

A Critical Study of Sustainable Waste Disposal Practices in the Modern Era

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Abstract: The rapid industrialization and urbanization of the modern era have significantly increased the production of waste, creating immense challenges for sustainable waste management. Traditional methods of waste disposal, such as land filling and incineration, are proving insufficient and unsustainable due to their environmental, social, and economic impacts. Consequently, the necessity for innovative and sustainable waste disposal practices has become a critical area of study. This comprehensive study examines current practices, challenges, and future directions in sustainable waste disposal, analyzing case studies, technological advancements, and policy interventions to provide insights into mitigating environmental impacts and promoting sustainable development in modern societies.

Keywords: Environment impacts, sustainable development, waste disposal practices, waste management, environmental impacts

1. INTRODUCTION

The rapid industrialization and urbanization of the modern era have significantly increased the production of waste, creating immense challenges for sustainable waste management. As global populations rise and consumption patterns shift toward convenience and disposability, waste disposal systems are increasingly strained (Hoorweg & Bhada-Tata, 2012). Traditional methods of waste disposal, such as landfilling and incineration, are proving insufficient and unsustainable due to their environmental, social, and economic impacts. Consequently, the necessity for innovative and sustainable waste disposal practices has become a critical area of study. Sustainable waste disposal is a multidimensional concept that incorporates environmental, economic, and social considerations to minimize the adverse effects of waste on the ecosystem. This approach goes beyond simply reducing waste; it actively encourages recycling, reuse, and resource recovery (Zaman & Lehmann, 2011). By transitioning toward circular economy models, communities and industries aim to achieve a balance between resource consumption and waste generation, thus fostering long-term environmental sustainability (Geissdoerfer et al., 2017). Modern awareness of the environmental consequences of improper waste disposal—including soil and water contamination, and greenhouse gas emissions—underscores the urgent need for effective waste management (United Nations Environment Programme [UNEP], 2021). The challenge of waste management is further compounded by the proliferation of e-waste, the pervasive problem of plastic pollution, and the

dangers posed by hazardous materials, making it crucial to develop innovative strategies and implement robust policy frameworks.

This comprehensive study examines current practices, challenges, and future directions in sustainable waste disposal, analyzing case studies, technological advancements, and policy interventions to provide insights into mitigating environmental impacts and promoting sustainable development in modern societies. Through this lens, the study underscores the importance of integrating sustainability principles into waste management systems to ensure a healthier and more resilient future for all.

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2. OVERVIEW OF WASTE GENERATION

Residential, commercial, industrial, and agricultural operations generate discarded materials, which are collectively known as waste. It encompasses all forms of waste, including solid, liquid, and gaseous materials that are no longer useful and require disposal or management. As global population and urbanization levels rise, waste generation has become a pressing environmental issue, posing

challenges to sustainable development and resource management (United Nations Environment Programme [UNEP], 2021). The scale and composition of waste generation vary significantly across regions and sectors. The amount of municipal solid waste produced per person is considerably higher in high-income countries than in low- and middle-income nations, largely due to increased consumption and the prevalence of disposable packaging (World Bank, 2018). In contrast, low-income countries often generate more organic waste, which is biodegradable but frequently mismanaged due to inadequate infrastructure. Industrial and hazardous waste are other significant components of global waste generation. Industrial activities, such as manufacturing, mining, and construction, contribute to the production of waste materials, including metals, chemicals, and construction debris. Improper handling of hazardous waste, often toxic, flammable, or reactive (EPA), poses significant risks to both human health and the environment. (Environmental Protection Agency [EPA], 2022).

Efforts to mitigate waste generation include waste prevention, recycling, and resource recovery initiatives. Circular economy principles, which emphasize reducing waste and maximizing the reuse of resources, are gaining traction globally as sustainable waste management strategies. Governments and organizations are increasingly adopting policies to minimize waste at the source, improve recycling rates, and promote the development of eco-friendly products (Ellen MacArthur Foundation, 2020). Pollution, greenhouse gas emissions, and public health risks, particularly in urban areas and developing countries, are all exacerbated by poorly managed waste. These environmental and social impacts of waste generation underscore the importance of effective waste management systems. Solutions require collaborative efforts between governments, industries, and communities to promote sustainable practices and reduce overall waste volume.

3. KEY PRINCIPLES OF SUSTAINABLE WASTE DISPOSAL

Effective waste management revolves around three fundamental strategies: reducing consumption, finding new uses for existing materials, and recycling resources (3Rs). By implementing these approaches, communities can decrease waste production, optimize resource utilization, and protect the environment. Modern waste management has evolved beyond these core concepts to embrace innovative models like circular economy and zero-waste initiatives. These advanced frameworks transform traditional waste perception by treating discarded materials as valuable resources that can be continuously reintegrated into production cycles, rather than viewing them as unwanted byproducts.

4. CURRENT SUSTAINABLE PRACTICES

4.1 Recycling Programs

The implementation of recycling initiatives plays a vital role in modern waste management by redirecting materials away from landfill sites and minimizing the need for virgin

resources through material recovery and repurposing. According to the United Nations Environment Programme (2021), these systematic efforts serve multiple environmental objectives: advancing sustainable practices, preserving valuable natural resources, cutting down energy usage, and reducing environmental degradation. As cities continue to expand and waste generation increases, recycling has emerged as a fundamental component of urban waste management infrastructure, becoming particularly crucial in densely populated metropolitan regions where waste volumes reach significant levels.

The effectiveness of recycling programs relies on key factors such as public education, accessible infrastructure, and supportive policies that encourage active participation. In many developed nations, curbside recycling systems have been introduced, enabling households to conveniently sort recyclable materials like paper, plastics, glass, and metals from general waste for efficient collection and processing (World Bank, 2018). These programs often involve a combination of single-stream or multi-stream systems, where single-stream allows all recyclables to be mixed in one bin, while multi-stream requires separating materials into different bins.

Despite the benefits, recycling programs face challenges such as contamination of recyclables, which reduces the quality of recycled materials and increases processing costs (Environmental Protection Agency [EPA], 2022). Fluctuations in the market demand for recycled materials, particularly certain plastics and paper products, can undermine the economic sustainability of recycling programs. To address this challenge, many municipalities have implemented waste reduction policies at the source, such as restrictions on single-use plastics and excessive product packaging (Ellen MacArthur Foundation, 2020). Because waste composition varies by region, recycling programs are often adapted to local needs. Furthermore, some countries use Extended Producer Responsibility (EPR) programs to make manufacturers responsible for their products' entire lifecycle, from production to recycling or disposal (OECD, 2020). By holding producers accountable for the post-consumer stage of their products, EPR programs aim to reduce waste generation and encourage design for recycling. Businesses are increasingly adopting recycling and waste reduction strategies as part of their corporate social responsibility (CSR) commitments, complementing municipal recycling efforts. Industrial recycling programs, in particular, target materials like metals, plastics, and construction debris for reuse in new manufacturing processes (EPA, 2022). While crucial for the transition to a circular economy, where resources are reused and waste minimized, the effectiveness of recycling programs depends on overcoming challenges in collection methods, public engagement, market development for recycled materials, and policy innovation.

4.2 Composting

Microorganisms transform organic waste into nutrient-rich fertilizer through composting, a sustainable waste management practice. This process reduces landfill waste, enhances soil fertility, and mitigates greenhouse gas emissions. Optimal aeration, moisture, and temperature are crucial for the efficient aerobic decomposition of materials like food scraps and yard waste. Farmers can use the resulting compost to significantly improve soil structure and fertility, contributing to sustainable agriculture (Siti et al., 2021). Home-based and community-scale systems are driving the growing popularity of decentralized composting for local organic waste management. This approach lightens the load on centralized systems, provides compost for personal use, and cultivates environmental awareness and local participation in sustainable waste management. (Barrena et al., 2022). Because organic waste in landfills decomposes to produce methane, a powerful greenhouse gas, composting plays a critical role in mitigating climate change by diverting that waste and preventing those emissions. Diverting organic waste to composting facilities significantly lowers greenhouse gas emissions. For instance, studies project that increasing composting practices in the United States could substantially decrease annual carbon emissions (Chen et al., 2022). Despite its numerous benefits, composting faces challenges, such as contamination of compost with toxic substances, which require further research to develop sustainable solutions. Ensuring pathogen removal during the composting process is also vital for producing safe compost. Temperatures above 50°C are often necessary to destroy pathogens and seeds, making the compost suitable for agricultural and horticultural use (Milinković et al., 2019).

Overall, composting is a practical and environmentally beneficial method of organic waste management. It contributes to sustainable development by reducing landfill dependency, lowering greenhouse gas emissions, and producing valuable compost for soil enhancement. Continued research and technological advancements are crucial to address challenges and optimize composting practices for broader adoption and effectiveness.

4.3 Waste-to-Energy (WTE) Technologies

Waste-to-Energy (WTE) technologies refer to processes that convert non-recyclable waste into usable energy, such as electricity, heat, or fuel. These technologies play a dual role in managing waste and generating energy, making them an integral part of sustainable waste management systems. Waste-to-energy (WTE) technologies play a key role in sustainable waste management by reducing the amount of waste sent to landfills (which in turn reduces greenhouse gas emissions) and by generating energy from materials that would otherwise be wasted (Themelis & Bourtsalas, 2019). Incineration is the most prevalent WTE technology, using high-temperature combustion to produce steam that drives turbines for electricity generation.

Modern incineration plants incorporate advanced pollution control systems, significantly reducing emissions compared to older facilities. Other WTE technologies, like gasification and pyrolysis, convert waste into syngas and other usable byproducts (Arena, 2012). The microbial breakdown of organic waste in the absence of oxygen, known as anaerobic digestion, is a popular WTE method. This process produces biogas, a renewable energy source that can replace fossil fuels. (Mattiussi et al., 2020). Despite the benefits, WTE technologies face several challenges. High initial investment costs, public opposition due to concerns about air pollution, and the need for continuous waste input to sustain operations are significant barriers to widespread adoption. Additionally, the environmental impact of WTE facilities depends on the efficiency of energy recovery and the effectiveness of emission control technologies. However, advancements in technology and stricter regulations have significantly improved the efficiency and environmental performance of WTE plants (Tan et al., 2021). WTE technologies are particularly valuable in regions where landfill space is limited or where renewable energy sources are needed to supplement energy demands. Countries such as Sweden, Japan, and Germany have successfully integrated WTE systems into their waste management frameworks, significantly reducing landfill dependency while generating energy to power homes and industries (Zaman & Lehmann, 2013).

While WTE technologies offer a promising approach to sustainable waste management and meeting energy demands, their effectiveness hinges on proper implementation, strong regulatory frameworks, and ongoing innovation to ensure both environmental safety and economic viability.

4.4 Comprehensive Producer Stewardship

Comprehensive Producer Stewardship, often referred to as Extended Producer Responsibility (EPR), represents a policy framework that fundamentally changes how end-of-life product management is handled. It shifts the responsibility from consumers and municipalities to the producers themselves. EPR mandates that producers assume both financial and operational responsibility for the collection, recycling, or safe disposal of their products once they are no longer in use. This approach incentivizes producers to design products with sustainability and recyclability in mind, ultimately leading to reduced waste generation, higher recycling rates, and a smaller environmental footprint. (OECD, 2020). EPR policies are typically applied to industries producing goods with complex waste streams, such as packaging, electronics, batteries, and automobiles. These policies incentivize producers to adopt eco-design principles by incorporating recyclability, durability, and reduced material usage in their product development. For example, electronics manufacturers are encouraged to use modular designs that make disassembly and material recovery easier (Gui et al., 2013).

To tackle waste management challenges, numerous countries have implemented Extended Producer Responsibility (EPR)

frameworks. In the European Union, the WEEE Directive places the financial burden on producers to manage the collection and recycling of electronic waste. Canada and Japan have followed suit with comprehensive EPR programs, addressing waste from packaging and household appliances, respectively (Hotta et al., 2009). These programs demonstrate how EPR can effectively increase recycling rates and reduce landfill dependency.

While EPR policies provide numerous environmental and economic benefits, they also face challenges in implementation. Producers may pass on the additional costs to consumers, leading to higher product prices. Inconsistent regulatory frameworks across regions can also create difficulties for multinational corporations. Moreover, monitoring and enforcing compliance remain critical challenges in many countries (Lindhqvist, 2000). To address these issues, governments and stakeholders are working to standardize EPR practices and improve accountability through transparent reporting and independent audits. Extended Producer Responsibility (EPR) offers a range of benefits, extending beyond simply environmental improvements. It plays a key role in fostering a circular economy by creating new opportunities for industries that specialize in waste recovery and recycling. By incentivizing producers to take responsibility for the entire lifecycle of their products and close the material loop, EPR encourages innovation in product design and contributes to the development of more sustainable production and consumption patterns. As such, EPR is increasingly viewed as an essential strategy for addressing the global waste crisis and transitioning towards sustainable resource management.

5 Challenges in Implementing Sustainable Practices

Achieving environmental, economic, and social sustainability hinges on the widespread adoption of sustainable practices. However, this transition faces significant hurdles across various sectors. One of the most prominent challenges is the financial burden associated with implementing sustainable solutions. Businesses, particularly SMEs, often struggle with the high upfront costs of investing in renewable energy systems, eco-friendly infrastructure, and sustainable materials. This financial constraint is further complicated by limited access to funding opportunities and the prevailing perception that sustainable practices may not generate immediate economic benefits (Cohen et al., 2021). Beyond financial challenges, the implementation of sustainable practices is also hampered by a lack of awareness and education about sustainability. Many organizations and individuals are simply not aware of the long-term benefits that sustainable practices can offer, and even those who are aware may lack the practical knowledge needed to integrate these practices into their day-to-day operations. The problem is compounded by inadequate training and a scarcity of resources for employees, policymakers, and community members, which can lead to

resistance to change and ultimately slow the adoption of much-needed sustainable solutions (Leal Filho et al., 2019).

The implementation of sustainable practices is often hampered by shortcomings in regulatory and policy frameworks. Inconsistent regulations across different regions can create confusion and make it difficult for organizations to implement standardized sustainable practices. Weak enforcement mechanisms can undermine regulations, allowing unsustainable practices to continue unchecked. Furthermore, a lack of sufficient incentives for sustainable practices can discourage organizations from investing in them. These challenges are often amplified in developing countries, where the absence of stringent environmental laws and a lack of governmental support for sustainability initiatives can severely limit progress (UNEP, 2021). Moreover, global supply chains pose additional complexities, as sustainability requires collaboration across borders, industries, and cultures. The success of sustainable practices hinges on consumer behavior. While there is growing awareness of sustainability, many consumers are unwilling to pay a premium for environmentally friendly products or change their consumption habits. This lack of demand can discourage businesses from investing in sustainability initiatives (White et al., 2019). Technological challenges further complicate the adoption of sustainable practices. While advancements in green technologies have been significant, they are not always accessible or scalable, particularly in resource-limited settings. Additionally, existing infrastructure in many regions is not compatible with sustainable solutions, requiring extensive retrofitting or replacement (Markard et al., 2012).

Despite these challenges, the growing emphasis on sustainability in global agendas, such as the United Nations Sustainable Development Goals (SDGs), is fostering a more favorable environment for change. Collaborative efforts among governments, businesses, and communities, along with innovations in technology and policy, are gradually overcoming these obstacles. Financial support, education, strong policy frameworks, and behavioral shifts are all crucial components of a multi-faceted approach to overcoming the challenges of implementing sustainable practices.

6 CASE STUDIES

6.1 Sweden's Waste-to-Energy Success

Sweden has achieved remarkable success in waste management, virtually eliminating landfill waste and establishing a highly efficient waste-to-energy (WTE) system that generates heat and electricity from non-recyclable waste. Currently, 49% of household waste is incinerated to generate energy, while another 49% is recycled or composted, leaving less than 1% sent to landfills. The country's 34 WTE plants produce around 14 TWh of energy annually, with 8-10 TWh used for district heating and 2-3 TWh for electricity. Sweden even imports 1.3–1.5 million tonnes of waste from other

countries, making use of excess capacity to fuel its energy production.

This approach significantly reduces landfill methane emissions, and 99% of pollutants from incineration are captured using advanced filtration technology. Sweden is not only a leader in waste-to-energy but also a pioneer in minimizing the environmental impact of waste. In addition to its highly efficient system for converting non-recyclable waste into energy, Sweden is exploring carbon capture and storage (CCS) technology to further reduce CO₂ emissions. The country also prioritizes resource recovery by extracting metals from the residual ash for recycling and utilizing the remaining material in road construction, effectively closing the loop and supporting a circular economy. Through innovative policies and efficient infrastructure, Sweden has transformed waste management into an environmentally sustainable energy source.

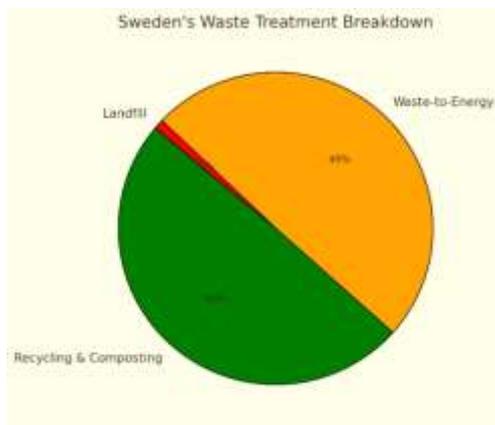


Figure 1. Sweden's Waste Treatment Breakdown [12]

6.2 India's Composting Initiatives

India generates over 150,000 tonnes of municipal solid waste (MSW) daily, with 65% being organic waste. Composting has emerged as a crucial solution to reduce landfill waste, lower methane emissions, and improve soil health. The Swachh Bharat Mission (SBM) and Solid Waste Management Rules, 2016, promote composting at household, community, and industrial levels. Cities like Indore, Pune, and Mysuru have successfully implemented large-scale composting plants, while residential societies and NGOs encourage home composting. The private sector, including waste management startups and CSR programs, further supports composting initiatives. As a result, composting has reduced landfill dependency, improved agricultural productivity, and contributed to a circular economy in India. (Ayilara et al., 2020; Soni et al., 2023; Zurbrügg et al., 2003.

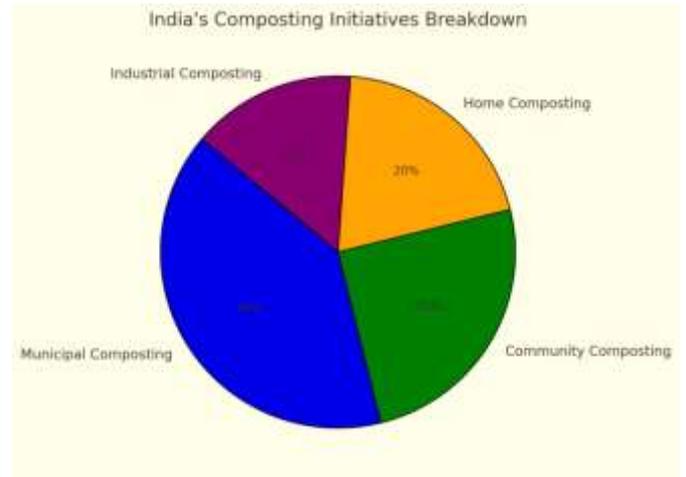


Figure 2. India's composting initiatives breakdown

40% of composting is done at the municipal level, through large-scale plants in cities. 25% is from community composting, including housing societies and markets. 20% comes from home composting, encouraged by NGOs and local initiatives. 15% is led by industrial composting, supported by private companies and fertilizer firms.

7 THE WAY FORWARD FOR WASTE MANAGEMENT TECHNIQUES IN INDIA

India's growing urban population and rising waste generation demand a sustainable and efficient waste management strategy. The key to addressing this challenge lies in strengthening waste segregation at the source, ensuring that households, businesses, and industries separate their waste effectively. Strict enforcement, awareness campaigns, and digital tracking systems can enhance compliance and efficiency. Additionally, expanding composting and biogas technologies is essential, as organic waste makes up over half of India's municipal solid waste. Investing in decentralized composting at the community level and large-scale biogas plants can significantly reduce landfill dependency while producing nutrient-rich compost and clean energy. India's recycling infrastructure needs modernization through formalizing the informal waste sector, integrating waste pickers into the circular economy, and establishing automated sorting and material recovery facilities. The Extended Producer Responsibility (EPR) framework should be strengthened to ensure that manufacturers take responsibility for the lifecycle of their products, particularly in managing plastic and e-waste. While waste-to-energy (WTE) plants can help convert non-recyclable waste into electricity, stringent emission control measures and sustainable incineration technologies must be in place to mitigate environmental risks. Decentralized WTE solutions can also be explored for high-waste-generation urban areas.

India faces a significant challenge in managing its waste, particularly its over-reliance on landfills. To address this, a

Table 1: Comparison with Other Waste Management Techniques

Waste Management Method	Efficiency	Environmental Impact	Cost Effectiveness	Adoption in India
Composting	High	Positive (reduces landfill methane)	Low cost, high ROI	Increasing rapidly
Waste-to-Energy (WTE)	Medium	Moderate (some emissions)	High setup cost	Limited adoption
Landfilling	Low	Negative (methane emissions, land use)	Low cost, but long-term issues	Declining
Recycling	High	Positive	Moderate cost	Growing but faces segregation challenges

fundamental shift towards a circular economy is necessary, where waste materials are prioritized for reuse, recycling, or repurposing rather than being discarded. A robust landfill reduction policy should be implemented, mandating that only inert, non-recyclable, and hazardous waste is permitted for landfill disposal. Furthermore, strengthening the existing Solid Waste Management Rules, 2016, and providing financial incentives to industries that utilize recycled materials can further encourage sustainable waste management practices. Crucially, strict penalties for illegal dumping and non-compliance, combined with the mandatory implementation of Extended Producer Responsibility (EPR), will ensure greater accountability and drive the necessary changes. Public participation is not just desirable but absolutely critical for the long-term success of waste management initiatives in India. Nationwide behavioral change campaigns can play a vital role in raising awareness and promoting responsible consumption and waste disposal practices. Integrating waste management education into school curricula will help instill these habits in future generations. Furthermore, the use of digital waste management tools can empower citizens to actively participate in the process. By effectively integrating policy support, technological innovation, and community involvement, India can achieve its goal of a sustainable, circular, and zero-waste model, paving the way for a cleaner and greener future.

8. ROADMAP WASTE MANAGEMENT TECHNIQUES IN INDIA

Waste management in India is a complex process designed to handle various types of waste sustainably. The process begins with segregation at the source, where households, industries, and communities separate their waste into distinct categories: dry waste, wet waste, hazardous waste, and e-waste. Public awareness campaigns often accompany this step to educate citizens about proper waste disposal practices. Segregated waste is then collected through door-to-door collection systems, with specialized vehicles transporting the waste to appropriate processing facilities. For recyclable materials, Material Recovery Facilities (MRFs) play a key role, sorting and processing materials such as paper, plastics, glass, and metals. Organic waste is typically managed through composting methods, including both aerobic composting and vermin-composting. For waste that cannot be recycled, India utilizes waste-to-energy (WtE) technologies, including incineration and biogas production, to recover energy from non-recyclable waste. However, some waste still ends up in sanitary landfills, where careful management of leachate and landfill gas is essential to minimize environmental impact. A significant aspect of the waste management strategy is Extended Producer Responsibility (EPR), where producers take responsibility for the waste generated by their products, particularly packaging and electronics, through collection and recycling programs.

India's approach to waste management involves both regulatory measures and public engagement initiatives. On the regulatory front, the government has implemented several key policies, including the Solid Waste Management Rules 2016, the Plastic Waste Management Rules, and the E-Waste

Management Rules. These rules place specific obligations on local governments and producers, requiring them to adhere to established protocols for waste management, with a particular focus on the proper disposal and recycling of plastic and electronic waste. Complementing these regulatory efforts, public participation and awareness programs play a pivotal role in promoting sustainable waste management practices. These programs actively involve communities, schools, and corporate sectors, fostering a culture of sustainability and encouraging responsible waste management behaviors. Collectively, these steps create a robust framework for managing waste in India, though challenges such as infrastructure gaps, enforcement, and behavioral change remain. Effective implementation of these techniques and continued public awareness are keys to managing waste sustainably.

9. CONCLUSION

India's waste management landscape is complex, with a mix of traditional and modern techniques. While land-filling remains prevalent, there's a growing emphasis on more sustainable methods like recycling, composting, biogas generation, and waste-to-energy. The successful implementation of these techniques, along with the exploration of emerging technologies, hinges on several crucial factors. A comprehensive approach is essential to tackling India's waste management challenges. This includes widespread public awareness and education about waste segregation and responsible disposal, robust policy frameworks and enforcement, continuous investment in technological advancements, and active community participation. By prioritizing these elements and embracing a circular economy, India can effectively minimize its environmental impact and create a cleaner, healthier future. This transition requires a concerted effort from individuals, communities, industries, and governments to build a more sustainable and integrated waste management system.

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