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LEAD ARTICLE

Mountains of Waste: Can Landfills Help Us Tackle Them?

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Our world is literally drowning in waste.

According to the World Bank, each person in the world generates 0.11–4.54 kg, or an average of 0.74 kg of solid waste daily.[1] This amounts to 2 billion tons of waste every year. At the current rates of human population and urbanisation growth, waste generation is slated to increase by 70% over the next 30 years and the world will be producing 3 billion tons of waste annually by 2050.[1]

Currently, high-income countries, which only account for 16% of the world's population, generate 34% of the world's municipal solid waste.[1,2] From a region-wise perspective, East Asia and the Pacific regions produce the highest amount of waste (23%).[1–4] As of now, more than 50% of all the municipal solid waste in the world is produced by just three countries—The United States of America or USA (258 million metric tons per year), China (220 million metric tons per year), and India (168 million metric tons per year).[3,4]

1 What Happens to the Waste?

Presently, only 19% of the world's waste is recovered through recycling and composting, 11% is incinerated, and the majority of waste (70%) is dumped in open areas (31%) or landfills (37%).[1] Proper waste disposal and treatment in controlled, stringently operated landfills occur only in high and upper-middle-income countries; in such countries, only 2% of waste is dumped in the open. However, low-income countries rely on open dumping for 93% of all their solid waste.[1]

Open dumping and badly constructed landfills cause huge problems as the waste in them age and begin to degrade.

Landfills are major sources of greenhouse gas emissions. As of 2020, data from the United States Environmental Protection Agency (US EPA) indicate that in the USA, landfill gas (made up of roughly 50% methane and 50% carbon dioxide) has contributed 100 million metric tons of greenhouse gases per year over the last decade. This makes landfills the third largest source (15%) of all anthropogenic greenhouse gas emissions after the transportation industry (30%) and cattle flatulence (27%).[5]

In addition, the water percolating through the waste forms a toxic cocktail of chemicals and bacteria called *leachate*, and recent work has shown that untreated landfill leachates are hotbeds of antibiotic resistance.[6]

This is because landfills where urban waste is dumped contain high levels of heavy metals such as cadmium, lead, chromium, copper, iron, and barium, in addition to chemicals from personal care products, pharmaceutical products, and antibiotics.[6,7] Bacteria that can survive in such conditions often have genes that code for efflux pump proteins to expel heavy metals that leak into the cells; such genes can also rid bacteria of antibiotic molecules leading to the development of multidrug resistance.[7,8] More alarmingly, recent work shows that microplastics in leachates act as vectors for bacterial biofilms that carry antibiotic resistance genes.[8,9]

2 The Indian Scenario and the Dangers of Unscientific Dumping

India generates 150,000 tons of solid waste per day, of which 90% is collected. According to the Indian government's Ministry of Housing and Urban Affairs, 20% of the collected waste is processed and the remaining 80% (108,000 tons) goes to dump sites (which are either open areas where garbage is simply deposited or poorly designed landfills).[10]

As of 2019, India has 1684 landfills, which are actually dump sites, with the highest numbers in Madhya Pradesh (378), Maharashtra (320), and Karnataka (215). Yet, the country is struggling to handle the waste it produces. [11]

India's oldest and Asia's largest dumping ground, the 132-acre Deonar landfill in Mumbai, is a ticking time bomb of untreated toxic waste that sits in one of the most densely populated

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areas of the city. Delhi's three landfills at Ghazipur, Bhalswa, and Okhla, are still collecting waste despite being full past capacity. This relentless dumping has caused the garbage piles in Ghazipur and Bhalswa to reach an immense height of 65 m, almost rivalling the Qutub Minar and Taj Mahal in height. In October 2018, a colossal 3-day fire in the 40-acre Bhalswa landfill—caused by the generation of massive amounts of inflammable methane—drove home to the authorities just how dangerous the overloaded and poorly monitored site had become.[12,13]

The Bandhwari landfill in Haryana, which is one of the biggest in North India, has also come under the public eye recently due to fires caused by methane build-up.[14–16] Spanning across 32 acres, this landfill is not only situated in the ecologically sensitive Aravalli forest, but is also regularly visited by wildlife; furthermore, roughly half the area of the landfill is supposed to be under the Aravalli Plantation Project.[14,16] However, unmitigated waste dumping in Bandhwari from nearby cities is slowly poisoning the area around it. The National Environmental Engineering Research Institute (NEERI) in 2019 established that the ground water in several areas around this landfill is heavily contaminated with bacteria and leachate containing heavy metals.[17]

As can be expected, residents and villagers living near these landfills are demanding that these sites be emptied[18] as their presence is not only polluting the air, but also contaminating the ground water, which in turn, is tainting the waters of nearby rivers and other water bodies.

3 A Scientific Approach to Managing Solid Waste: Landfill Principles

In 1992, the International Solid Waste Association (ISWA) defined landfill as "the engineered deposit of waste onto and into land such that pollution or harm to the environment is prevented, and through restoration, the land may be used for other purposes".[19]

However, this statement was not a very good definition as the very nature of a landfill precludes the *prevention* of *pollution or harm to the environment*. Late in the 1990s, as waste generation across the world kept increasing, another issue with conventional landfills soon became apparent: there was simply not enough land to *safely* hold all the waste that was being generated.

To tackle these problems, a new approach to solid waste management was conceived and the idea of a *sustainable landfill* began to take root. Such a landfill would be "designed and operated in such a way that it minimises both short-term and long-term environmental risks to an acceptable level".[20] The key to practising sustainable landfilling is to identify the specific nature of landfill hazards within the context of environmental risks. These risks need to be evaluated by understanding a region's hydrogeology, topography, weather, flora, fauna, and myriad other factors so that the proper location, design, management, and control of landfills could be achieved.[21] Sustainable landfills must be operated such that leachate and gaseous emissions from the landfill into the surroundings are minimised by stabilising the waste (by rendering it non-toxic) quickly and efficiently.[23]

Sustainable landfills are designed to operate on three broad principles, namely, dilution-and-attenuation, containment, or entombment.[21] In most dumpsites without boundary engineering, landfill leachate is allowed to seep into the surroundings under the premise that *dilution and natural degradation* would eventually attenuate the waste. These landfills rely on biological, physico-chemical, and geological processes to reduce the toxicity of the leachate. However, such an approach has not been effective, especially when such dumpsites are close to public water supply systems.[21]

Containment landfills or sanitary landfills, which are common in developed countries, ultimately rely on the dilution and attenuation of toxins in the waste over long periods of time.[21] Such landfills are carefully designed and monitored to collect leachates and contain them until they are treated or released at such slow rates that most pollutants and toxins are degraded/diluted past harmful levels. This ensures that the leakage of hazardous material from the landfill is acceptably low. At present, such landfills must not only manage leachate effluents, but also gas emissions.[21,22]

Entombment is a form of landfilling that operates on the premise of excluding water from the waste. Without liquid infiltration, the waste will not decompose and produce either leachate or gas pollutants. This method will theoretically store waste forever (essentially, until the containment system fails) or until new technologies to deal with the waste are developed.

The final objective of a truly sustainable landfill is to promote the assimilation of waste into the surrounding environment.[21,22]

But as of now, all forms of sustainable landfill are based on short-term containment and ultimately rely on detoxifying waste as quickly as possible. Currently, many pollutants and wastes, especially plastics, require anywhere between 30 years to several centuries to degrade and become non-toxic.[21,22] Given the current rates of human population growth, waste generation, and competition for land, such timelines are simply infeasible. Therefore, it is critical that the processes of degradation and attenuation of toxic wastes in engineered landfills are accomplished in the shortest possible time.

4 New Approaches to Managing Solid Waste: Pre-treatment Options and Bioreactor Landfills

It is clear that the concepts of sustainable landfills that were described in the 1990s and earlier are no longer sustainable enough to manage today's rate of waste generation. Therefore, to manage waste effectively, other options such as recycling, biological processing (such as composting and biomethanation), incineration, and fuel generation through gasification and pyrolysis (where waste is used to create different forms of fuel) need to be practised to reduce waste loads in landfills.[22]

Coupled with this approach, landfills may also be used as waste treatment plants. This allows for quick and efficient degradation of raw or pre-treated waste into stable states that are relatively harmless to environmental health. Such landfills are known as bioreactor landfills and are operated on the premise that by optimising temperatures, moisture content, and aeration, rapid and complete waste degradation can be achieved. A bioreactor landfill can be described as "a sanitary landfill site that uses microbiological processes to transform and stabilise decomposable organic waste within 5–8 years of bioreactor process implementation".[24]

In bioreactor landfills, leachates are collected, stored, treated, and recirculated to enhance waste degradation; sometimes, extra water, sludge, nutrients, and aeration are provided to speed up the process. Bioreactor landfills have several advantages over other conventional landfill types.[24]

First, they are amenable to being used as energy generation systems. Many bioreactor landfills over the last decade have been designed to maximise generation and recovery of landfill gas which serves as a fuel to generate electricity. Much work has gone into understanding how efficiently landfill gas can be captured and how much energy can be recovered from it in the form of electricity.[25,26] In USA, 70% of all bioreactor landfills generate electricity from landfill gas; 1 million tons of landfill waste typically emit 12,200 m^3 of landfill gas per day, which is enough to produce 0.78 MW of electricity.[27]

Second, bioreactor landfills are quite cost-effective in the long run. This is because the compost-like material that is formed at the end of waste degradation in bioreactor landfills can be used as fertiliser, and the landfill cells can be reused, while the landfill gases produced are an extra source of income. Added to this, there is no extra cost of treating leachates separately, and a reduction in the post-closure maintenance and monitoring costs for the landfill.[27]

Third, there is an overall reduction in the environmental impact of the landfill. Since such landfills typically render waste into non-toxic compost in 7–8 years, the contaminating life span of the landfill is considerably reduced when compared to conventional landfills.[24,28] Furthermore, since leachates are collected and treated within the landfill itself, landfill gases are collected for fuel generation, and the final product of waste degradation is a non-toxic compost, the risks associated with environmental hazards are considerably lower for bioreactor landfills.[27]

5 Advances in Landfill Design, Construction, and Management

Over the last 3 decades, much has been learnt about effective ways to construct and run landfills. With this accumulated information, nations can now make informed decisions on the most effective types of landfills and where to locate them based on the nature of waste generated, local environmental factors and hydrogeological features, local weather conditions, road access, and socio-economic factors.[22,29,30]

In addition, there have been many advances in landfill engineering technologies to prevent hazardous materials from leaking out of landfills.[31] Most engineered landfills now have bases and sides reinforced with leachate resistant soil liners and geosynthetic or compacted clay liners. To further ensure that leachates do not enter groundwater systems, geomembranes made of high-density polyethylene are also used. Since the sides and bases of landfills also experience slope-induced shear stresses and other forces, geomembranes are often reinforced with padded layers of geotextiles made of non-woven materials to prevent tearing. Besides these, engineered and bioreactor landfills must also have well-designed leachate drainage and recirculation systems, respectively, in place for efficient functioning. Although there has been much work on the design of such systems, their usefulness and value in Asian are still being evaluated.[32–34]

Conventional landfills that have reached their full capacities are capped using the same type of materials used to line landfills, namely, clay liners, geomembranes, and geotextiles.[35] Capping is done to shield the environment from the accumulated wastes in landfills as they decompose, as well as to prevent rainwater from infiltrating the landfill. When gas-tight membranes are used in capping, they reduce the loss of landfill gas and improve its capture for use as fuel. [36] Another method used to limit water entry into landfills is through *phytocapping*, where the capped landfill is overlaid with soil and plants.[37] The plant canopies intercept rainfall, their roots store moisture in the soil layers, and evapo-traspiration reduces the amount of water that percolates into the landfill. Furthermore, the root microbiota of phytocaps help in oxidising methane from landfill gas leaks. Phytocapping is also being explored as an avenue for carbon sequestration as the vegetation on the landfill can fix the carbon dioxide in landfill gas.[38]

Although most capped landfills are literal wastelands, being contaminated and unusable for decades, they can be used beneficially. In Europe and Australia, pilot initiatives to generate solar energy by installing photovoltaic panels on flat landfill surfaces have been undertaken.[39,40] Solar energy generation often competes for land with other industries as photovoltaic arrays require large tracts of flat land; therefore, the combination of unwanted landfill land with the space requirements for harvesting solar power is convenient.[34]

6 The Economics of Managing Waste: Costs and Profits in Landfilling

In most nations where land is cheap, landfills are the most *immediately economically viable* options for managing waste. However, this really is not so. Due to such landfills being operated as open dumping sites, the hidden costs of environmental pollution and health hazards are overlooked. Ultimately, the price paid for waste management in these situations is far more than the costs of engineered landfills.

According to the US EPA, the construction, operation, and maintenance of a landfill can cost anywhere between 1.1 and 1.7 million US Dollars (US$).[41,42] Despite this, the garbage industry in most parts of the world has outperformed the market since 2015.[42] This is because landfills generate revenue by charging *tipping fees*, a standard rate that needs to be paid for each truckload/ton of garbage deposited in the landfill. On average, privately run landfills in the US charge roughly 54 US$ per ton of waste, which translates to a revenue of about 1.4 million US$ per year for small landfills and 43.5 US$ per year for large landfills.[41,42]

Apart from tipping fees, landfills can also offer alternate forms of revenue, namely, from landfill mining and generation of electricity from landfill gas. A private scrap metal company in the US recovered nearly 37,000 tons of metal worth roughly 7.5 million US$ in just 4 years by mining a landfill. The exercise not only brought in returns from the metal, but also extended the life of the landfill.[43] In the US, landfill gas generates about 10.5 billion kilowatt-hours of electricity every year;[42] at the country's current cost of electricity (roughly 13 cents per kilowatt-hour)[44], this earns approximately 1319 million US$ per year.

In India, the landfill business is worth hundreds and thousands of crores of Indian Rupees (INR). In Mumbai alone, waste management in landfills using a combination of incineration, recycling, and sanitary landfilling is likely to cost anywhere between INR 500 and 1000 crores per year; this estimate does not include collection or tipping fees.[45] The Brihanmumbai Municipal Corporation (BMC) had a budget of INR 30,692 crore for waste management in 2019–20, of which INR 177 crore was set aside for a mega project on solid waste management and INR 100 crore was set aside for a waste-to-energy plant at Deonar.[46] Despite the high cost of land in Mumbai, a well-constructed and properly managed waste management facility could save the city up to INR 640 crore per annum.[47,48]

7 The Ultimate Goal of Waste Management: Sustainability

Waste is not only an environmental concern, but also a resource issue and an ethical matter.[49,50] Between 2002 and 2008, a new philosophy of 'zero-waste lifestyle' gained traction in the USA, where people concentrated on waste prevention rather than end-of-the-line waste management. Zero-waste philosophy encourages changes in resource life cycles such that all products are reused optimally, and no trash is routed to landfills, incinerators, or the ocean.[51]

To practise sustainable waste management, we need to achieve something akin to zero waste. To do so, we must turn our thinking towards understanding how landfills can be utilised within a zero-waste framework. This means that we must swiftly adopt efforts such as landfill mining to extract usable waste, landfill reclamation, and using bioreactor landfills to quickly process waste for safe environmental reassimilation.[52]

We simply cannot leave our waste packed into the earth for our descendants to deal with.

Therefore, one of the keys to sustainable waste management in landfills is to promote rapid turnover of waste into reusable material (at best) and non-toxic matter (at worst) within them.

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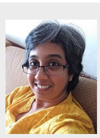

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