# Emerging Biotechnological Approaches in Solid Waste Management: A Comprehensive Review

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*Abstract*- **With rapid urbanization, there is an urgent need to manage the ever-increasing waste which has made it essential to approach various technologies for its worldwide management. India is facing a massive waste management challenge as the urban and rural population of India generates over 62 million tonnes of municipal solid waste per annum. Solid Waste Management (SWM) provides effective and practical options for sustainable management and disposal of solid waste collected by municipal authorities. Solid waste, generally termed refuse, is regarded as any unwanted, harmful, and wasted material by the human society which includes urban wastes, agricultural wastes, biomedical wastes, e-wastes, and hazardous wastes. Managing solid waste requires procedures and regulations with minimal effect on the environment. Segregation of waste at the source, collection & transportation by municipal authorities, recycling, waste reduction, and elimination through incineration and open dumping are the Conventional approaches for solid waste management. Biotechnological approaches viz. Bioremediation and Landfill Bioreactors are quite promising in waste management. Vermicomposting with efficient microbes is another biotechnological approach that aids in the safe management of compostable waste collected from various sources- agricultural, industrial, domestic, and hospital. Integrated solid waste management is the need of the hour to manage solid waste in a sustainable manner so that the impact of the waste can be minimized & quality of life can be improved.**

*Index Terms*- **Bioremediation; Biotechnological approaches; Conventional methods; Landfill bioreactors; Solid waste management.**

## INTRODUCTION

Solid waste is any unwanted, harmful, discarded, or abandoned material by human society generated during the day-to-day work of human society.[1] Different types of waste is generated which can be categorized as municipal solid waste, agricultural and animal waste, medical and hazardous waste, industrial non-hazardous waste, radioactive waste, debris from construction and demolition along with extraction and mining waste, sewage sludge, fossil fuel combustion waste and fuel production waste.[2] Solid Waste Management (SWM) refers to the approaches followed and strategies used for the storage and disposal of solid waste (SW) without causing any pollution and harm to the already existing species.[3,4] Accurate information on the composition of waste is necessary to apply the proper SWM practices. The physical composition of India's solid waste is determined on the basis of wet weight, it mainly consists of 40-60% of biodegradable organic fraction, 30-40% of fine earth and ash, 3-6% of plastic and paper, and less than 1% of glass and metals.[5]

## IMPACTS OF SOLID WASTE

Improper disposal results in several environmental impacts, most often leading to health hazards and other environmental impacts. Major impacts are discussed below:

- **Public Impact:** Regions with little to no waste management suffer the most with serious impacts due to the mismanagement of the waste which invites disease vectors, clogged drains, and become breeding grounds for mosquitoes along with the increase of toxic gases in the environment due to open burning of solid waste.
- **Ecological and Climatic Impact:** Open dumping of the waste alters the soil type, thus, affecting the flora and fauna of the region. Marine life suffers from death and other ecological effects when waste is dumped into the oceans without prior treatment. Changes in climate and other impacts caused on the environment have been the driving force for the government and various other authorities to work on the proper solid waste management of discarded waste in India. Greenhouse gas emissions from the SWM practices such as landfills and open dumping have been a significant contributor to global warming.
- **Economic Impact:** Proper municipal solid waste management helps in inviting immigrants and tourists boosting the economic growth of the region which further helps in increasing employment opportunities in both private and public sectors. Clean aesthetics play a significant role in improving the image and pride of a place which enhances the scenic beauty inviting new businesses and residents to the area.[6]

## VARIOUS APPROACHES FOR THE MANAGEMENT OF SOLID WASTE

Protection of human civilization from the drastic effects of man-made solid waste requires major efforts to establish an effective and sustainable solid waste management plan to combat the issue of solid waste mismanagement in our country. Management of 62 million tonnes per annum of solid waste generated by the rural and urban population of India requires stringent but pliable approaches to manage this problem in a cost-effective manner with minimum impact on the environment.[7]

Before deciding to opt for Conventional or Biotechnological approaches for SWM, it is important to acknowledge the sources of solid waste and characterize SW on the basis of recyclability, reusability, combustibility, disposability, and decomposability, and then accordingly subject to proper collection and transfer to the municipal sites for further disposal and treatment.[8]

1. **Segregation and Storage at the Source:** Municipal Solid Waste (MSW) is majorly categorized into two main divisions- Organic and Inorganic. Organic waste is further divided into putrescible (decomposing food waste), fermentable (decomposes fast) and non-fermentable (resists decomposition). Inorganic waste includes non-biodegradable SW.[9] Segregating SW on the basis of the given categories in different waste collection bins can help in reducing the impact on the environment.[10]
2. **Collection and Transport:** Door-to-door solid waste collection vehicles are equipped with color-coded containers, which along with the help of manual labor, collect the waste from the source separately on the basis of its disposability.[11] Municipal agencies use removal trucks, tractor-trailers, mini dumpers in urban areas, rickshaws, and tricycles in rural areas, to transport the waste to nearby dumping and landfill sites.[12] Collection and transport efficiency depends on the income level of the nation, thus, low income countries are less efficient in comparison to high income nations that have higher collection rates.[13]
3. **Recycle and Waste reduction:** The concept of 'Waste Hierarchy' and the '4R's-Reduction, Reuse, Recycling & Recovery' help in the sustainable management of solid waste when applied at the source and the municipal level for the conversion of waste into valuable resources to improve the development strategies in a feasible way and give impetus to a circular economy.[6,14-16] Valorization of waste material through various chemical and biological processes helps in managing and recovering the energy and nutrients from the bio-wastes.[16,17]
4. **Disposal Methods:** Conventional SWM and disposal methods have been practiced to sustainably manage the collected solid waste with visible impacts on the environment.[18] Biotechnological approaches give a new ray of hope, allowing the disposal of solid waste with little impact on the environment.[19] Integrated SWM is the need of the hour to safely and economically dispose of waste.[3,20]

## CONVENTIONAL METHODS

Conventional practices are generally easy practices that don't take into account the pollution and damage caused by them during the disposal and treatment of solid waste.[18,21] Conventional approaches include the following:

- **Open Dumps:** It is the old and unscientific practice of dumping solid waste on open land with a large surface area without any environmental protection and control.[15] The degradation of waste in open areas leads to many health hazards, soil, and air pollution along with breeding areas for mosquitoes and other harmful insects.[15]
- **Incineration:** Degradation of hazardous solid waste by oxidizing it at higher temperatures between 980-2000℃ and reducing the waste volume to 80-90% along with ash as a by-product.8 Oxidation and ash production lead to the generation of hazardous pollutants like dioxins, furans, and PAHs, these pollutants, when inhaled, can lead to serious respiratory tract diseases.[5,6,8,12]
- **Pyrolysis:** Degradation of solid waste mainly plastics and polyethylene, in the absence of oxygen at a higher temperature of 300-850℃ created by plasma torches along with the synthesis of harmful gases like $H_2$, CO, $CH_4$, $SO_x$, and $NO_x$ in addition to char as the by-product.[8,12]
- **Gasification:** This is the process of partial oxidation of dried and segregated waste with insufficient or minimal oxygen at temperatures above 650℃. $SO_x$ and $NO_x$ are not emitted due to insufficient oxygen in this controlled conditions. [8,12]
- **Open Burning:** Open Burning is a global practice and is defined as the burning of any matter in open areas where the emissions from the burning directly impact the surrounding.[22] It serves as a non-point source of pollutants such as particulate matter, sulfur dioxide, furans, toluenes, hydrocarbons, etc that directly affect human health.[22] Also, black carbon produced during burning leads to higher temperatures resulting in the melting of glaciers and graying of the monuments.[15]

## BIOTECHNOLOGICAL APPROACHES

Biotechnological practices for SWM provide a sustainable and promising approach for the proper disposal and treatment of solid waste with little impact on the environment using environmentally-safe and cost-effective methods.[19]

1. **Composting:** The decomposition and degradation of the biodegradable solid organic waste material under the action of microorganisms in warm and moist conditions is referred to as composting.8 Humus is produced as the byproduct of composting which is used as a substitute for fertilizers, which enhances the physical, chemical and biological properties of the soil.[23] Microorganisms like Streptomyces rectus, Thermomonospora fusca, Thermopolyspora bispora, Thermoactinomyces sp., Bacillus subtilis and Pseudomonas fluorescens, etc. are used for microbial decomposition.[2,6] Composting plants have been established in Baroda, Mumbai, Kolkata, Delhi and other various cities of India.[8]

Organic Microorganisms Biodegradable + $O_2$ → Stabilized organic residuals + Microbial biomass + $CO_2$+$H_2O$ + Heat [24]

2. **Vermicomposting:** Vermicomposting is the non-thermophilic and bio-oxidative process of composting biodegradable solid waste with the assistance of earthworms and associated microbes.[25] *Eisenia foetida* (red worms), *Lumbricus rebellious*, *Pheretima* sp., and *Perionyx excavates* sp. along with epiges, endoges and detrivores are the most favorable earthworms used for this purpose.[26] Vermicompost is a highly porous byproduct formed as the liquid collected from the vermicomposting pits and is highly nutritious providing many nutrients and growth-regulating hormones to the crops when sprayed in agricultural land along with inhibiting the invasion of insects and other pests.[25] Vermicomposting plants are built in several cities of India- Hyderabad, Bangalore, Faridabad, etc.[8]
3. **Bioreactor Landfills:** Landfills are mainly referred to the dumping of solid waste into a large pit which is then covered with soil and left undisturbed for the natural degradation of the waste, but due to leachate and landfill gas production, this method affects the environment in precarious ways.[7,27] To combat the stated issues, Bioreactor Technology is used that helps in leachate

management to recover bioenergy as landfill gas and residue as manure. Physical shredding of the waste to uniform size helps in easy and effective degradation as the consistent and uniform particle size helps in reducing the time taken for degradation. Additional chemical buffers for adjusting the pH along with circulation of the solid waste for leachate cycling are regulated. The presence and absence of oxygen is strictly monitored to control the biological outputs of the degrading waste.[27]

4. **Anaerobic Digestion & Biomethation:** Disinfecting and stabilizing the farmland residue, industrial sludge, and animal slurries in the absence of oxygen for generating 'Biogas' which can be further used as a source of power generation, this process is termed as anaerobic digestion and biomethation.[8] For providing controlled conditions, treatment is carried out in closed systems which further helps in preventing the escape of bad odor, pollution, and flies.[5,6] Biomethation depends upon various parameters such as feedstock composition, temperature, pH, C/N ratio, Retention time, etc.[28] Nisargruna Biogas Plant is based on this principle that has been established by BARC, India.[8]

5. **Bioremediation:** Solid waste and other types of waste often increase the toxic contents in the soil and groundwater, making them unhealthy and lethal for human use.[29] Bioremediation is an alternative, eco-friendly, and lucrative approach to degrading waste and detoxifying soil using microbial action.[30] Bioremediation is of two types:

a. **In situ Bioremediation:** It involves the treatment of soil and solid waste at the contaminated site. Degradation can be done using three different ways.

i. **Biosparging:** injecting air under the groundwater to increase the pressure of air in the soil to release toxins.
ii. **Bioventing:** the process of pumping in oxygen, nitrogen, and phosphorus to aerate the soil and provide enough $O_2$ to microbes for degradation.
iii. **Bioaugmentation:** microbes having specific metabolic capabilities are introduced to enhance the degradation action.

b. **Ex situ Bioremediation:** It involves contaminated solids and waste being transported to another site for treatment and degradation. Treatment is generally divided into three ways.

i. **Composting:** biodegradation at temperatures between 55-65°C.
ii. **Land forming:** a sandwich layer of excavated soil between clean soil and clay & concrete is prepared which is further allowed to stand for natural degradation.
iii. **Biopiling:** an aeration system along with the irrigation and nutrient system on a treatment bed is prepared with a leachate collection system.[29,30]

**SOLID WASTE MANAGEMENT IMPLEMENTATION- STATUS IN INDIA**

According to the 'Annual Report 2020-21' on the 'Implementation of Solid Waste Management Rules, 2016' prepared by 'Central Pollution Control Board, Delhi' to forward it to the 'Central Government (Ministry of Environment, Forests and Climate Change)' along with suggestions/recommendations; it was observed that a total of 160038.9 TPD (tons per day) of solid waste is generated in the country out of which only 152749.5 TPD is collected with a collection efficiency of 95.4%. 50% of waste i.e. 79956.3 TPD is treated and 29724.1 TPD waste, approximately 18.4% is landfilled, whereas, a huge amount of waste 50655.4 TPD (31.7% of total waste generated) remains un-accounted of any management strategy. The table given below signifies the effect (positive or negative) every SWM strategy has on the environment, along with the percentage of waste that is being treated and managed using the given approach in the data retrieved for the particular years.[31]

**TABLE-1 APPROACHES USED FOR THE MANAGEMENT OF MUNICIPAL SOLID WASTE IN INDIA**

| Sr. | Method | Impact on Environment | SWM in India |
|---|---|---|---|
| 1. | Open Dumping | These are looming hotspots for combined pollution of air, soil, and water. Provides breeding surfaces to mosquitoes, flies, rats, and dogs, thus becoming vector channels for communicable diseases such as plague, typhus, malaria, dengue, etc.[32] | Out of total waste generated in India, the 'What a Waste 2.0' report by the World Bank 2018 states that 77% of total waste is disposed of in open dumpsites.[33] |
| 2. | Incineration | Requires trained personnel and regular maintenance. Release of smoke, heavy metals, carcinogens dioxins, particulates, and nitrogen oxide pollutes the environment and produces cancer-causing chemicals.[34] | Mostly, hazardous wastes are incinerated in order to avoid the dissemination of these hazardous components into the environment. Around 6.67% of total hazardous waste generated in India is incinerated.[35] |
| 3. | Pyrolysis | Emission of heavy metals, dioxins, and volatile organic compounds leads to diseases like respiratory disorders and lung cancer. Toxins accumulate in soil and water, entering the food sources, making the food harmful for human consumption.[36] | Every year approximately 5.6 million tonnes of plastic waste is generated in India, most of which along with the disinfected plastics are subject to pyrolysis.[37] Plastic and biomass subjected to pyrolysis produce biofuel that can act as alternatives for depleting fossil fuels.[38] |
| 4. | Gasification | Gasification plants have occupational, health, and safety hazards. The release of | Partial oxidation focuses on the production of 'synthetic gas' consisting of hydrogen and |

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| | | alkaline compounds, halogens and other heavy metals adversely degrade human and animal health.[39] | carbon monoxide with high calorific values that can be used for electricity production.[40] |
| 5. | Open Burning | Large quantities of particulate matter, PAHs, PCDD/Fs, PBDD/Fs, DLCs, and heavy metals are released into the environment that affects humans by increasing chances of skin, heart, lungs, and carcinogenic disorders.[41] | In 2014, it was observed that a total of 23719 MT/day of MSW was openly burned which was estimated to increase 1.5 times by 2021.[22] |
| 6. | Composting | Requires minimal investment as initial capital along with a lower level of training required to manage the compost pits. Regulates the soil ecosystem by repressing the production of plant pathogens.[34] | Out of 51-53% of compostable material segregated from the total municipal solid waste, it was found that only 10-12% i.e. a small fraction is disposed of by composting because composting needs segregation of waste, and segregation waste at large scale becomes a cumbersome process.[42] |
| 7. | Vermicomposting | Effective, convenient, cost-effective and a safe method to rebuild and restructure the soil while aerating by creating pores with the help of worms.[25,26] Increases the water holding capacity and increases the nutrients for crop production in the soil.[26] | When compared to composting, vermicomposting is majorly practiced in Indian cities- Hyderabad, Bangalore, Mumbai, and Faridabad. The odorless-granular product produced is used as a biofertilizer which enhances crop production. Household vermicomposting kits have been developed to promote vermicomposting at the level of waste production.[42] |
| 8. | Bioreactor Landfills | Recirculation of leachate enhances the speed of microbial decomposition of the waste along with reducing the time period of leachate management and efficiently recovers gas and other byproducts while the bioreactor is in action. Also, reduces the cross-contamination chances.[27] | Help to permit the rapid decomposition and stabilization of the decomposable organic waste components in an environmentally secure set up which increases the rate of biodegradation by providing a suitable environment for degradation in a closed manner for energy production and recovery from waste material.[42] |
| 9. | Biomethation | No greenhouse gas emission as all the gas is produced in an enclosed system. Along with no flies and rodents destructing the area.[34] | Biomethation has been commercialized for the production of 'Biogas' leading to energy recovery from waste products. Biogas mainly consists of 55-60% of methane gas, along with carbon dioxide and nitrogen giving a high calorific value of 5871 kcal/$m^3$.[42] |
| 10. | Bioremediation | High concentration of waste depletes microbial growth required for decomposition but optimal environmental conditions such as pH, temperature and nutrient content can help revert back the conditions.[29,30] | A cost-effective and eco-friendly approach to manage and degrade solid waste along with the decomposition of inert, harmful, and metal variants from the waste through the microbial attack.[29,30] |

**INTEGRATED SOLID WASTE MANAGEMENT (ISWM)**

'Integrated Solid Waste Management System Hierarchy' proposed by the Municipal Authorities of India suggests the most and least preferred method for the disposal and treatment of solid waste under the Swachh Bharat Mission.[3,20] Following the '4Rs' at the source and opting for Biotechnological approaches such as composting and bioreactor landfills along with the usage of refuse-derived fuel can help in managing solid waste with minimal impact and effect on the environment.[15,43]

## CONCLUSION

Management of Solid Waste through effective measures helps in the sustainable development of the Earth. Biotechnological approaches are quite promising in combating the issue of SWM when combined with Conventional practices. Integrated Solid Waste Management is the need of the hour for managing solid waste with minimal impact on the environment.

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