dose of gamma radiation (Note: The thermal equivalent of 1 Gy radiation dose is 1 J/kg) is adequate for making the normal sludge free from pathogen and odour
[70]. The process parameters in SHRI facility were adjusted while irradiating the sludge received from the primary settling tank of a WWTP, so that fecal coliform bacteria present in the sludge were completely eliminated and the residence time of the irradiated liquid slurry was controlled to prevent their regrowth. Irradiated sludge was found to be appropriate for using direct disposal in a landfill or for use as manure after drying. It could also be used as a medium for growing of *Rhizobium sp.*, a plant growth promoting microorganism, facilitating the formation of an effective bio-fertilizer.

Another major industrial-scale sewage sludge hygienisation facility based on Co-60 radiation sources was developed at Tucuman in Argentina by PIBA [71]. In this facility, a concentric source loading tank was located inside the irradiation tank. The facility was designed to have 32 locations, where a specially constructed support structure would lodge nine sources in vertical position. Industrial Co-60 sources (model FIS 60–05) with the average activity of each source ranging between 7 and 10 kCi were employed. As the hygienisation facility was designed for peak radiation capacity of 700 kCi, therefore, 70 number of Co-60 sources of 10 kCi activity were needed. At the initial phase, only 8 of the available 32 locations were chosen to place the radiation sources in the source loading tank, whereas, the other 24 locations were kept free to facilitate any changes in the arrangements of the radiation sources. The facility was designed to enable hygienisation of a sludge volume of 140 m³/day, with the batch volume and irradiation time being 6 m³ and 30 min, respectively [71]. As per the successful bidding, the capital cost of this facility turned out to be USD 3,200,000, whereas, the operating cost for 25 years was estimated to be about USD 4, 69,000.

Recently in March 2019, the first sewage sludge hygienisation plant in the country became operational in Ahmedabad, Gujarat [72]. This dry sewage sludge irradiation facility envisages a peak dry sludge load of 100 TPD (tons/day) when it becomes fully operational [73]. The plant is designed for a peak radiation capacity of 1.5 MCI which will be provided by the Co-60 sources procured from the Board of Radiation and Isotope Technology (BRIT)) [74]. However, the source strength will be augmented in the steps of 150 kCi, looking at the increase in the sludge load. Currently, the facility hygienises about 6 tons of dry sludge per day and within next 3–4 years, an average dry sewage sludge load of 30–40 tons/ day is expected [74]. The author visited the facility in September 2019; and from the discussions with the technical experts it emerged that the aforesaid hygienisation facility presently receives dewatered sludge mainly from the Sewage Treatment Plant (STP) of 180 MLD (Million liters per day) capacity, located at the Pirana Road. On an average, the Pirana Road STP experiences daily accumulation of 12–15 m³ of sludge, the weight being in the range of 8–10 TPD. It was also found that the STP treats 160–165 MLD of wastewater. Assuming uniform composition of raw municipal sewage as a rough estimate, it was found that for 1 ton of sludge accumulation, about 16.5 Million liters of wastewater needs to be treated.

It is to be noted that for hygienising the present sludge load of 6 TPD, 150 kCi Co-60 pencil is used [73]. The dried sludge is first sent to the crusher and grinder, so that particle sizes are reduced to less than or equal to 5 mm. The crushed sludge is then
loaded in the parallelepiped tanks made of stainless steel. Each tank has a carrying capacity of about 250 kg; however, the sludge per tank is limited to about 220 kg. The tanks are placed on a conveyor belt which facilitates only linear translation of the loaded tanks. The sludge-loaded tanks on the conveyor belt move through a U-shaped path so that both the vertical faces of the tank that represent the largest area of exposure are exposed to the Co-60 radiation. The calculated optimized dose for killing all the pathogens is 10 kGy and for each of the tanks to receive this optimal radiation dose, the required exposure time is about 54 min. The radiation facility abides by the radiation safety protocol as per the regulations of BARC. The irradiation unit is controlled using an automated routine in a Programmable Logic Control (PLC) software platform developed by SYMEC Engineers (India) Private Ltd. A source loading scheme is already available with BARC for the industrial-scale irradiation units, and after every source loading, dosimetry is performed. The final product following the hygienization is supposed to contain less than 1000 coliforms or 3 Salmonella sp./4 g < 1 pfu/4 g of enteric viruses <1 helminth ova/4 g [Note: PFU means Plaque-Forming Unit and it indicates the number of virus particles that are capable of lysing host cells and forming a plaque]. The hygienized sludge is rich in organic carbon (~20–40% by weight). However, in order to further enhance the nutrition value of the irradiated sludge, a solution comprising of consortium of Plant Growth Promoting Bacteria (PGPB) named BioNPK is employed. Bio-NPK helps in nitrogen fixation, phosphate solubilization, potassium mobilization and in the bio-control of plant pathogens. The beneficial bacteria consortium helps in converting the nitrogen and phosphorus to usable form for the cash crops, leading to higher yield. The PGPB is cultured in an in-house laboratory facility, which was set-up in collaboration with Anand Agricultural University, in Gujarat. Gujarat Agro Industries Corporations (GAIC) is supposed to commercialize the hygienized sludge under the brand name ‘Bio-Gold’ [73].

The irradiated sludge has demonstrated initial success in enhancing the soil productivity, and about 12% increase in the crop yield has been observed for every 1% increase of organic matter in the soil. However, as 90% (by weight) of the fecal sludge consists of human manure, and human manure is not still approved as a fertilizer, therefore, for wider acceptance of the irradiated municipal sludge, necessary approval from Fertilizer Control Order (FCO) is required. In this context, it can be mentioned that GOI provides a subsidy of Rs. 1.5 per kg for city compost. Any such incentive for the irradiated sludge will pave a pathway towards using it as a nature-based solution (NbS) in the agricultural field.

11.4 Scope for Irradiation-Based Advanced Treatment Facilities in Urban Centres: A Case Study for Bengaluru City

In order to mitigate the ever-growing problem of Bangalore city’s sewerage, as well as, for rejuvenating the minor irrigation system in parched rural areas that are facing
a grim situation due to sheer lack of ground water, Koramangala-Challaghatta Valley (KC Valley) project was envisaged in the state of Karnataka [75]. The K-C Valley project is being equipped for drawing 440 MLD of sewage water from three STPs in Bengaluru [76]. Following a secondary treatment, the treated wastewater will be pumped to the Lakshmisagara Lake in Narasapura, near Kolar. From the Lakshmisagara reservoir, the treated water will flow through an underground drainage network and will be supplied to the parched districts like Kolar and Chikkaballapur. This secondary treated water has been planned for recharging the ground water aquifers. Also, the drainage network through which the treated water would flow connects about 134 lakes in Kolar and Chikkaballapur. Hence, the water quality and overall health of those lakes are expected to improve over time upon being continuously fed by treated water [77]. As evident from the several recent newspaper reports [78, 79], review articles [80], as well as, the recent order of National Green Tribunal (NGT) [81], several major water bodies around Bengaluru, viz. Bellandur lake, Agara lake and Varthur lake inter-alia, are subjected to severe pollution owing to the inefficient management of solid waste, as well as, discharge of untreated sewage waste and industrial effluents. Phosphate-rich toxic froth, arising mainly from the industrial effluents and agricultural run-off, has been widely reported in the media, for its potential hazardous impact on the civic health. As per the NGT report [81], Karnataka Pollution Control Board (KPCB) found chemical (in the form of nitrates and phosphates) in the water of several lakes, the source of such chemicals predominantly being the domestic sewage. The current STPs are not equipped with the technology to treat and remove nitrates and phosphates.

At present, there are 24 STPs in and around the Bengaluru city with a total treating capacity 760-Million litres per day (MLD), but the city generates nearly double that amount of sewage. Hence, the treating capacity of these plants needs to be ramped-up soon enough. The BWSSB (Bangalore Water Supply and Sewerage Board) has chalked out an ambitious Rs 2,500-crore plan and hopes to receive a long-term loan from the Asian Infrastructure Investment Bank (AIIB), which is supposed to aid in revamping all old STPs, rehabilitating old sewage lines and reducing unaccounted water (UFW) [82]. A recent survey conducted by the Japan International Cooperation Agency (JICA) corroborates the aforesaid facts, showing that only 60% of Bengaluru’s sewage is being treated in the existing STPs [83]. The study conducted by JICA predicts shows that in 2024, the total sewage generation will touch a very high level of 1502 MLD. Hence, the treatment of wastewater needs to be given utmost importance in the context of the city of Bengaluru.

The author visited the KC Valley STP Compound, which is currently equipped to treat a peak sewage load of 308 MLD. Another 150 MLD STP is currently under construction within the same STP compound. The schematic shown in Fig. 11.3 illustrates the current treatment plant configuration and flow arrangements in KC Valley compound.

From the discussion with experts it emerged that KC valley STP Compound currently receives and treats about 255 MLD of sewage water (the plant utilization factor is 0.828) and after secondary treatment, the treated sewage water is sent to the Challaghatta pumping house. During the monsoon, the total sewage inflow rate
increases by 10–20 MLD. Additionally, it came out that on an average, the estimated accumulation of sludge is about 1 TPD for every 6 MLD of wastewater received in various STP units of the KC Valley compound. Upon being collected in the sedimentation tank, the sludge undergoes open drying. About 20–30% (by weight) of the dried-up sludge is taken away by the local farmers. The rest of the sludge is taken to the 60 MLD STP unit, which has a biogas power plant (peak power of 8 MW) for running the plant. The amount of the power produced from this biogas plant depends on the quality of the sludge (i.e. the calorific value). However, on an average 6–7 MW is produced regularly. After producing the biogas, currently the residual biomass is taken away for landfilling, but this residual biomass has the potential to serve as both manure, as well as, fuel. Hence, there is a definite potential for the commercialization of manure pellets and fuel pellets made from the residual biomass. Previous literature indicates as well, that sludge pelletization is one of the most cost-effective pathways of dealing with sludge, as it paves way for transforming sludge into a valuable, odourless and storable fertilizer or heat source \[ \text{[84]} \]. In this regard, detailed characterization and evaluation are required for the dried-up sludge, as well as, residual biomass obtained from the biogas plant. However, as the sludge has substantial pathogenic load, therefore, proper sludge hygienisation procedure needs to be followed.

The author also visited the 50 MLD Kadubeesanahalli STP in Bengaluru, which is currently treating a sewage load of 30 MLD. Presently, at Kadubeesanahalli STP, the average accumulation of sludge is about 1 TPD per 15 MLD of sewage water.

Fig. 11.3 A schematic layout of KC Valley STP compound and its connection to Lakshmisagara reservoir
received; however, the amount of the sludge may vary depending on the quality of the wastewater. There were about 10 sedimentation tanks full of solid waste, with well-grown vegetation on some of them. The sedimentations tanks have high loads of deadly pathogens (viz. *E. coli*, *B. coli*, Fecal Streptococci) and physical access to the tanks is strictly restricted owing to potential health hazards they pose. Looking at these scenarios, it will be reasonable to mention that a sludge hygienisation facility is the need of the hour in the city of Bengaluru. The model followed by Ahmedabad Municipal Corporation (AMC) can be replicated in Bengaluru to ensure smooth installation and operation of the sewage sludge hygienisation facility. However, the municipal, as well as, the local civic bodies need to form a regulatory platform to address the administrative issues associated with the proposed establishment. As this is an indigenous technology developed by BARC, therefore, BARC and DAE would be very keen to assist in setting up such a facility, as it would publicize and bolster the reliability of the technological solutions developed in India.

### 11.5 Economic Features of the Proposed Sludge Hygienisation Facility in Bengaluru with Reference to Sludge Hygienisation Plant Located at Ahmedabad

In the dry sludge hygienisation facility located in Ahmedabad, the cost of 150 kCi Co-60 pencil procured from BRIT is approximately INR 1.5 Cr. Therefore, for achieving the full activity level of 1.5 MCi, the total cost of procurement of Co-60 pencils will be approximately INR 15 Cr. The cost of putting up the bacteria culture laboratory and other accessories will be another INR 10 Cr. Machineries (e.g. Crusher and grinder, Conveyer belt system, control units, BioNPK solution sprinkler, stainless steel tanks, etc.) will cost about INR 5 Cr. The civil works (e.g. construction works for the warehouse, the submersion pool for the radiation source, etc.) will cost around INR 5 Cr. Therefore, the capital cost for the full-scale irradiation plant will be approximately INR 35 Cr. The operation and maintenance cost will be approximately INR 1.5 Cr per year. Looking at all the major cost components, the tentative commercial price that has been envisaged for Bio-Gold lies in the range of Rs. 3–5. It is expected that, if FCO gives the approval for this pathogen-free hygienised and enriched fertilizer and the brand is popularized; the cost incurred in establishing the Sludge Hygienisation unit can be recovered in about 8–10 years, assuming even the conservative market price of Rs. 3 per kg.

#### 11.5.1 Bengaluru Scenario

Considering the present inflow of sewage water into the KC Valley STP compound (i.e. 255 MLD), and the average rate of sludge accumulation (1 TPD for every 6
MLD of wastewater), the total amount of accumulated sludge turns out to be about 42.5 TPD. When the capacity of the STP compound is enhanced to 440 MLD, the amount of accumulated sludge will be approximately 61 TPD (assuming the current plant utilization factor of 0.828).

In the dry sludge hygienisation facility at Ahmedabad, in order to deliver 10 kGy radiation dose to 6 tons dry sludge per day, 150 kCi Co-60 pencil is found to be adequate. Therefore, for hygienising 61 TPD sludge, peak source strength of 1.5 MCi (i.e. approximately 10 pencils with a strength of 150 kCi each) will be required, so that the exposure time can be effectively reduced. The thickness and the size of the stainless-steel buckets need to be planned accordingly. The capital cost for setting up the facility will be about 30–40% higher as compared to that in Ahmedabad, considering the costs of a metropolitan city. Therefore, the capital cost for putting up a dry sludge hygienisation at Bengaluru facility will be about INR 43 Cr. The operating cost will be approximately INR 2–2.5 Cr per year, depending on the profile of the contractor. A schematic diagram for the proposed STP facility aided by the sludge hygienisation unit is depicted in Fig. 11.4.

In order to have a further futuristic estimate, if we take the average of the sludge accumulation rates found at the two different STPs in Bengaluru, viz. 1 TPD per 6 MLD of wastewater at KC Valley STP compound and 1 TPD per 15 MLD of wastewater at Kadubeesanahalli STP; the average sewage sludge accumulation rate turns out to be 1 TPD for every 10 MLD of wastewater. Considering the estimated peak sewage generation of 1500 MLD in Bengaluru in 2024 as suggested by JICA, using the rough estimate for average sludge accumulation and STP utilization factor of 1, the total amount of accumulated sludge will be approximately ~150 TPD.

In order to hygienise 150 TPD of dried sludge, 25 number of Co-60 source pencils, each with activity of 150 kCi, will be required and the total cost for procuring the

![Fig. 11.4](image-url) A schematic layout of the proposed STP complex comprising of secondary treatment of wastewater and sludge hygienisation facility
Co-60 sources will be about INR 37.5 Cr. It can either be a single facility, or two separate facilities with a capacity of hygienising 75 TPD dry sludge each can be planned. For a standard-size facility to be established (including radiation facility, warehouse, sludge dumping ground, housing for machinries etc.), about 1500 square yards of space is needed. Therefore, suitable locations need to be chosen based on the availability of the land area, as well as, commutability to the facility.

It is to be noted that organic carbon is very essential component in the context of irrigational soil quality of Karnataka, as the soil health diagnosis under ‘Bhoochetana’ initiative in Karnataka, conducted in the fields of nearly 100,000 farmers showed widespread soil degradation [85]. Therefore, hygienised fertilizer rich in organic carbon will be a boon for the Karnataka farmers. Hence, if the commercialization of manure pellets and biomass fuel pellets made from the hygienised sludge is done with meticulous planning, the cost can be recovered with a finite period, even with an affordable lower price being assigned during the initial period. In this context, it is worth mentioning that the production cost of gas-based urea is about Rs. 900 per 45 kg bag (i.e. Rs. 20/kg), and the farmers pay a final price of Rs. 5.50/kg upon getting a discount of over 70% The subsidy on urea increased from Rs. 24,337 crore to Rs. 53,629 crore between FY 2010–11 and FY 2019–20 [86]. Therefore, if the dependency on urea is reduced, Govt’ can save a huge amount of money which can be used effectively in other high-priority areas.

Furthermore, the hygienisation of the sewage sludge will also ensure that the spread of the dangerous and lethal pandemics, such as the COVID-19, is curbed; which may otherwise reach an unmanageable scale due to the unsafe and imprudent handling of the raw dried sludge. The landfilling will be much safer and free from pathogenic load which would also pave way towards a sustainable and hygienic land reclamation and creation of urban groves, leading to a greener city.

11.6 Conclusion

From the thorough discussion presented in the chapter, it is evident that advanced treatment of urban wastewater, as well as, the proper hygienisation of the municipal sewage sludge is of utmost importance considering the current pandemic situation caused by the persistent SARS-CoV-2 virus. Although the dominant mode of SARS-CoV-2 transmission revolves around the travel of the respiratory droplets, the transmission through the oral-feral route adds a further dimension to the potential risk of community spread of COVID-19. As the fecal sludge serves as the medium for the growth of the pathogen colonies, therefore, there is a finite chance that the active fragments of SARS-CoV-2 strain ending up in the urban wastewater through faecal shredding, as well as, through imprudent discharges into the municipal sewer from the domestic and the healthcare facilities would be able to multiply in the sludge. Such a multiplication of contagious virus particulates in the sludge will make it unsafe for open drying, and subsequent handling for the purpose of landfilling. Therefore, to ensure a safer and cleaner management of municipal sewage sludge, radiation-based
hygienisation is quintessential in the context of dense urban centres. The preliminary assessment of the irradiation-based dry sludge hygienisation facility located at Ahmedabad indicates that such a facility has a definite potential to be replicated in other metropolitan cities, as well as, growing Tier-II cities. A case study for Bengaluru ensures that such a sludge hygienisation facility would facilitate a safer management of the municipal sewage sludge by making it pathogen free. Furthermore, as the irradiated dry sludge is usually rich in organic carbon, hence, the use of irradiated dry sludge as the bio-fertilizer, upon being enriched by plant growth promoting bacteria, would help in restoring the health of the otherwise carbon-deficient soil. Overall, such a facility will enhance the cleanliness as well as, the greenness of the densely populated Indian urban settings.

Acknowledgements The author would like to extend sincere gratitude to Dr. Virendra Kumar (Head, AMS, RTDD, BARC) and to Shri Sudhir Dave (Consultant, AMC) for their invaluable inputs and words of advice. The author is also grateful to the officials of the two STPs in Bengaluru (KC Valley STP and Kadubeesanahalli STP), as well as, the Pirana Road STP in Ahmedabad for the cordial interactions.

References

1. McLaren RG, Smith CJ (1996) Issues in the disposal of industrial and urban wastes. In: Naidu R, Kookana RS, Oliver DP, Rogers S, McLaughlin MJ (eds) Contaminants and the soil environment in the Australasia–Pacific region (717 pages); pp 183–212. Springer, Dordrecht. https://doi.org/10.1007/978-94-009-1626-5_6
2. Saravanane R, Ranade VV, Bhandari VM, Rao AS (2014) Urban wastewater treatment for recycling and reuse in industrial applications: Indian scenario. In: Chapter 7: Industrial wastewater treatment, recycling and reuse (576 pages); pp. 283–322. Elsevier Ltd
3. Wastewater Management: A UN-Water Analytical Brief (2017) Download from: https://www.unwater.org/app/uploads/2017/05/UNWater_Analytical_Brief_Wastewater_Management.pdf. Accessed 18 July 2020
4. World Urbanization Prospects: The 2018 Revision, Economics & Social Affairs, United Nations. Download from: https://population.un.org/wup/Publications/Files/WUP2018-KeyFacts.pdf. Accessed 15 July 2020
5. Urbanisation. https://www.teriin.org/resilient-cities/urbanisation.php. Accessed 15 July 2020
6. Urban wastewater treatment for 21st century challenges, European Environment Agency (EEA) (July 2020) https://www.eea.europa.eu/themes/water/european-waters/water-use-and environmental-pressures/uwwt/urban-waste-water-treatment. Accessed 20 July 2020
7. Wastewater management and sustainable development (Greenfacts), https://www.greenfacts.org/en/wastewater-management/index.htm. Accessed 20 July 2020
8. Gwalior – India (SFDs Worldwide). https://sfd.susana.org/about/worldwide-projects/city/21-gwalior. Accessed 20 July 2020
9. Lusaka - Zambia (SFDs Worldwide). https://sfd.susana.org/about/worldwide-projects/city/46-lusaka. Accessed 20 July 2020
10. Jeffrey N (November 2018) The devastating impact of poor wastewater management, Water and Sanitation for the Urban Poor (WSUP). https://www.wsup.com/blog/thedevastating-impact-of-poor-wastewater-management/. Accessed 20 July 2020
11. Collection and disposal of wastewater. Download from: https://www.who.int/water_sanitation_health/medicalwaste/130to134.pdf. Accessed 20 July 2020
12. Thornton I et al (February 2001) Pollutants in urban wastewater and sewage sludge, Report Prepared by ICON (I.C. Consultants Ltd), London (UK), for Directorate-General Environment. Download from: https://www.ec.europa.eu/environment/archives/waste/sludge/pdf/sludge_pollutants.pdf

13. Benneouala M (2017) Biodegradation of slowly biodegradable organic matter in wastewater treatment plant (WWTP): In depth analysis of physical and biological factors affecting hydrolysis of large particles. Chemical and process engineering. INSA de Toulouse, English. NNT: 2017ISAT0003. Download from: https://tel.archives-ouvertes.fr/tel-01549254/document

14. Henze M, Comeau Y (2008) Wastewater characterization; Chapter 3 In: Henze M, van Loosdrecht MCM, Ekama GA, Brdjanovic D (eds) Biological wastewater treatment: principles modelling and design, IWA Publishing, London, UK. ISBN: 9781843391883

15. Health risks associated with wastewater use, http://www.fao.org/3/w5367e/w5367e04.htm. Accessed 20 July 2020

16. Bibby K, Peccia J (2013) Prevalence of respiratory adenovirus species B and C in sewage sludge. Environ Sci Process Impacts 15(2):336–338. https://doi.org/10.1039/c2em30831b

17. Carr R (2001) Excreta-related infections and the role of sanitation in the control of transmission; Chapter 5 In: Fewtrell L, Bartram J (eds) Water quality: guidelines, standards and health. World Health Organization (WHO). IWA Publishing, London, UK. ISBN: 1 900222 28 0

18. Mateo-Sagasta J, Zadeh SM, Turrall H (2017) Water pollution from agriculture: a global review (Executive summary), Published jointly by Published by the Food and Agriculture Organization (FAO) of the United Nations (UN) Rome and the International Water Management Institute (IWMI), Colombo. Download from: http://www.fao.org/3/a-i7754e.pdf

19. World Water Development Report (WWDR) (2014) United Nations World Water Assessment Programme (WWAP). ISBN:978-92-3-104259-1

20. Sanctis MD, Moro GD, Chimenti S, Ritelli P, Levantesi C, Di Iaconi C (2017) Removal of pollutants and pathogens by a simplified treatment scheme for municipal wastewater reuse in agriculture. Sci Total Environ 580:17–25

21. Liberti L, Notarnicola M (1999) Advanced treatment and disinfection for municipal wastewater reuse in agriculture. Water Sci Technol 40:235–245

22. Cui B, Liang S (2019) Monitoring opportunistic pathogens in domestic wastewater from a pilot-scale anaerobic biofilm reactor to reuse in agricultural irrigation. Water 11:1283. https://doi.org/10.3390/w11061283

23. Use of Reclaimed Water and Sludge in Food Crop Production (1996) Chapter 2 In: Municipal wastewater, sewage sludge, and agriculture; water science and technology board commission on geosciences, environment, and resources. National Research Council, National Academy Press, Washington, D.C. https://www.nap.edu/read/5175/chapter/4. Accessed 20 July 2020

24. Strauch D (1991) Survival of pathogenic micro-organisms and parasites in excreta, manure and sewage sludge. Rev sci Tech Off Int Epiz 10(3):813–846

25. Carrington EG (2001) Evaluation of sludge treatments for pathogen reduction, report submitted to the European Commission Directorate-General Environment, 45 pages. Report No.: CO 5026/1. Download from: https://ec.europa.eu/environment/archives/waste/sludge/pdf/sludge_eval.pdf

26. Al-Gheethi AA, Efaq AN, Bala JD, Norli I, Abdel-Monem MO, Abdel-Kadir MO (2018) Removal of pathogenic bacteria from sewage-treated effluent and biosolids for agricultural purposes. Appl Water Sci 8, Article no. 74. https://doi.org/10.1007/s13201-018-0698-6

27. EPA Guidelines for Water Reuse (1992) Environmental Protection Agency, Washington, D.C., USA, 247 pages. Publication ID: EPA 625/R-92/004

28. Industrial Wastewater Management and Disposal (2009) Water quality protection note, Department of Water, Government of Australia. Download from: https://www.water.wa.gov.au/__data/assets/pdf_file/0008/4040/89343.pdf. Accessed 20 July 2020

29. Polprasert C, Kittipongvises S (2011) Water-quality engineering: In: Wilderer P (ed) Treatise on water science, 2102 pages. Hardcover ISBN: 9780444531933

30. Jungclaus GA, Lopez-Avila V, Hites RA (1978) Organic compounds in an industrial wastewater: a case study of their environmental impact. Environ Sci Technol 88–96. American Chemical Society. Download from: https://pubs.acs.org/doi/pdf/10.1021/es60137a015
31. Ramírez N, Marcé RM, Borrull F (2011) Determination of volatile organic compounds in industrial wastewater plant air emissions by multi-sorbent adsorption and thermal desorption-gas chromatography-mass spectrometry. Int J Environ Anal Chem 91(10):911–928
32. Hjortenkrans DST, Bergbäck BG, Höggerud AV (2007) Metal emissions from brake linings and tires: case studies of stockholm, Sweden 1995/1998 and 2005. Environ Sci Technol 41(15):5224–5230. Download from: https://pubs.acs.org/doi/10.1021/es070198o
33. Wang Q, Feng Y, Huang XHH, Griffith SM, Zhang T, Zhang Q, Wu D, Yu JZ (2016) Nonpolar organic compounds as PM 2.5 source tracers: investigation of their sources and degradation in the Pearl River Delta, China. J Geophys Res Atmos 121:11862–11879. https://doi.org/10.1002/2016JD025315
34. Loos R et al (2012) EU wide monitoring survey on waste water treatment plant effluents, JRC Scientific and Policy Reports, European Commission, 138 pages. Download from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.819.3420&rep=rep1&type=pdf
35. Lindholm-Lehto PC, Ahkola HSJ, Knuutinen JS (2017) Procedures of determining organic trace compounds in municipal sewage sludge-a review, Environ Sci Pollut Res 24:4383–4412. https://doi.org/10.1007/s11356-016-8202-z
36. Minzatu V, Negrea P, Negrea A, Ciopec M, Bumbu B, Golban A, Vasile A (2016) Removal of organic compounds from industrial wastewater using physico-chemical methods. WIT Trans Ecol Environ 209:185–195. https://doi.org/10.2495/WP160171
37. Regulated Medical Waste, Guidelines for Environmental Infection Control in Health-Care Facilities (2003) https://www.cdc.gov/infectioncontrol/guidelines/environmental/background/medical-waste.html. Accessed 20 July 2020
38. Biomedical Waste Guidelines. Download from: https://www.ehs.uci.edu/programs/enviro/Bio-Waste%20Guidelines.pdf. Accessed 20 July 2020
39. Datta P, Mohi GK, Chander J (2018) Biomedical waste management in India: critical appraisal. J Lab Physicians 10(1):6–14. PMID: 29403196
40. Kaur B (December 2019) Biomedical waste in Delhi: what monitoring without figures, asks report. https://www.downtoearth.org.in/news/waste/biomedical-waste-in-delhi-whatmonitoring-without-figures-asks-report-68474. Accessed 22 July 2020
41. Safe management of wastes from health-care activities Second edition (2014) World Health Organization. https://www.euro.who.int/__data/assets/pdf_file/0012/268779/Safemanagement-of-wastes-from-health-care-activities-Eng.pdf. Accessed 22 July 2020
42. Kappan R (July 2020) Straight to the landfills: Bengaluru’s waste management takes a hit amidst pandemic. https://www.deccanherald.com/specials/point-blank/straight-to-the-landfills-bengaluru-waste-management-takes-a-hit-amidst-pandemic-862621.html. Accessed 22 July 2020
43. Kearney TE, Larkin MJ, Levett PN (1994) Metabolic activity of pathogenic bacteria during semicontinuous anaerobic digestion. Appl Environ Microbiol 60:3647–3652
44. Sahlström L (2003) A review of survival of pathogenic bacteria in organic waste used in biogas plants. Bioresour Technol 87:161–166
45. Weiss SR, Navas-Martin S (2005) Coronavirus pathogenesis and the emerging pathogen severe acute respiratory syndrome coronavirus. Microbiol Mol Biol Rev 69(4):635–664. https://doi.org/10.1128/MMBR.69.4.635-664.2005
46. Kitajima M, Ahmed W, Bibby K, Carducci A, Gerba CP, Hamilton KA, Haramoto E, Rose JB (2020) SARS-CoV-2 in wastewater: state of the knowledge and research needs. Sci Total Environ 739, Article 139076
47. Gu J, Han B, Wang J (2020) COVID-19: gastrointestinal manifestations and potential fecal-oral transmission. Gastroenterology 158(6):1518–1519. https://doi.org/10.1053/j.gastro.2020.02.054
48. Rokkas T (2020) Gastrointestinal involvement in COVID-19: a systematic review and meta-analysis. Annals Gastroenterol 33:1–11. https://doi.org/10.20524/aog.2020.0506
49. Xiao F, Sun J, Xu Y, Li F, Huang X, Li H, Zhao J, Huang J, Zhao J (2020) Infectious SARS-CoV-2 in feces of patient with severe COVID-19, Research Letter in Emerging Infectious Diseases (EID), 26(8). Download from: https://wwwnc.cdc.gov/eid/article/26/8/20-0681_article
50. Jiang FC, Jiang XL, Wang ZG, Meng ZH, Shao SF, Anderson BD, Ma MJ (September 2020) Detection of severe acute respiratory syndrome coronavirus 2 RNA on surfaces in quarantine rooms, Research Letter in Emerging Infectious Diseases (EID), 26(9). Download from: https://wwwnc.cdc.gov/eid/article/26/9/20-1435_article

51. Transmission of SARS-CoV-2: implications for infection prevention precautions (July 2020), Scientific Brief; https://www.who.int/news-room/commentaries/detail/transmissionof-sars-cov-2-implications-for-infection-prevention-precautions. Accessed 22 July 2020

52. Bakker E, Worsham K (June 2020) Treating medical waste during COVID-19 in the global south. https://www.ircwash.org/blog/treating-medical-waste-during-covid-19-globalsouth. Accessed 4 September 2020

53. Jiang RD et al (July 2020) Pathogenesis of SARS-CoV-2 in transgenic mice expressing human angiotensin-converting enzyme 2. Cell 182(1):50–58. https://doi.org/10.1016/j.cell.2020.05.027

54. Aw T (2018) Environmental aspects and features of critical pathogen groups. In: Rose JB, Jiménez-Cisneros B (eds) Part 1: The health hazards of excreta: theory and control, Michigan State University, E. Lansing, MI, UNESCO. https://doi.org/10.14321/waterpathogens.2

55. de Graaf M et al (2017) Sustained fecal-oral human-to-human transmission following a zoonotic event. Curr Opin Virol 22:1–6. https://doi.org/10.1016/j.coovirol.2016.11.001, PMID: 27888698, PMCID: PMC7102779

56. Coronavirus disease 2019 (COVID-19) Situation Report-32 (February 2020), World Health organization (WHO). Download from: https://www.who.int/docs/defaultsource/coronaviruse/situation-reports/20200221-sitrep-32-covid-19.pdf. Accessed 22 July 2020

57. Q&A: similarities and differences - COVID-19 and influenza, https://www.who.int/news-room/q-a-detail/q-a-similarities-and-differences-covid-19-and-influenza. Accessed 22 July 2020

58. Dutt A (March 2020) From throat to lungs and blood: how coronavirus impacts the human body. https://www.hindustantimes.com/india-news/how-coronavirus-impacts-the-humanbody/story-0VTwWF88NJZzNvZ7Ut9pfuN.html. Accessed 22 July 2020

59. Karamitros T, Papadopoulou G, Bousali M, Mexias A, Tsiodras S, Mentis A (March 2020) SARS-CoV-2 exhibits intra-host genomic plasticity and low-frequency polymorphic quasispecies, bioRxiv preprint. https://doi.org/10.1101/2020.03.27.009480

60. Song P, Li W, Xie J, Hou Y, You C (October 2020) Cytokine storm induced by SARS-CoV-2. Clin Chim Acta 509:280–287. https://doi.org/10.1016/j.cca.2020.06.017

61. Ong SWX, Tan YK, Chia PY, Lee TH, Ng OT, Wong MSY, Marinimuthu K (April 2020) Air, surface environmental, and personal protective equipment contamination by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) from a symptomatic patient. JAMA 323(16):1610–1612. https://doi.org/10.1001/jama.2020.3227

62. How to choose your waste management technology to treat COVID-19 waste; COVID-19 waste management factsheet (UNEP). Download from: https://wedocs.unep.org/bitstream/handle/20.500.11822/32778/FS3.pdf. Accessed 2 September 2020

63. Keller U (1983) Technology of sewage sludge hygienisation. Zentralbl Bakteriol Mikrobiol Hyg B 178(1–2):111–141. PMID: 6649988

64. Breer C (1983) Bacteriological control of various methods of sewage sludge hygienisation. Zentralbl Bakteriol Mikrobiol Hyg B 178(1–2):155–157. PMID: 6649990

65. Lessel T (1997) Disinfection of sewage sludge by gamma radiation, electron beams and alternative methods (IAEA-TECDOC-971), Proceedings of Consultants‘ Meetings: Sewage Sludge and Wastewater for Use in Agriculture, Vienna, pp 29–45. Download from: https://www.osti.gov/etdeweb/servlets/purl/592126

66. Irradiated sewage sludge for application to cropland (October 2002); Report of FAO-IAEA Joint Research Project, Division of Nuclear Techniques in Food and Agriculture; Report no. IAEA-TECDOC-1317. Download from: https://www-pub.iaea.org/MTCD/Publications/PDF/te_1317_web.pdf. Accessed 22 July 2020

67. Sabbagh S, El-Mahmoudi AS, Al-Dakheel YY (2014) Waste water sterilization by cobalt Co-60 for the agricultural irrigation: a case study. Int J Water Resour Arid Environ 3(1):11–18. ISSN 2079-7079
68. Gautam S, Shah MR, Sabharwal S, Sharma A (2005) Gamma irradiation of municipal sludge for safe disposal and agricultural use. Water Environ Res 77(5):472–479
69. Swinwood JF, Waite TD, Kruger P, Rao SM (1994) Radiation technologies for waste treatment: a global perspective. IAEA Bulletin 36:11–15
70. Lavale DS, Shah MR, Rawat KP, George JR (1997) Sewage sludge irradiators: batch and continuous flow, Invited paper (IAEA-SM-350/56), pp 289–301. Download from: https://www.osti.gov/etdeweb/servlets/purl/644028
71. Graino JG (2001) Radiation technology for sewage sludge treatment: the argentime project, use of irradiation for chemical and microbial decontamination of water, wastewater and sludge, Vienna, Paper ID: IAEA-TECDOC-1225, pp 163–179. Download from: https://inis.iaea.org/collection/NCLCollectionStore/_Public/32/037/32037236.pdf
72. Kaushik H (March 2019) Ahmedabad: sludge treatment plant is operational now. https://timesofindia.indiatimes.com/city/ahmedabad/sludge-treatment-plant-is-operationalnow/articleshow/68237506.cms. Accessed 22 July 2020
73. New sludge gamma irradiator in India. https://iiaglobal.com/news/new-sludge-gamma-irradiator-india/. Accessed 22 July 2020
74. Ahmedabad Municipal Corporation’s sludge-to-fertilizer plant ready. https://www.dnaindia.com/ahmedabad/report-ahmedabad-municipal-corporation-s-sludge-to-fertilizer-plantready-2725521. Accessed 22 July 2020
75. KC Valley, a unique project in the country. https://www.thehansindia.com/posts/index/Latest-News/2018-12-17/KC-Valley-a-unique-project-in-the-country/460292. Accessed 22 July 2020
76. Why domestic wastewater from Bengaluru is being sent to Kolar and Chikkaballapur. https://scroll.in/article/944539/why-domestic-wastewater-from-bengaluru-is-being-sent-tokolar-and-chikkaballapur. Accessed 22 July 2020
77. A silver lining to the KC Valley project. https://www.thehindu.com/news/national/karnataka/a-silver-lining-to-the-kc-valley-project/article29956197.ece. Accessed 22 July 2020
78. Varthur lake in Bengaluru catches fire again, migratory birds at risk. https://www.indiatoday.in/india/story/varthur-lake-bengaluru-fire-migratory-birds-risk-1435322-2019-01-21. Accessed 22 July 2020
79. Varthur lake spills toxic foam again; here’s why ‘chemical snowfall’ is overflowing from Bengaluru lake. https://www.india.com/news/india/varthur-lake-spills-toxic-foam-aga-inheres-why-chemical-snowfall-is-overflowing-from-bengaluru-lake-2179643/ Accessed 22 July 2020
80. About 85 per cent of Bengaluru’s water bodies severely polluted: study. https://www.downtoearth.org.in/news/water/about-85-per-cent-of-bengaluru-s-water-bodies-severelypolluted-study-59189. Accessed 22 July 2020
81. NGT report (December 06, 2018; M.A. No. 96/2018), Karnataka Pollution Control Board (KPCB), Download from: http://www.greentribunal.gov.in/WriteReadData/Downloads/125-2017(PB-I)OA6-12-18.pdfhttp://www.greentribunal.gov.in/WriteReadData/Downloads/125-2017(PB-I)OA6-12-18.pdf. Accessed 22 July 2020
82. BWSSB Draws up Rs 2,500-cr plan to upgrade STPs. https://economictimes.indiatimes.com/news/politics-and-nation/bwssb-draws-up-rs-2500-cr-plan-to-upgrade-stps/articleshow/67879750.cms. Accessed 22 July 2020
83. Why Bengaluru’s sewage treatment plants may never be enough for the city. https://www.thenewsmatinee.com/article/why-bengaluru-sewage-treatment-plants-may-never-beenough-city-93663. Accessed 22 July 2020
84. Wattiez AL (2000) Mineralization of nitrogen from pelletized sewage sludge - a laboratory incubation study. Graduate Thesis in Biology, Swedish University of Agricultural Sciences, Department of Forest Ecology. ISSN 1104-1870, ISRN SLU-SEKOL-SEKOL-10-05
85. Chander G et al (2016) Soil mapping and variety-based entry-point interventions for strengthening agriculture-based livelihoods - Exemplary Case of ‘Bhoochetana’ in India. Curr Sci 110(9):1683–1691
86. Sahu P (January 2021) DBT scheme for fertiliser subsidy may be rolled out in FY22. https://www.financialexpress.com/economy/dbt-scheme-for-fertiliser-subsidy-may-be-rolled-out-in-fy22/2174500/. Accessed 2 September 2021