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Solid Waste Management in Indian Himalayan Region: Current Scenario, Resource Recovery, and Way Forward for Sustainable Development

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With the growing population, solid waste management (SWM) is becoming a significant environmental challenge and an emerging issue, especially in the eco-sensitive Indian Himalayan region (IHR). Though IHR does not host high local inhabitants, growing tourist footfall in the IHR increases solid wastes significantly. The lack of appropriate SWM facilities has posed a serious threat to the mountain-dwelling communities. SWM is challenging in the highlands due to the remoteness, topographical configuration, increasing urbanization, and harsh climate compared to plain areas. Difficulty in managing SWM has led to improper disposal methods, like open dumping and open burning of waste, that are adversely affecting the fragile IHR ecosystem. Open dumping of unsegregated waste pollutes the freshwater streams, and burning releases major pollutants often linked to the glacier melt. Processes like composting, vermicomposting, and anaerobic digestion to treat biodegradable wastes are inefficient due to the regions' extreme cold conditions. IHR specific SWM rules were revised in 2016 to deal with the rising problem of SWM, providing detailed criteria for setting up solid waste treatment facilities and promoting waste-to-energy (WtE). Despite governments' effort to revise SWM; measures like proper collection, segregation, treatment, and solid waste disposal needs more attention in the IHR. Door-to-door collection, segregation at source, covered transportation, proper treatment, and disposal are the primary steps to resource recovery across the IHR. Approaches such as waste recycling, composting, anaerobic digestion, refuse-derived fuel (RDF), and gas recovery from landfills are essential for waste alteration into valuable products initiatives like 'ban on single-use plastic' and 'polluters to pay' have a potential role in proper SWM in the IHR. Research and technology, capacity building, mass awareness programs, and initiatives like 'ban on single-use plastic' and 'polluters to pay' have a potential role in proper SWM in the IHR. This review highlights the current status of waste generation, the current SWM practices, and SWM challenges in the IHR. The review also discusses the possible resource recovery from waste in the IHR, corrective measures introduced by the government specific to IHR and, the way forward for improved SWM for achieving sustainable development of the IHR.

Keywords: indian himalaya region, solid waste management, resource recovery, sustainable development, waste to energy

INTRODUCTION

IHR provides ecosystem services in the form of energy, food, water, and other resources (Gupta et al., 2019), contributing to supporting the livelihood of about 50 million people living in the IHR (Aayog, 2018). IHR extending from the Indus river in the west to the Brahmaputra in the east covers 533,604 sq. Km, across ten hill states and four districts of India (Aayog, 2018). A map showing the kernel density estimate of the amount of waste generated in the IHR in 2018–2019 is represented in **Figure 1**. IHR is about 16.2% of the country's total geographical area, including 16,627 glaciers, covering 40,563 sq. Km (ISRO report, 2016), and forest cover of about 205,563 sq. Km—38.52% of the total IHR geographical area (ISFR, 2019). Mountain headwaters down-streaming from snowfall fed glaciers form an essential source of North Indian Rivers. All the rivers originating from the higher Himalayas have a 30–50% annual flow from glacier's melt runoff (ISRO report, 2016). The ceaseless water flow fulfills the water requirements of the people residing across the Indo-Gangetic plains of India (Chauhan et al., 2012).

Over the last few decades, IHR is rapidly transforming with progressive development, achieving significant economic growth with tourism as one of the fastest-growing economic sectors in the IHR (Aayog, 2018). However, the rapid economic transformation has led to the rise in extensive risks to the ecosystem, people, and the wildlife of the IHR due to an increase in urbanization, consumption patterns, over-crowded tourist destinations, illegal dumping, mining operations, and ill-equipped SWM systems (Aayog, 2018; Alfthan et al., 2016). Major challenges of solid waste management in the IHR are represented schematically in **Figure 2**. This economic turnaround has resulted in unchecked solid waste generation, thus over-burdening the IHR (Kumar S. et al., 2016). Hence, maintaining the health of the IHR concerning its flora, fauna, residing communities, and cultural diversity, along with sustainable development, should be prioritized (Aayog, 2018).

SWM infrastructure plays a vital role in sustainable development in the IHR. The lack of SWM facilities for collection, segregation, processing, and disposal of waste has emerged as a major issue in the IHR (Sapkota et al., 2015). Besides, SWM is more complex and challenging in highlands than in plain areas due to the remoteness,

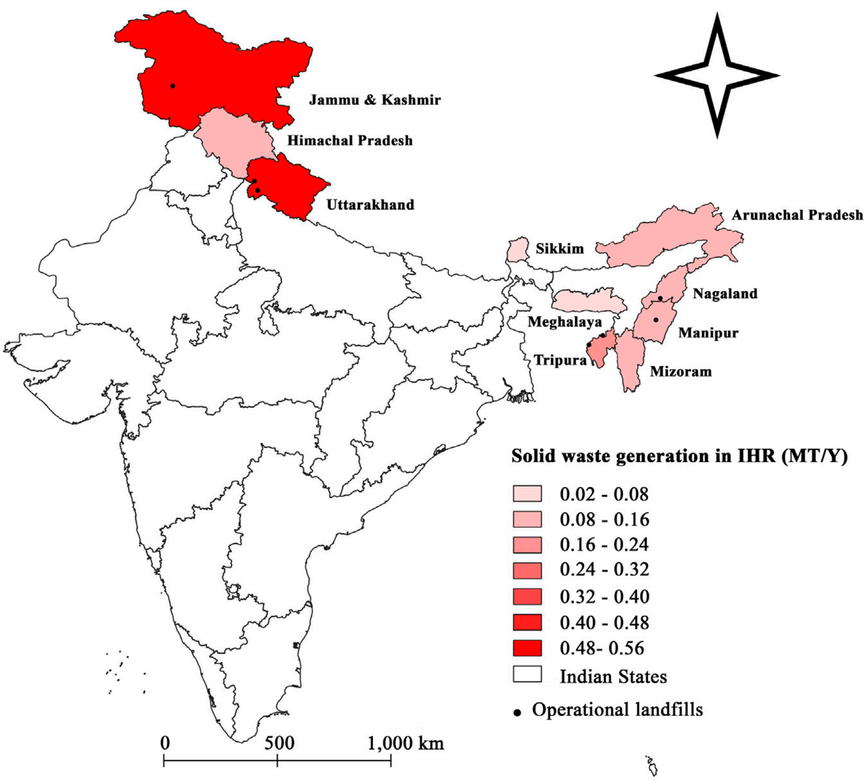

FIGURE 1 | The state-level estimate of total solid waste generated in the IHR. The map shows the kernel density estimate of the amount of waste generated in the IHR, using QGIS 3.12.3. In 2018–2019, 1.905 MT/Y solid waste was generated, out of which a mere 0.263 MT/Y was reported to be landfilled. Till 2019, there were only six operational landfills in the IHR (Data source: CPCB, 2019).

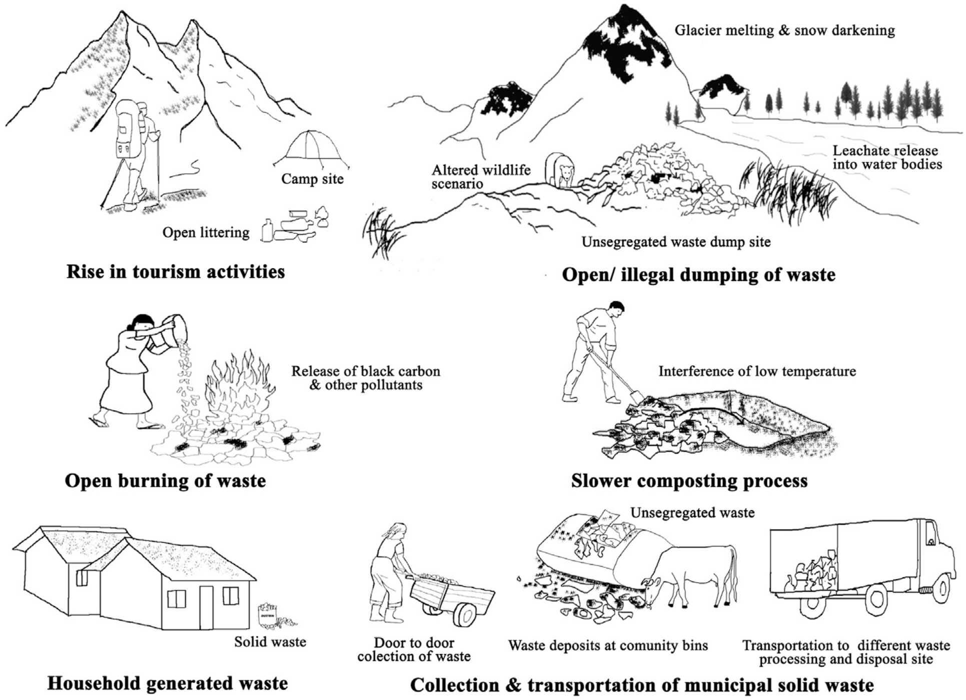

FIGURE 2 | A schematic representation depicting the major challenges of SWM in the IHR. The primary challenges summarized in the image are open littering due to the rise in tourism activities; irregular topographical configuration; open/illegal dumping of waste; slower composting process; improper waste collection and disposal; and open burning of waste leading to release of black carbon, and other pollutants that may cause snow darkening and glacier melt.

topographical configuration, and vulnerability to natural hazards and disasters. Since proper SWM facilities are not in place, open burning is practiced for the disposal of waste. Open burning has adversely affected the ecosystem; the release of major pollutants, including black carbon and other light-absorbing impurities into the air, are often linked to glacier retreat (Thind et al., 2019, **Figure 2**). The other informal means of waste disposal practiced in the region is the dumping of unsegregated waste in the gorges and rivers that have polluted the freshwater streams and led to a much larger footprint, thousands of kilometers downstream (Mushtaq et al., 2020).

The composition of municipal solid waste (MSW) varies depending on the inhabitants' local economy and consumption patterns. Modernization and adoption of plastic packaging in rural IHR region perhaps have added the burden of SWM. The systematic way of collection and segregation of MSW plays a significant role in deciding the right method for waste management practices (Kumar et al., 2017). The re-utilization of solid waste is a viable option and can recover valuable and economic resources, which supplements the growing energy demands. Several approaches for waste recycling and resource recovery from WtE facilities and safe residual waste disposal through sanitary landfills are some of the technologies for waste alteration into valuable products (Vázquez and Soto, 2017; Dev et al., 2019; Hereher et al., 2019; Berardi et al., 2020). The proper implementation and sustenance for any planned SWM in the IHR should be possible through public participation, necessary finances, capacity building, and selection of specific waste technology for the region.

The current review selectively discussed a broader impact of solid wastes in the IHR and some of the downstream challenges that have prevailed in the past few decades. The review further recommends waste recycling approaches for re-utilization and resource recovery using WtE facilities for energy generation as a viable option for sustainable development in the IHR. Finally, a way forward has been discussed for the possible improvement of the existing SWM practices in the IHR by strictly implementing the revised SWM rules, community participation, civil awareness, capacity building, research and technology, and promoting initiatives like 'ban on single-use plastic' and 'polluters to pay.'

CURRENT STATUS OF WASTE GENERATION IN THE INDIAN HIMALAYAN REGION

The young towering mountains, magnificent landscapes, expedition areas, and religious spots all across the IHR allures visitors and pilgrims throughout the world, receiving a footfall of about 100 million tourists yearly (Aayog, 2018). Over the last few decades, tourism in IHR has become one of India's fastest-growing economic sectors. Undoubtedly, it is expected to grow at an average annual rate of 7.9% from 2013 to 2023 and is projected to witness a rise in tourists to 240 million by 2025 (Aayog, 2018). But the downside to this economic turnaround for the IHR is the unmonitored activities resulting in unchecked solid waste generation. Already, tourism-related activities like trekking, expeditions, etc., generate about 8.395 million tonnes per year (MT/Y) of solid waste, causing a concern toward the ecologically

TABLE 1 | Status of total solid waste generation, collection, treatment, and landfilled in the IHR states (Data Source: CPCB, 2019). A total of 1.905 MT/Y solid waste is generated, and out of which 1.688 MT/Y is collected, 0.413 MT/Y is treated, and 0.263 MT/Y is landfilled in IHR.

State	Total solid waste generated (MT/Y)	Collected (MT/Y)	Treated (MT/Y)	Landfilled (MT/Y)
Arunachal Pradesh	0.098	0.078	nil	nil
Jammu and Kashmir	0.559	0.530	NA	NA
Himachal Pradesh	0.142	0.124	0.054	0.069
Meghalaya	0.062	0.062	0.018	0.059
Mizoram	0.092	0.078	0.011	NA
Nagaland	0.124	0.079	0.050	0.012
Sikkim	0.027	0.024	0.005	0.019
Tripura	0.163	0.142	0.055	0.087
Uttarakhand	0.558	0.525	0.191	NA
Manipur	0.080	0.046	0.029	0.017
Total	**1.905**	**1.688**	**0.413**	**0.263**

Abbreviation: MT/Y, million tonnes per year; 'NA' represents data not available.

sensitive areas (Kuniyal, 2005; Aayog, 2018). The waste generated is inconsistent throughout the year as tourist inflow varies in summers and winters, which burdens the otherwise afflicted waste collection, transportation, treatment, and disposal facilities. The waste generated by trekkers and campers is left behind in such delicate locations due to a lack of waste management education and awareness program and the absence of any formal management system for the appropriate collection of solid waste (Puri et al., 2020). The unprecedented wastes are significantly changing the wildlife scenario in the Himalayas as extensive littering has altered the hunting abilities of many critically endangered species (Geneletti and Dawa, 2009; NDTV. news, 2018; **Figure 2**.). To mount the pressure and disrupt the critical ecosystem further, about 11 million urban populations (Census of India, 2011) in IHR are generating about 1.905 MT/Y of solid waste (CPCB, 2019; **Figure 1**.). Out of generated waste, 1.688 MT/Y is collected, 0.413 MT/Y is treated, and a mere 0.263 MT/Y waste is landfilled (**Table 1**; CPCB, 2019), inferring that there is a severe need for improvement in the waste management system across the urban local bodies (ULBs) of IHR. The untreated wastes are generally disposed off unscientifically by various informal means-open burning and dumping in the gorges and rivers-polluting the freshwater streams (Kumar et al., 2017; **Figure 2**.). On the other hand, about 32 million rural populations of IHR (Census of India, 2011) have no choice to efficiently dispose off their waste resulting in a cumulative burden on these topographically fragile mountains (Alfthan et al., 2016). To eliminate the accumulated solid waste, people in the region have adopted similar informal disposal methods that will impact the environment and public health (Kumar et al., 2017; **Figure 2**.).

CURRENT SCENARIO OF SOLID WASTE MANAGEMENT PRACTICES IN THE INDIAN HIMALAYAN REGION

Composition and Type of Solid Waste Generated in the Indian Himalayan Region

The composition of generated waste mainly depends on the residing population's local economy, consumption patterns, and eating habits (Alfthan et al., 2016). The waste composition data focusing on the IHR is scarce. A study on waste composition for high-altitude subtropical regions across IHR, covering ten cities of eight states of North-East India and two towns of Uttarakhand and Himachal Pradesh, have revealed 54.83% was biodegradable waste; 21.06% inert, ash, and debris waste; 8.77% paper; 8.18% plastic; 4.45% glass and ceramics, and 2.71% metal (Kumar S. et al., 2016; **Figure 3**.). The higher composition of biodegradable waste may be attributed to less usage of packaged products in the region than the other high-income countries (Alfthan et al., 2016). Mainly, biodegradable waste is generated from households, and inert waste is generated from road sweeping and maintenance, construction, excavation materials, and demolition (CPCB, 2019). However, a steady increase in non-organic waste is also monitored in the IHR due to the rise in development, per capita income, and increased tourists' footfall (Kumar S. et al., 2016).

Existing Solid Waste Management Practices Across Indian Himalayan Region

The existing SWM systems in IHR face major challenges associated with inadequate facilities of solid waste collection, transportation, treatment, and disposal. The following practices are being carried out across IHR.

Collection and Segregation of Municipal Solid Waste

Mostly across the ULBs in the IHR, door-to-door garbage collection systems have been employed with the collaboration of the informal sector, private agency, non-government organizations (NGOs), housing society, through tipper trucks, dumper placers, and open body trucks, etc. (Kumar S. et al., 2016). The waste segregation is attempted to be carried out at the source in different color-coded bins for wet biodegradable waste, non-biodegradable waste, and domestic hazardous waste (Sharma and Jain, 2019). Rag pickers/scrap dealers also segregate waste in most municipal bodies from the source using large waste sacks to collect non-biodegradable recyclables such as plastics, glass, metals, cartons, etc. (Thakur et al., 2018; CPCB, 2019). Across the IHR, the other collection

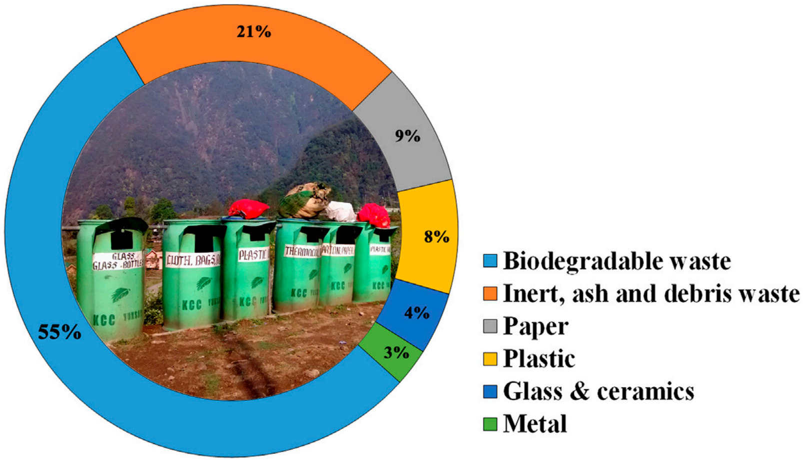

FIGURE 3 | The component fraction of MSW generated in the IHR. The most dominant fraction comprises biodegradable waste, followed by inert, ash and debris, paper, plastic, glass and ceramics, and metals (Data source: Kumar S. et al., 2016). The picture of the waste segregation bins at the center of the image is taken at the base of the trekking route of Khangchendzonga National Park, West Sikkim. The bins are arranged by Khangchendzonga conservation committee (KCC) based at Yuksom, West Sikkim.

systems where people deposit their waste are the centralized bins (big iron dustbins), which can be spotted at the roadsides in urban localities and market places where often biodegradable and non-biodegradable waste is collectively dumped (Kumar S. et al., 2016). Mostly, due to lack of community involvement, the usage of such centralized bins/dumpers remains inefficient, and consequently, the locations of these bins usually become the dirtiest and most stinky places in the town (Kumar S. et al., 2016).

Transportation of Municipal Solid Waste

Across ULBs in the IHR, MSW is primarily transported in covered vehicles to avoid spillage of the garbage along the route to the processing and disposal facilities (CPCB, 2019). However, manual loading of dumped waste in open spaces and waste transportation in uncovered trucks is also reported from parts of IHR (Mushtaq et al., 2020). Waste collectors, rag pickers, and street sweepers are involved in collecting and transportation of waste to the respective disposal sites where the lack of workers' protective equipment and their ignorance have led to various occupational health-related hazards in the IHR (Thakur et al., 2018). The improper way of transportation leads to littering of waste, and in the rainy season, leachate runoff from the vehicles into the streets was also observed (Kumar S. et al., 2016; Joshi and Ahmed, 2016).

Processing of Municipal Solid Waste

For a proper SWM plan and a sustainable environment, all the collected waste should be subjected to various waste treatment techniques to obtain value-added products. Across IHR, a large part of the biodegradable waste is subjected to composting in compost pits, whereas the inert and non-biodegradable waste is indiscriminately landfilled (CPCB, 2019). However, organic waste composting is difficult to carry out in IHR due to the lack of segregation at most sources, fewer processing facilities installed, and cold climate conditions (Hou et al., 2017; Alfthan et al., 2016; CPCB, 2019). There are only 15 composting units, three vermicomposting, three biogas, and 2 RDF/pelletization facilities operational in IHR states treating 0.413 MT/Y of MSW (CPCB, 2019; **Tables 1**, **2**). One WtE plant based on gasification technology has been established in the municipal corporation, Shimla, Himachal Pradesh, with a 1.75 MW capacity to generate electricity (CPCB, 2019). To the best of our knowledge, there is no report of any operational WtE plants across the IHR states.

TABLE 2 | A number of solid waste processing facilities operational in the IHR states (Data Source: CPCB, 2019). A total of 15 composting, three vermicomposting, three biogas, and two refuse-derived fuel (RDF) plants are operational in IHR.

State	Composting	Vermicomposting	Biogas	RDF/ Palletization
Arunachal Pradesh	1	1	1	1
Himachal Pradesh	4	nil	nil	1
Jammu and Kashmir	2	2	2	Nil
Meghalaya	1	Nil	nil	Nil
Mizoram	1	Nil	nil	Nil
Nagaland	1	Nil	nil	Nil
Sikkim	2	Nil	nil	Nil
Tripura[a]	150.1MTPD	0.40MTPD	nil	Nil
Uttarakhand	2	Nil	nil	Nil
Manipur	1	Nil	nil	Nil
Total	**15**	**3**	**3**	**2**

Abbreviations: MTPD, Metric tonnes per day.

[a]*In the state of Tripura, the operational solid waste processing facilities were not mentioned in the consolidated annual report of CPCB for the year 2018–19. However, 150.1 MTPD of solid waste was subjected to the composting process, and 0.40 MTPD to vermicomposting was reported.*

TABLE 3 | The existing dumpsites and operational landfills in the IHR (Data source: CPCB, 2019).

State	Existing dumpsites	Operational Landfills
Arunachal Pradesh	31	nil
Jammu and Kashmir	19	nil
Himachal Pradesh	54	nil
Meghalaya	6	nil
Mizoram	23	nil
Nagaland	13	1
Sikkim	2	nil
Tripura	17	2
Uttarakhand	42	2
Manipur	21	1
Total	**228**	**6**

Disposal of Municipal Solid Waste

The efficient scientific methods for the disposal of MSW is critical for IHR across the ULBs and rural areas as it is extremely eco-sensitive. However, mostly the collected MSW is dumped at the disposal sites on open unused lands or hill slopes (CPCB, 2019). A total of 0.263 MT/Y of solid waste is disposed off in the IHR, where only six landfills are currently operational across IHR states (**Figure 1**; **Table 3**). Open dumping sites are reported to be prevalent across the IHR (**Table 3**; CPCB, 2019).

Open Burning of Waste

Since the collection, segregation, treatment, and disposal systems are mostly inefficient across IHR, open burning of domestic waste is one of the preferred ways to manage solid waste (Kumari et al., 2019; **Figure 2**.). Open burning is a significant source of air pollution and particulate matter emissions (Li et al., 2016). Due to the release of major pollutants such as dioxins, carbon monoxide, sulfur oxides, toluene, benzene, nitrogen oxides, ethyl benzenes, etc., into the atmosphere has deteriorated the air quality (Ferronato and Torretta, 2019; Cheng et al., 2020). The most severe impact of open burning on IHR is the production of black carbon, and it is hypothesized that due to the black carbon and other light-absorbing impurities, the snow on these glaciers has darkened that may have a considerable role in the melting of mid-latitude glaciers (Li et al., 2016; Thind et al., 2019; **Figure 2**.). The snow darkening effect has been reported in Rohtang pass and other glaciers on the eastern Pir Panjal Range of the Himalayas (Thind et al., 2019).

Open Dumping of Waste

Open dumping is another major unscientific practice of waste disposal in many developing countries (Norsa'adah et al., 2020; Singh et al., 2020). In the places where MSW collection systems are not available, people prefer to dump their waste at an un-allotted location by the roadsides–usually in streets or in open dumpsites and water streams (Kumar et al., 2017; Mushtaq et al., 2020). Apart from domestic sources, municipal dumpsites with organic and inorganic waste also contribute to river water pollution (CPCB- river stretches report, 2018). A total of 228 open dumpsites are present across the IHR states (CPCB, 2019; **Table 3**). Open dumping of unsegregated waste leads to the creation of huge stinking piles, which also serve as breeding homes for vectors of various diseases that affect human lives (Alfthan et al., 2016; **Figure 2**.). The wastes rotting in the open release toxic chemicals that seep into the soil underneath and contaminate the groundwater (Naveen et al., 2017; **Figure 2**.). Rainfall also carries away the leachate via runoff to the adjacent water bodies and results in wholesale contamination of the water resources, i.e., rivers, lakes, ponds, etc. (CPCB, 2019). Any form of pollution in the upper stretches of the river basins may have a detrimental impact downstream and add further to water bodies' pollution. At present, there are 66 stretches of polluted rivers in IHR states ranging across different priority classes characterized according to the biological oxygen demand (BOD) (CPCB- river stretches report, 2018; **Table 4**). In recent decades, the irresponsible exploitation of river resources has led to an increase in water pollution. Though pollution of rivers occurs through many channels, namely, industries, agriculture, domestic/community households, etc., but since industrial activity in the hilly regions is limited due to the geo-climatic conditions, MSW mismanagement can be attributed as the primary reason behind the pollution of the mountainous streams (Mushtaq et al., 2020). The contaminated water may adversely affect the health of humans, animals, and soil productivity. The heavy metal contaminated water resources used for irrigation purposes can also affect agricultural output by restricting plants' growth (Kumar et al., 2017).

CHALLENGES OF SOLID WASTE MANAGEMENT IN THE INDIAN HIMALAYAN REGION

The basic challenges of SWM are the inappropriate methods of waste collection, transportation, and disposal. According to the CPCB (2019), lack of infrastructure, insufficient budget allotment to the municipal authorities, and improper waste collection/segregation systems are some of the major challenges for

TABLE 4 | State-wize polluted river stretches characterized according to priority classes of IHR states (Data source: CPCB- river stretches report, 2018). The stretches lie in the Priority-I (BOD >30 mg/L), Priority-II (20–30 mg/L), Priority-III (10–20 mg/L), Priority-IV (6–10 mg/L), and Priority-V (3–6 mg/L).

State	Priority-I	Priority-II	Priority-III	Priority-IV	Priority-V	Total
Arunachal Pradesh	NA	NA	NA	NA	NA	NA
Jammu and Kashmir	Nil	1	2	2	4	9
Himachal Pradesh	1	1	1	Nil	4	7
Meghalaya	2	Nil	nil	3	2	7
Mizoram	Nil	Nil	1	3	5	9
Nagaland	1	Nil	1	2	2	6
Sikkim	Nil	Nil	nil	Nil	4	4
Tripura	Nil	Nil	nil	Nil	6	6
Uttarakhand	3	1	1	4	nil	9
Manipur	Nil	1	nil	Nil	8	9
Grand Total	**7**	**4**	**6**	**14**	**35**	**66**

'NA' represents data not available.

SWM. Additionally, most of the dumpsites are being operated without following any SWM norms and end up receiving mixed waste that causes environmental and health-related hazards leading to open-fires (CPCB, 2019). It has also been reported that even after notification of the revised SWM rules (2016) and initiatives by the government, most of the states have struggled in the proper implementation of the policies/strategies (CPCB, 2019).

IHR also embraces its own set of difficulties regarding the SWM practices owing to its challenging landscape and harsh environment. Due to poor connectivity and socio-economic condition of the residents, the waste generated in the terrain areas never reaches the proper SWM facilities (Alfthan et al., 2016). As a result, waste generated is either dumped along the mountain slopes or burnt openly. The situation is worst during winters when heavy snowfall in the IHR cut-off many areas from the rest of the country. The temperature in the Himalayan region is typically cold (average maximum of 20°C and minimum −15°C) and offers sub-zero temperature conditions (Saini et al., 2019). These freezing conditions pose a technical challenge for efficient composting and sometimes may even lead to the failure of the composting process in the cold hilly regions (Hou et al., 2017). The improper treatment and disposal of MSW lead to the emission of pollutants, including greenhouse gases; heavy metals (Hg, Pb, Ni, Sb, etc.); acid gases; polycyclic aromatic hydrocarbons; polychlorinated biphenyls; and carcinogenic agent (polychlorinated dibenzo-p-dioxins and dibenzofurans) (Tian et al., 2013; Liu et al., 2017).

Apart from the region's inherent limitations posing as a challenge to SWM, the IHR is also a popular tourist destination in the country. The North-Western Himalayas, in particular, is a major religious pilgrimage. Modern tourism is also rampant in the region, and the number of visitors is increasing every year (Aayog, 2018). The tourists serve as a floating population and add to the generation of waste in the IHR.

RESOURCE RECOVERY FROM WASTE IN THE INDIAN HIMALAYAN REGION (AN ALTERNATIVE FOR SUSTAINABLE DEVELOPMENT)

With the inevitable rise in the native population, tourist inflow, and improper or defective approach to SWM, escalating waste streams have posed a great threat to the mountain ecosystem (Alfthan et al., 2016). Although there are many challenges in the collection, transportation, segregation, and disposal of solid waste in the IHR, very little intervention is carried out in terms of resource recovery. Therefore, to fulfill the advent demand of resources, SWM and resource recovery is a matter of concern in the IHR. Resource recovery from WtE facilities (composting/vermicomposting, anaerobic digestion, RDF, and gas recovery from landfills) and safe residual waste disposal through sanitary landfills are some of the possibilities that must be explored proficiently for IHR (**Figure 4**.).

Composting

Composting is a well-established and widely accepted approach that involves the decomposition and transformation of organic biomass under the action of several microorganisms into humus-like material that has the ability to fertilize crops (Zhao et al., 2017; Sanchez-Monedero et al., 2018; Yu et al., 2019). The conversion of organic matter is carried out either in the presence of oxygen (erobic composting) or in the absence of oxygen (anaerobic digestion) (Mittal et al., 2018; Li et al., 2019; Rasapoor et al., 2020).

Aerobic Composting

In cold hilly regions, the temperature is one of the main parameters that define the overall composting process (Xiao et al., 2009; Hou et al., 2017; Xie et al., 2017). The presence of cold ambient conditions lengthens the mesophilic phase and reduces the thermophilic phase, ultimately resulting in low compost quality (Shukla et al., 2016; Hou et al., 2017; Xie et al., 2017). To overcome such problems, the addition of cold-tolerant microbial consortia with efficient hydrolytic activities have been reported to breakdown complex organic waste into nutrient-rich compost that can be utilized as fertilizer (Hou et al., 2017; Xie et al., 2017). Cold-tolerant bacteria with potential hydrolytic activities such as protease, lipase, pectinase, cellulase, amylase, xylanase has been reported from IHR (Kumar et al., 2015a; Kumar et al., 2015b, Kumar R. et al., 2016; Kumar R. et al., 2018 Kumar et al., 2019; Kumar et al., 2020; Himanshu et al., 2016; Borker et al., 2020; Mukhia et al., 2021). However, reports on utilizing such bacterial consortia for organic waste management in IHR are scarce. Few reports on improved organic waste degradation and plant growth-promoting bacteria to enhance compost/soil quality from IHR are available (Mishra et al., 2008; Adhikari and Pandey, 2020; Borker et al., 2020). In mountain regions, the issue of efficient composting using scientific interventions is less studied and needs special attention.

Initiatives for the promotion of improved composting using cattle dung mixed with agro-forest green waste have been taken by the government of India to promote rural livelihood in the IHR by sanctioning organized clusters through the SFURTI (Scheme of Fund for Regeneration of Traditional Industries) scheme at Sikkim (MSME, 2020a) and Himachal Pradesh (MSME, 2020b). The initiative involves the scientific intervention of utilizing cold-tolerant bacteria with plant growth-promoting potential to convert cattle dung and green waste into enriched compost/vermicompost. The cluster includes the establishment of a common facility center in a rural area with a microbial culture room, bioreactor room, compost quality test room, training hall, and model 20 concrete compost pits. More such grass root level initiatives would be required in the field of improved composting at IHR.

Anaerobic Digestion

Due to the increase in waste production and energy consumption by human activities across IHR, anaerobic digestion (AD) technology can be the other alternate practice utilized for organic waste management. AD converts organic waste by

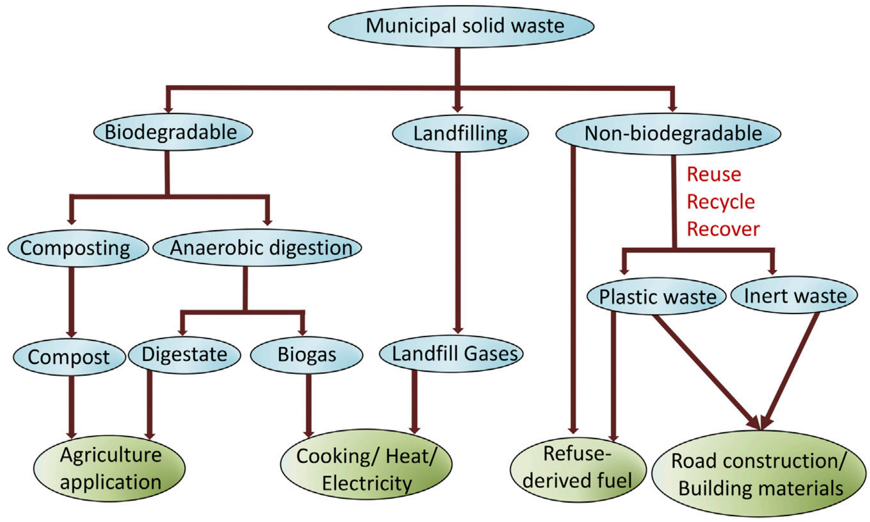

FIGURE 4 | Overview of resource recovery from MSW. MSW is segregated into biodegradable and non-biodegradable waste. Biodegradable waste undergoes composting process and produces organic fertilizer, whereas anaerobic digestion ends up with the production of biogas and undigested material (digestate). Both fertilizer and digestate pose potential applications in the field of agriculture. The energy produced in the form of biogas can be used for cooking purposes and to generate electricity. The non-biodegradable waste such as plastic and inert waste can be recycled and reused into materials that can be used to construct roads, buildings, and RDF. The unprocessed or untreated waste is targeted to landfilling that can produce landfill gas, which helps in electricity generation.

hydrolysis, acidogenic fermentation, hydrogen-producing acetogenesis, and methanogenesis to bio-energy (biogas) that can be transformed into electric energy and heat energy (Mittal et al., 2018; Dev et al., 2019; Li et al., 2019). The biogas recovery promotes sustainable practices bringing out cost-effective and social benefits by reducing greenhouse gases, improving sanitation, and indoor air pollution (Alfthan et al., 2016; Mittal et al., 2018).

In India, the number of biogas plants has increased from 1.27 to 4.54 million between 1990 to 2012 (Lohan et al., 2015), and about 2.07 billion m^3/year biogas production is estimated which is relatively lower than expected (Mittal et al., 2018). It has been reported that IHR states like Jammu and Kashmir have made use of only 0.06% of total biogas plants installed in the country (Lohan et al., 2015). The foremost reason behind such a low number is the cold ambient temperature in IHR (Saini et al., 2019). The temperature plays a significant role in biogas production; hence, the cold temperature in IHR acts as a limiting factor in carrying out sufficient AD process (Lohan et al., 2015). Therefore, biogas production at cold temperature regions requires more instrumentation, set-up expenditure, and new, improved, cost-effective technologies. To surmount the low-temperature problem and achieve proper functioning of biogas plants, the floating drum type of biogas plants has been developed in Kashmir (Lohan et al., 2012; Lohan et al., 2015). Lohan et al. (2015), have also reported the development of various insulating materials that can sufficiently maintain the digester's temperature. Defense Institute of High-Altitude Research has installed a biogas plant at Leh-Ladakh, India, where the dual process of erobic digestion is employed, followed by AD (Balat and Balat, 2009). For adequate biogas production, various additives such as activated carbon, biochar, phenazine, and carbon fibers can also be used in biogas plants (Rasapoor et al., 2020).

Sweden is one of the countries which produces biogas from sewage treatment plants, industries, and landfills and uses it efficiently as vehicle fuel (Olsson and Fallde, 2015). Like Germany and Italy, other countries have also developed an extensive technique for producing renewable energy from energy crops via biogas production through the AD process (Lindfors et al., 2020). In China, using an integrated solar energy system in biogas production during low-temperature conditions has proven to be more efficient to achieve the optimum temperature for carrying out a sufficient AD process (Gaballah et al., 2020). In the high-altitude region of Bolivian Altiplano, Alvarez et al. (2006) have reported biogas production from the Llama and dairy cattle manure. Other studies conducted at higher altitudes by Ferrer et al. (2011) and Garfí et al. (2011) also showed biogas production from cow and guinea pig manure. The indigestible materials left after AD are reported to have crop fertilizing ability (Garfí et al., 2011; Owamah et al., 2014). Additionally, the role of anaerobic psychrophilic microorganisms has also been reported to convert organic waste into biogas under cold conditions (Dev et al., 2019). Hence, improvements like cold-tolerant anaerobic microbial consortia and advanced engineering to improve anaerobic biodigesters may help carry out effective AD in the IHR, which further facilitates the increase in biogas plants in IHR.

Human Excreta Composting

In IHR, areas such as Ladakh's union territory and Lahaul and Spiti district of Himachal Pradesh experience minimal rainfall during monsoon and heavy snowfall during winters, making the availability of water difficult (Bodh and Mehta, 2018; Saini et al., 2019). The temperature goes into sub-zero conditions in winters freezing the water supply, and to overcome this hurdle, this region has been practicing a unique traditional system of dry toilets for generations (Oinam, 2008; Gondhalekar et al., 2015). The dry toilets have helped the inhabitants deal with water scarcity, and the decomposed end product has been supplementing the agroecosystem of the region with manure (Oinam et al., 2008). The dry toilet is a two-tiered structure in which the upper section is attached to the house's living room, and the lower section is used as a store for collecting the night soil (Oinam et al., 2008; Bodh and Mehta, 2018). After every time the toilet is used, the feces are covered by a dry mixture of wood chips, ash, animal dung, sand, etc. (Oinam et al., 2008; Borker et al., 2020).

The inappropriate way to handle traditional dry toilet causes several problems. One of the issues associated is the intense foul odor and unhygienic conditions. There remains a threat of communicable disease or parasitic infections if the human excreta are improperly decomposed or mishandled (Oinam et al., 2008; Carlton et al., 2015). Moreover, heavy metals in human excreta are another issue that causes soil toxicity (Tervahauta et al., 2014; Harder et al., 2020). Further, heavy metals in soil affect the indigenous microbial population's metabolic activity, leading to decreased soil fertility (Iglesias et al., 2018), and when these heavy metals enter the food chain, they are responsible for causing various health-related issues (Xu et al., 2019). Thus, even heavy metals will be persistent, and it becomes essential to properly decompose before utilization of human excreta for compost preparation. Social apprehensions, modernization, and increase in tourism have led to the popularization of septic toilets and the decline of these traditional toilets, which has led to an increase in the dependence on chemical fertilizers, impacting the fragile agroecosystem of the high-altitude region (Borker et al., 2020). For decades this age-old practice of dry toilets has conserved water in freezing winter and sustained organic farming with the supply of manure; however, there have been very few initiatives taken to promote the use of traditional toilets.

To find a scientific solution to the issue, the National Mission on Himalayan Studies (NMHS), implemented by the Ministry of Environment, Forest & Climate Change (MoEF&CC), has granted a project on improvisation of night soil composting using microbiological interventions (NMHS, 2018). Under the project, formulations containing efficient hydrolytic and plant growth-promoting indigenous cold-tolerant bacteria with suitable carrier material were developed (India science wire. news, 2019; CSIR-IHBT, 2020). The formulations were given to dry toilet users for trials in the Lahaul valley of northwestern Himalaya. The feedback received from the users was very inspiring as they claimed a complete reduction of foul odor, reduced biomass, and improvement in the final compost quality (**Supplementary Figure S1**). With increased demand and product popularity; awareness, interaction, and training programmes were conducted across 5 g-panchayats of Lahaul valley, and 'Compost booster: formulations for odorless rapid night soil degradation' was distributed to approximately 160 dry toilet users in December 2020 and January 2021 (NMHS, 2020). Similar interventions in other IHR where dry toilets are being used like Ladakh, Spiti are also proposed to be covered in the future. There are reports of other countries using human excrement as a potential source for organic fertilizer (Low-tech magazine, 2010). Japan, China, and Sweden are some countries using human excrement as a source of fertilizer in agriculture (Low, 2013; Carlton et al., 2015; Akram et al., 2019). A study carried out in Sweden to enhance nutrient recycling from human and animal excrement reported that recycling excrement enhances plants' nutrient availability and could reduce the dependency on synthetic fertilizers and lead to sustainability (Akram et al., 2019). Thus, a traditional practice combined with modern scientific knowledge, including microbiological interventions and engineering the toilet structures, can prove to be more efficient and acceptable in attaining a sustainable future in the mountain ecosystem.

Plastic Solid Waste

Plastic has become an inherent part of our society, and the amount of plastic consumption has increased due to the rising population and changing consumption patterns. In India, 12 MT/Y plastic products are used, and approximately 70% of plastic is considered waste (Kumar A. et al., 2018). In IHR alone, about 0.087 MT/Y of municipal plastic waste (MPW) is generated (**Supplementary Table S1**; PWM report, 2019). However, there is no existing system in rural or urban bodies for the collection, transportation, processing, and disposal of all kinds of plastic waste. But directives are given to ULBs and Gram panchayats to ensure the setting up of plastic waste facilities (PWM-Swachh Bharat, 2019). Recycling and resource recovery from plastic waste seems to be a promising solution to assuage the widespread problem (Saleem et al., 2018; Yao et al., 2018). Approximately 5.6 MT/Y of plastic waste is recycled in India, and about 3.8 MT/Y is not collected or is being littered in the environment (PWM-Swachh Bharat, 2019). Though India's recycling rate is higher than the global average of 20%, the existing waste is still landfilled or ends up polluting the water streams and causes soil infertility (PWM-Swachh Bharat, 2019). A popular solution for plastic reuse is making it an integral component for construction purposes, such as in the construction of roads (Appiah et al., 2017), manufacturing of tiles (Awoyera and Adesina, 2020), and building materials (Mansour and Ali, 2015). In IHR, single-use plastic waste is now used to manufacture poly bricks (The better India. news, 2019) and construction of roads (The Indian express. news, 2019a; The Indian express. news, 2019b).

Resource recovery is another alternative that can be utilized for producing oil, wax paraffin, benzene, styrene, terephthalic acid, di-isocyanate, hydrocarbons, hydrogen, and carbon nanotubes from plastic waste through different techniques such as pyrolysis, hydrocracking, and gasification (Fivga and Dimitriou, 2018; Salaudeen et al., 2018; Yang et al., 2018; Yao et al., 2018; Zhang F. et al., 2020; Qureshi et al., 2020). The non-recyclable fraction of the plastic waste recovered after mechanical treatment (MT) can be used as RDF in energy extensive plants like chemical, cement, or paper manufacturing plants (Onwosi et al., 2017). These plastic wastes may also be combined with certain oily sticky binding agents such as sawdust, starch, dolomite, molasses fibrous, etc., in order to form a denser bulk briquette, which further can be used as RDF (Chiemchaisri et al., 2010).

Inert Waste

The term ’inert waste’ refers to the type of waste that cannot undergo physical, chemical, and biological transformations (Sharma et al., 2020). Inert waste is generated mainly from construction, excavation, demolition, and glass processing activities (Menegaki and Damigos, 2018; Sharma et al., 2020). Such type of wastes also contributes to environmental and health-related issues. Therefore, reusing, recycling, and obtaining value-added products is the best way to handle inert wastes. For example, ash generated from various industrial and mining activities can be recycled to prepare geopolymers with a great polymerization affinity (Ahmari and Zhang, 2015; Capasso et al., 2019). The recycled aggregates obtained from concrete and demolition waste can construct roads, landscaping, cementitious materials, and concrete (Sharma et al., 2020). The glass waste materials can also be recycled many times without significant alteration in their chemical characteristics (Shayan and Xu, 2004; Sharma et al., 2020). The glass waste has potential application to use as an aggregate in construction (Mohajerani et al., 2017; Mohammadinia et al., 2019), as a low-cost adsorbent material four thin layer chromatography techniques (Ying et al., 2009; Sharma et al., 2020) and in removal and recovery of phosphate from water (Jiang et al., 2017). The waste metal scrap can be recycled over and over again as its properties are not altered and can also be transformed into new metals, as a coating material and in the production of concrete as a partial replacement of sand (Andersson et al., 2017; Shemi et al., 2018; Melugiri-Shankaramurthy et al., 2019). Hence, the recovery of various inert waste material can be a promising solution for IHR.

Refuse-Derived Fuel

Refuse-derived fuel is an alternative fuel consisting mainly of combustible components of waste materials such as textiles, non-recyclable plastics, labels, cardboard, paper, and rubber (Rotter et al., 2011). RDF is characterized mainly by its high calorific value, i.e., 11–25 MJ/kg original substance, and homogenous particle size (5–300 mm) (Sarc and Lorber, 2013). RDF production is subjected to a multi-step process of separation technologies such as sieving, sifting, grinding, and can be followed by briquetting or in the generation of RDF-fluff (Sprenger et al., 2018; Rajca et al., 2020). The type of fuel generated is generally cheaper, readily available, and comparatively produces less CO_2 than conventional fuels such as coal (Schwarzböck et al., 2016). RDF can be used in energy-intensive industries like chemical, cement, paper manufacturing as a co-combustion in existing modified plants or as a mono-combustion in specially built processing plants (Rotter et al., 2011). In many European countries, annually, 4-5 million tonnes of estimated RDF are produced from MSW (Gallardo et al., 2014). The European countries have adopted MT, or mechanical biological treatment (MBT) plants technologies for the production of a high calorific value fraction (HCVF) that can be utilized in RDF production (Rajca et al., 2020). Poland is one of the countries that are the primary benefactor of RDF and known to use in cement plants for over 15 years (Berardi et al., 2020). It may be suggested that IHR may also adopt such processing facilities to transform waste into RDF and fulfill the growing energy demand.

Landfills

Landfilling is another MSW disposal method used worldwide (He et al., 2019; Hereher et al., 2019). It is known as the most cost-effective method of waste disposal. Poor landfill management contributes to environmental and public health-related problems (Kumar et al., 2017). Therefore, proper sanitary landfill systems are required for MSW treatment (Hereher et al., 2019). A sanitary landfill system’s main objective is to minimize environmental and health-related issues (Hereher et al., 2019). Therefore, site selection for sanitary landfills is the utmost priority to make the landfill site a point source of no pollution (SWM rules, 2016). During this practice, landfill gas (LFG) is generated, which is recognized as the emission of greenhouse gases, including methane and carbon dioxide. The LFG can be utilized as a renewable energy source to generate electricity (Tsai, 2007). For example, in China, 3.30 billion Nm^3 of LFG will be produced and utilized in the year 2020, that could generate electricity of 7.39 billion kWh or 1.70 billion Nm^3 (Fei et al., 2019). Also, the liquid portion contacted with the stored landfill waste is generally known as landfill leachate. The landfill leachate is toxic to the environment due to a high concentration of ammonium nitrogen, heavy metals, phosphorus, and organic matter (Nguyen and Min, 2020). It exhibits a potential risk of polluting streams, rivers, groundwater, and soil. There have been reports of processing landfill leachate ammonia that can act as a suitable substrate for generating electricity through an alkaline membrane fuel cell (Zhang M. et al., 2020) and algae-cathode microbial fuel cell system (Nguyen and Min, 2020). However, the primary focus on proper collection and treatment of landfill leachate must be carried out to contain hazardous materials. Nowadays, landfills are instrumented with a leachate collection system and proper liners to eliminate leachate run-off possibilities (Mandal et al., 2017). But, still, rainwater percolation through landfills, weather variation, moisture content of the soil covering the landfilled waste, and also the innate moisture content of buried solid waste are among several reasons that affect the quality and quantity of the leachate (Mandal et al., 2017; Nguyen and Min, 2020). The two major pollutants, ammonium nitrogen and organic matter of the landfill leachate, are treated by electrochemical oxidation that effectively reduces the concentration of pollutants in the leachate (Mandal et al., 2017). The bioreactor landfill is another economically beneficial approach that recirculates leachate to control moisture content in the landfills and rapidly stabilizes the solid waste through accelerated microbial activity (Morello et al., 2017; Li et al., 2018). This transition from conventional landfill to bioreactor landfill improves the leachate quality, controls the landfill’s moisture content, and enhances LFG generation and recovery (Morello et al., 2017; Li et al., 2018). Currently, in IHR, six landfills are operational, and till now, no sanitary landfills have been reported (CPCB, 2019; **Figure 1**). The landfills with advanced technologies could probably emerge as a timely solution to the improved SWM practice in the IHR.

WAY FORWARD

Despite the improved SWM policies and regulations, conventional methods of waste management are still prevalent across IHR. Strict implementation of revised SWM rules, civil awareness, community participation, good waste management practices, capacity building, and adoption of new and innovative technologies could be the way forward for improved SWM for achieving sustainable development of the IHR.

Key Solid Waste Management Rules Revised Specifically for Indian Himalayan Region

SWM rules (2016) provides additional criteria and actions for all the hilly states to ensure proper waste management. The SWM rules have stated communities' involvement at the local level to promote in-house composting, biogas generation and maximize waste processing at the source level to minimize transportation cost and environmental impacts. SWM rules (2016) have also provided directives to collecting waste from the hilly areas otherwise unapproachable by handcarts, tricycles and are only accessible on foot. The door-to-door collection system should collect the segregated waste, and waste collectors must wear personal protective equipment kits and use leakproof backpack containers. The local bodies should facilitate the construction, operation, and maintenance of solid waste processing units such as bio-methanation, microbial composting, vermicomposting, anaerobic digestion, and RDF/palletization, thereby decentralizing the waste processing facilities. The biodegradable organic waste shall be utilized using processing facilities, and the inert waste can also be used for building roads or filling-up of appropriate hill areas. Additionally, in the IHR, the used-tires can be reutilized for the building of retaining walls for the narrow hill roads. SWM rules (2016) have clearly stated to avoid landfill construction on the hills. Suitable land for sanitary landfill should be identified down the hill within 25 km in the plain areas. The dumping of mixed waste should be stopped, and only non-usable, non-combustible, non-recyclable, non-reactive, and non-combustible inert waste, pre-processing rejects, and residues from waste processing facilities should be landfilled. The collection of all residual waste from processing facilities and inert waste shall be stored at different transfer stations across the region in an enclosed area. The collected residual waste from all transfer stations shall be transported and disposed off at the sanitary landfill. Moreover, SWM rules (2016), have stated that local bodies shall frame bye-laws to prohibit citizens from littering waste on the streets. The local bodies shall charge tourists at entry points to sustain SWM service at tourist destinations. The tourists shall also be given strict direction not to dispose off any kind of waste (water bottles, liquor bottles, tetra packs, soft drink cans, and any other form of plastic or paper waste) on the streets or downhill, and instead deposit waste in litter bins placed by the local bodies.

Information, Education, and Communication for Good Waste Management Practices

Information, education, and communication (IEC) concerning good waste management practices should be a key feature for mass awareness to make people realize that waste management is not the burden of the municipality alone; it is a matter of concern for every individual (Joshi and Ahmed, 2016). People should also realize their role and responsibilities regarding proper source segregation of solid waste, avoid waste littering in the streets, open dumping, and burning of waste. The IEC campaign for mass awareness must reach all the sectors, including education (school, colleges, and universities), offices, the health sector (hospitals and clinics), private sectors (hotels and malls), market places, residential areas, and villages (Ghosh, 2016).

Ban on the Usage of Plastics and Polluters to Pay

PWM rules (2016), emphasized the ban of manufacturing and selling of <50 microns thickness plastic carry bags, and many IHR states have partially or completely banned the use of plastic carry bags (**Supplementary Table S1**). Additionally, PWM rules have ensured that open burning of plastic waste, plastic littering in public, and dumping near drains and rivers should be strictly prohibited and have promoted the use of compostable carry bags. In Himachal Pradesh and Uttarakhand, there is also a provision of a fine ranging from Rs. 500 to Rs 5,000 for littering and use of polythene carry bags (G-SHE, 2018). In Himachal Pradesh, the government has drafted a policy to buy-back single-use plastics and non-recyclable plastic wastes from individuals, ragpickers, and ULBs (The tribune. news, 2019). The purchased plastic waste will be utilized in making roads and as a fuel in the cement industries. Other states can also take up such initiatives to prevent plastic waste littering and minimize ecological damage. Aayog (2018) has also endorsed some key action programs in IHR, such as 'green cess' and 'payments for environmental services,' including charging from tourists for the service provided and entrance fees. For sustainable tourism aspects, Aayog (2018) has specified that the state planning commissions must supervise the tourism departments and different associated sectors to genuinely implement these critical agendas in IHR for the environment, tourism, and sustainable development. 'Pay-as-you-throw' (PAYT) scheme implemented in Germany follows the polluter to pay principle that charges the residents of municipalities according to the amount of waste they generate and send for the waste management (Morlok et al., 2017). In addition to a well-developed infrastructure for solid waste collection and public awareness, such PAYT schemes may also be replicated in the eco-sensitive IHR for better SWM plans and increasing the rate of recycling.

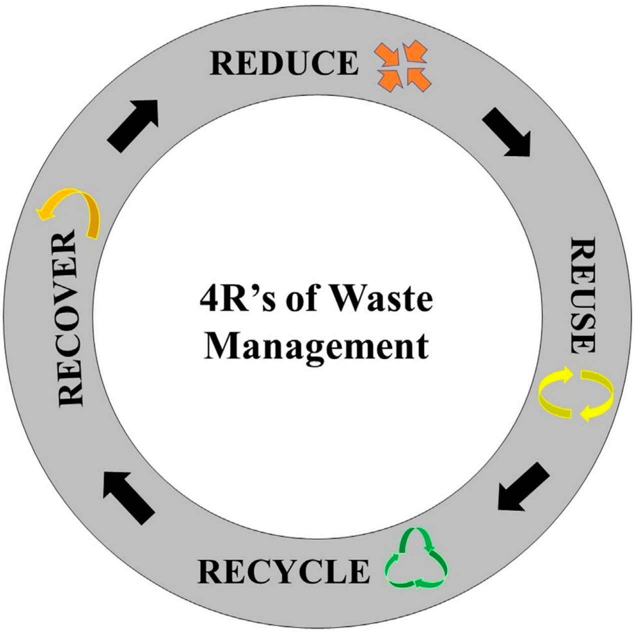

FIGURE 5 | 4R's concept for good waste management. Reduce, reuse, recycle, and recover are the four good waste management practices sequentially organized in order of importance. The foremost goal is to reduce or avoid the minimum purchase of materials that are harmful to the environment. Reuse suggests the use of materials again for other purposes rather than disposing off unscientifically. Recycle emphasizes reusing waste materials (like plastic, metal, and e-waste) by recycling them into new products. Recover highlights the processing of waste to obtain valuable products. Hence, the adoption of 4R's concept can contribute to good waste management practices in the IHR.

4R Concept (Reduce, Reuse, Recycle, and Recover)

To solve the waste management challenges, the practice to manage waste must be put in place, starting from the household's small scale to bigger scales of the city, state, and the country (Chowdhury et al., 2014). 4R concept (Reduce, reuse, recycle, and recover) can play a pivotal role to fulfill the aim of sustainable waste management (Das et al., 2019; Ruslinda et al., 2019; **Figure 5**.). Reduce; means avoiding the minimum purchase of harmful materials to the environment instead of finding alternative materials for use. Reuse; suggest the reuse of materials for other purposes rather than throwing it out unscientifically. Recycle; emphasizes recycling waste materials (plastic, metal, and e-waste) into value-added products instead of dumping. Recover; means waste materials are rich sources of the substrate to recover efficient materials (nutrient and energy) from it; therefore, using them contributes to sustainability. These practices provide a reliable waste separation system at the source, i.e., a house-to-house solid waste collection service (Das et al., 2019). Among the European countries, Germany has one of the highest recycling rates. It recycles more than 60% of municipal solid waste, and merely 30% of waste is used to produce a significant amount of energy. Only 1% of waste is subjected to landfills (Mühle et al., 2010). The main reason to decrease the amount of waste going to landfills is to minimize the emissions of effluents from landfills into the air, soil, and groundwater (Mühle et al., 2010). Adoption of such 4R concept in the IHR may help in managing MSW in a better way.

Capacity Building

The aim of developing the capacity building in the IHR is to meet the increasing demand for skilled workers in terms of training, new skills, knowledge, and entrepreneurial opportunities. Establishing such capacity buildings will require the involvement of both center and state levels, including private sector entities (NGO's), research/training institutes, educational institutes (schools and colleges), business and technology centers to develop skills that run and strengthen mountain services (Aayog, 2018). In Sweden, institutional capacity building is used to provide necessary guidance with the participation of the public and private sectors (Lindfors et al., 2020). This combination of activities from different sectors and their collaborators facilitated the development of local biogas systems and was used to understand the potential of biogas production (Lindfors et al., 2020). Industrial symbiosis is another way where sectors come together either through by-exchanging products or by utility sharing to address common concern issues (Boons et al., 2017). Thus, the involvement of several different sectors helps in the successful implementation of sustainable techniques. There are also few non-government organizations such as the healing Himalaya foundation (https://healinghimalayas.org/), zero waste Himalaya (http://thanal.co.in/zero-waste-himalayas-campaign/), and waste worriers (https://wastewarriors.org/) who took the initiative to clean the waste generated specifically in the Himalayan region. Such organizations' main motto is to spread waste management awareness and develop programs to protect the environment and human health from the toxic side effects of waste materials.

Modern Collection System and Cluster Approach

The modern underground collection system is one of the effective approaches to tackle MSW in urban areas. The municipal corporation has installed underground waste bins at many Dharmshala and Shimla locations, which offers an advanced method for storing MSW (Sharma et al., 2018). It makes the waste segregation, collection, transportation, and disposal convenient by reducing the surface footprint and allowing more open space and reduced foul odor (Sharma et al., 2018). However, this collection system mode is expensive and cannot be installed in different places across IHR. Since the towns and cities in the hilly regions are small and scattered, a cluster-based approach for waste collection is preferable to club the resources of neighboring ULBs and Gram panchayats. The waste collected by the door-to-door collection system from inaccessible high-altitude regions can be stored at different transfer stations in the lower areas (Alfthan et al., 2016). The cumulative waste can be picked by smaller trucks and transferred to waste processing facilities and then to landfill sites. This economically viable Cluster/Mini-cluster model can be helpful for proper waste management in IHR.

Research and Technology

Research and technologies need to focus on the overall connection between various wastes and their impact on the environment, human and animal health. It is also crucial to understand the public attitude toward waste generation and their involvement in waste management practices (Alfthan et al., 2016).

Compost additives such as biochar and cocopeat for erobic composting can help reduce the overall composting process and results in the production of good quality compost (Xu et al., 2016; Guo et al., 2020). One of the additives, biochar, is reported to provide favorable conditions to the microbial population involved in the degradation of organic waste, reducing greenhouse gas emissions, organic pollutants, and heavy metals (Sanchez-Monedero et al., 2018; Guo et al., 2020).

During the anaerobic digestion process, biogas production's efficiency and sustainability are hampered due to the inaccessibility of anaerobic microorganisms to some of the available organic substrates, leading to insufficient degradation (Raposo et al., 2012). Advanced technologies such as thermal hydrolysis can act as a promising treatment for the AD process to enhance biogas' performance and production (Ferrentino et al., 2019; Li et al., 2019; Lucian et al., 2020). Organic matter treatment with thermal hydrolysis disrupts the cell walls, solubilizes the organic matter, and makes the organic matter available for the anaerobic microbial populations (Lucian et al., 2020). Therefore, such an advanced technology system for biogas production can also prove to be proficient in IHR.

Conventional technologies such as incineration and landfills for plastic waste treatment cause ill effects on the environment and human health (Zhang F. et al., 2020). Some advanced technologies, viz. pyrolysis, hydrocracking, gasification, and chemolysis are developed to recover plastic waste resources (Al-Salem et al., 2017; Ragaert et al., 2017). Whereas treatments like photodegradation, mechanochemical degradation, and thermo degradation practices have been used for plastic waste degradation (Yang et al., 2018; Zhang F. et al., 2020). These approaches can be considered in the recovery of plastic waste produced in the IHR.

The introduction of new MBT plants, a type of waste processing facility in several countries, has increased RDF production (Rajca et al., 2020). MBT plant aims to stabilize the organic fraction of waste and recover recyclable valuable materials (Montejo et al., 2013; Rajca et al., 2020). In European countries, the main reason behind the installation of MBT plants is to avoid the direct treatment of biodegradable waste from landfills (Fei et al., 2018; Van Fan et al., 2020). Hence, to treat the unsegregated waste produced in IHR, such technology can help prevent the adverse effects on landfills' environment.

The landfill is yet another approach for SWM; however, the generation of leachate is a significant drawback (Hereher et al., 2019; Mahtab et al., 2020). Advanced oxidation processes (AOPs) are an approach to remove bio-refractory and toxic component produced from leachate (Mahtab et al., 2020). AOPs efficiently mineralize the recalcitrant compounds into decomposable mixtures, preventing leachate spillage into the environment (Mahtab et al., 2020; Umamaheswari et al., 2020). Therefore, adopting such technology can minimize leachate runoff into the groundwater, streams, and rivers, thereby preventing soil and water pollution.

The government of India recognized the importance of research and technologies in the IHR, and many research institutes were established with focused mandates on sustainable developments. Research institutes like CSIR-Institute of Himalayan Bioresource Technology (https://www.ihbt.res.in), G.B. Pant National Institute of Himalayan Environment (NIHE) (http://gbpihed.gov.in), ICAR-Vivekananda Parvatiya Krishi Anusandhan Sansthan (http://www.vpkas.icar.gov.in) and ICAR-National Organic Farming Research Institute (NOFRI), Tadong, Gangtok (https://icar.org.in/content/icar-nofri) were all established to contribute toward the ecologically sensitive IHR. National Mission on Himalayan Studies (https://nmhs.org.in) is a mission implemented to support innovative research and interventions which can ameliorate the health of the Himalayan ecosystem. Indian Himalayan Central University Consortium (IHCUC) to study the agroecosystem of Himalayan states is another initiative established by the NITI Aayog (https://niti.gov.in/).

CONCLUSION

IHR is a unique eco-sensitive zone under continuous threat from the rising amount of waste generated by the inhabitants and the tourists visiting the region. The inadequate waste infrastructure, informal means of waste disposal, lack of proper implementation of SWM rules, and civil awareness have increased the environmental pollution, health risks to people and wildlife of the IHR. The measures planned to curb this threat lack the effective execution to achieve proper waste management and sustainable development goals. Robust implementation of planned facilities for reuse, recycling, maximum resource recovery from various WtE facilities, combined with safe residual waste disposal through sanitary landfills and public participation, is the quintessential requirement. The selection of specific waste technology, capacity building, and initiation of several environmental taxes can provide necessary revenues for the sustenance and development of SWM. IHR state-specific strategies should be implemented, focusing mainly on conservation and socio-economic development. Until these challenges and emerging issues are not met, IHR will continue to be over-burdened by the rapid economic transformation.

AUTHOR CONTRIBUTIONS

AT: writing- original draft preparation, data curation; SK: writing-original draft preparation, figure generation; SS: writing, figure generation; SP: writing; AK: writing; RK: conceptualization, supervision, finalizing the manuscript, funding acquisition.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2021.609229/full#supplementary-material.

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