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RESEARCH ARTICLE

ADVANCEMENTS AND CHALLENGES IN ACHIEVING SUSTAINABLE WASTE MANAGEMENT IN INDIA

Leela Kaur*

Department of Environmental Science, Maharaja Ganga Singh University, Bikaner (Rajasthan) - 334004, India.
****Corresponding Author Email: leela.kaur@gmail.com***

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ABSTRACT

India's pursuit of sustainable waste management has witnessed notable technology advancements. Waste to energy technologies convert waste into energy carriers such as electricity and heat. Waste to energy solutions contribute to circular economy objectives by minimizing waste output and increasing efficiency in resource use. These processes encompass thermal techniques like combustion, gasification, and pyrolysis, along with biological methods including anaerobic digestion and landfill gas capture. Advantages of waste to energy include diverting waste from landfills, extracting valuable resources, producing renewable energy, and mitigating environmental impacts. Challenges such as public perception, technological innovation, cost-effectiveness, and integration with other waste management approaches should be considered for successful implementation. Achieving a sustainable and resource-efficient future requires embracing waste to energy technologies worldwide. By converting waste into energy and resources, waste to energy plays a crucial role in enabling the circular economy. India is now facing a huge garbage problem, creating an immediate demand for sustainable ways to curb environmental pollution and resource depletion. By combining sustainable waste management with energy recovery, waste to energy technologies offer a promising solution to move towards circular economy goals. The present paper analyses the existing scenario of waste pollution with vision of waste circularity. It explores the potential of waste to energy technologies in India, examines their environmental and economic implications, and highlights challenges and opportunities in their adoption.

KEYWORDS

Waste management, Innovation and Technology, Waste to Energy, Circular economy, Sustainable resource management.

1. INTRODUCTION

Globally waste is the outcome of industrialization and urbanization. It is growing significantly due to population rise. According to World Bank estimates, 2.24 billion tonnes of waste was generated in 2020 and it is likely to be increased by 3.88 billion tonnes in 2050 (World Bank, 2022). Waste pollution which is considered a global crisis, is disrupting human and environmental health. It contributes to the triple planetary crisis of climate change, biodiversity loss, and pollution (UNEP, 2025). The Global Waste Management Outlook Report divulges that the direct cost of waste management in 2020 was USD 252 billion which would possibly attain USD 640.3 billion by 2050 (Global Waste Management Outlook Report, 2024).

Figure 1 depicts projected waste generation and cost of waste management at the global scale by 2050 which shows both would increase at the accelerated rate. The report says that the operational waste management strategies could save up to $270.2 billion. Also, adopting a circular economy model could bring in an extra $108.5 billion each year. The report wants stakeholders to act right away to reduce waste and see it as a resource.

The market for waste-to-energy technologies is growing, though, because more waste is being made, energy costs are high, people are worried about the environment, and there is not enough space for landfills. They also help cut down on the amount of waste and greenhouse gases that are released into the air.

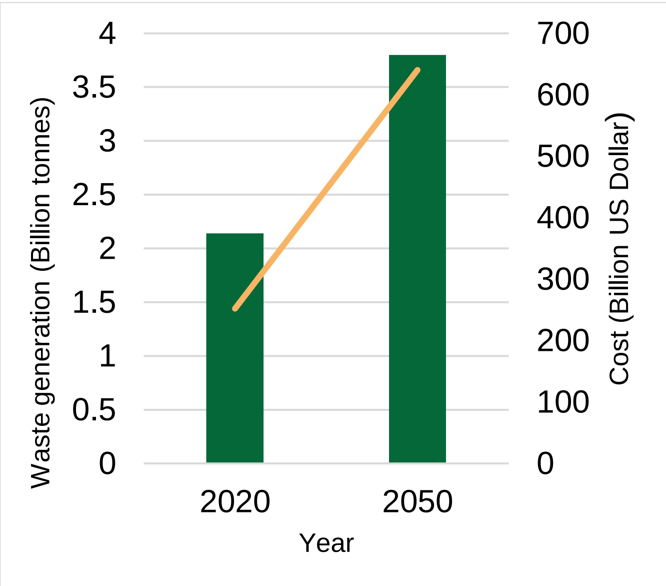

Figure 1: Projected waste generation and cost of waste management at the global scale by 2050.

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India is the most populous country in the world with current population of 1.46 billion people which may reach to 1.67 billion in 2050. The trend of waste generation is a like. 62 million tonnes of municipal solid waste isgenerated in 2020 and it is projected to be enhanced by 13 times in 2050 as illustrated in Figure 2.

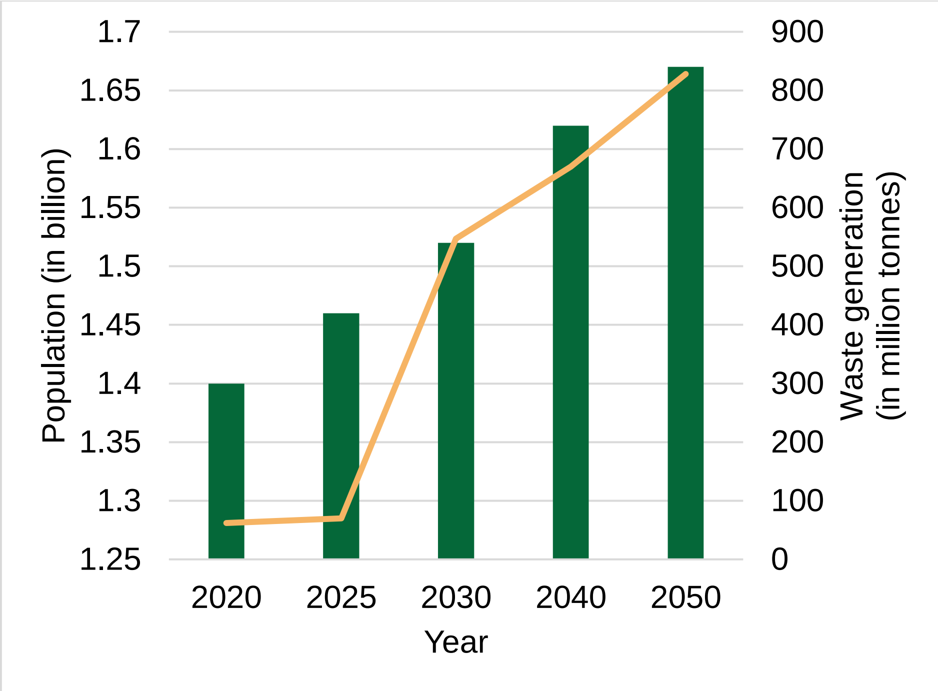

Figure 2: Nexus between population and waste generation of India.

The United Nations General Assembly has designated 30 March as the annual International Day of Zero Waste, starting in 2023, to promote zero-waste initiatives that support the 2030 Agenda for Sustainable Development. The observance is facilitated by UNEP and UN-Habitat to raise awareness about zero-waste practices. The 2025 Zero Waste Day is focused on the fashion and textile sector, highlighting the environmental and social challenges of its current linear business model and promoting scalable solutions within the industry (UN Habitat, 2025). The UNEP Beat Waste Pollution page provides a comprehensive overview of how unsustainable production and consumption habits have escalated the waste pollution crisis. Embracing a lifecycle approach can help reduce waste generation. This involves prevention, reduction, recycling, and reuse. By changing upstream dynamics, such as materials redesign and shifting consumption mentality, we can halve projected global MSW generation by 2050 (UNEP, 2025). The paper provides various aspects of waste to energy technologies and their contribution in circular economy and sustainable resource management.

2. Waste to Energy Technologies

Municipal solid waste (MSW) can be classified into six categories i.e., organic waste, paper, plastic, glass, metals, and other wastes such as textiles, wood, rubber, leather, etc. Globally around 44 % MSW is organic waste; 38 % is recycling waste including plastic, glass, metal, cardboard and paper. The rest 18 % waste is wood, rubber and leather, and other wastes (Figure 3). Whereas, in the context of India, MSW consists of 40% to 55% of biodegradable organic waste, 10% plastics, 6% of paper and 32% others. The representative composition of municipal solid waste includes wet waste (53.7%), dry waste (10%) and inert waste (37.25%) (CPCB, 2025).

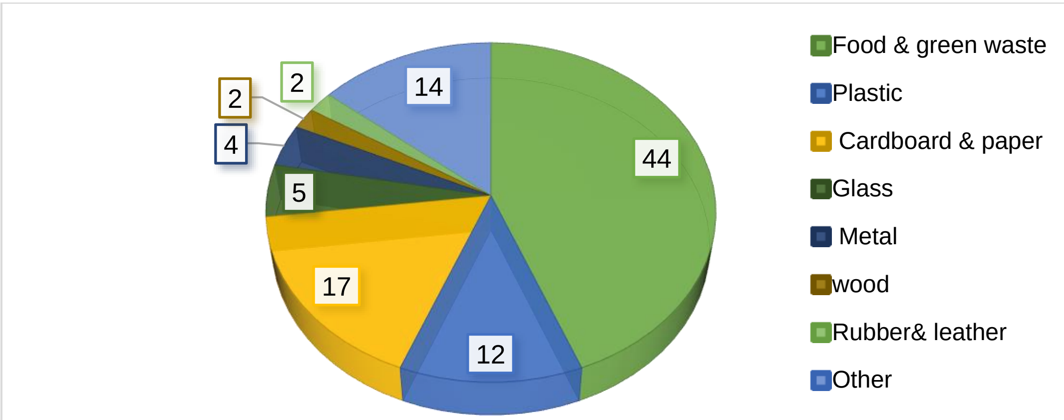

Figure 3: Global composition of municipal solid waste.

The problem of MSW management could be lessened by adopting waste to energy technologies. Waste-to-energy technologies turn trash that can't be recycled into useful forms of energy, like heat, fuels, and electricity.

These technologies include gasification, pyrolysis, anaerobic digestion, incineration, and landfill gas recovery (Table 1). Thermo-chemical and biological processes are the main types of waste to energy technologies. Combustion, pyrolysis, and gasification are all examples of thermo-chemical processes. On the other hand, biological processes include anaerobic digestion and bioethanol fermentation. These technologies give us cheap ways to get energy that are very important for industrial processes like drying, packaging, and storing industrial goods. Generally, thermal technologies convert the waste directly into heat energy while thermo-chemical and biochemical ones first convert the waste into secondary energy carriers such as syngas, torrefied pellets, biogas, bioethanol and biooil, which can subsequently be burnt (in furnaces, steam turbine, gas turbine or gas engine) to produce energy in the form of heat and/or electricity (Lee et al., 2023; Quan et al., 2026). The conversion of solid wastes into secondary energy carriers allows for a cleaner and more efficient energy harnessing process (Gumisiriza et al., 2017).

Table 1: Waste to energy technologies and their characteristics.

Technology	Types	Characteristics
Thermal Conversion Technologies		The waste goes through thermal treatment using technologies that alter the material by high-temperature treatment.
	Incineration	The incineration process is the primary waste-to-energy method in which incinerators burn waste material through controlled combustion at high temperature. The electricity that the power plant generates is through its heat system that creates steam.
	Gasification	The process of gasification occurs when waste material is subjected to high temperatures within a controlled oxygen atmosphere, resulting in the conversion of the material into syngas. The resulting syngas can be used to produce power and heat or used as a fuel for vehicles.
	Pyrolysis	The pyrolysis process is the thermal degradation of waste in the absence of oxygen to yield a solid residue or char, as well as a liquid product or oil, and a gaseous product or combustible gas. The materials generated can undergo recovery for energy or can be utilized as a necessary raw material in a different manufacture process.
Biological Conversion Technologies		The procedure utilizes biological processes to convert organic waste materials into energy in biological conversion technologies.
	Anaerobic Digestion	Micro-organisms breakdown organic material through anaerobic digestion which results in the formation of biogas consisting mostly of methane and carbon dioxide. The biogas generated is used to produce electricity, generate heat and fuel vehicles.
	Landfill Gas Recovery	Methane, a potent greenhouse gas, is produced by landfills through the natural breakdown of organic waste materials. Methane can be used for electrical energy generation or other energy applications through the use of landfill gas recovery systems.

Because of the way Indian MSW is made up, anaerobic digestion and composting work best for organic waste, while incineration and gasification work best for dry waste that cannot be recycled. These technologies are especially helpful because they deal with the problems of high calorific value and moisture content in waste that can't be recycled, making sure that energy recovery works well (Begum et al., 2023; Hasan et al., 2023). Because MSW has a low calorific value, burning it does not produce enough thermal energy. To get more energy out of MSW, it is pre-treated to make refuse-derived fuel (RDF). There are 544 waste-to-energy plants in India (Malav et al., 2020). 39% of this is composting, 38% is vermicomposting, 15% is biogas, and 8% is RDF. Figure 4 shows facilities for waste to energy technologies in India.

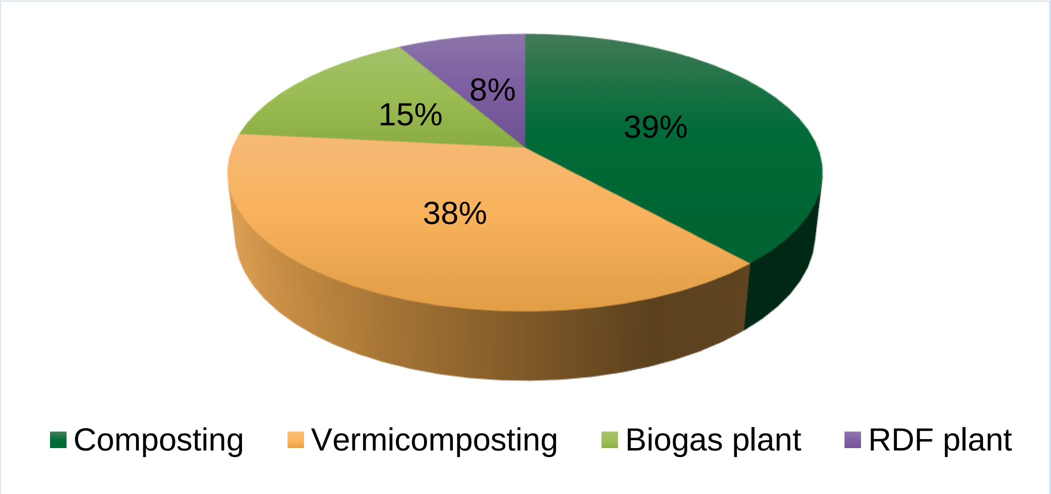

Figure 4: Facilities for Waste to energy technologies in India (Adapted from: Malav et al., 2020).

Analytic Hierarchy Process is applied for evaluating these technologies based on technical, economic, environmental, and socio-cultural criteria. On a general note, anaerobic digestion should be the first choice of technology for municipal solid waste management, while hydrothermal carbonization and incineration should be considered the next options if environmental concerns are put as a first priority in decision making.

Anaerobic digestion: This process completely depends on the microorganisms to first break down and then convert organic wastes into biogas and digestate without oxygen. Presently, this technology is gaining wider acceptance as a viable solution for sustainable waste management, particularly in those urban areas where the amounts of waste generated are very high and the availability of the landfills space is limited. The main products of this waste treatment are biogas which in turn can be used for both the generation of power and heat and digestate which can be a good source of fertilizer if its composition meets the requirements. Besides being carried out in controlled environments such as anaerobic digesters, this same principle is exploited to recover biogas from landfill sites during natural decomposition of the waste. The list of environmental advantages of this technology is very long when compared to traditional ways of waste management like landfilling and incineration. The technology has a very minimal impact on the environment when assessed across various impact categories but especially concerning emissions and effects on the climate change. Differently from landfills that are a major source of emissions of carcinogenic substances and other pollutants, anaerobic digestion systems emit much lower levels of air pollutants and greenhouse gases and hence their reduced impact on air quality and climate change. Moreover, it produces a renewable energy source as biogas which helps in reducing fossil fuels dependency. With the advancement in technologies, anaerobic digestion is anticipated to expand its financial capability.

Refuse-Derived Fuel (RDF): Municipal solid waste (MSW) has the potential to generate 1700 MW of energy recovery through refuse-derived fuel (RDF) from urban waste in India which serves as a sustainable alternative to fossil fuel resources (Kothari and Thorat, 2014; Shukla and Srivastava, 2017).

Densified Refuse Derived Fuel (d-RDF) represents a newly developed technology which produces high energy output through its creation from municipal solid waste materials including plastics and paper and cardboard. The process of converting waste into solid fuel creates multiple advantages which include better waste transportation methods and decreased dioxin emissions during incineration and enhanced energy performance. Co-incineration plants gain economic advantages from this process which enables India to produce energy while protecting the environment and creating job opportunities. RDF plant development will establish supporting systems which enable smart cities to achieve self-sustaining operations.

The Okhla waste to energy plant (Delhi) processes 1,950 tonnes of waste daily, generating 16 MW of electricity. The project proves its ability to handle emissions challenges which must be solved before waste-to-energy systems can achieve widespread implementation. Pune's decentralized biogas plants convert organic waste into biogas for local use, showcasing a scalable model for medium-sized cities.

3. Circular Economy and Sustainable Development Goals (SDG)

The circular economy model requires organizations to decrease waste production while implementing waste reduction activities and developing systems for material reuse and recycling. The primary function of waste-to-energy technologies serves to accomplish project goals through two specific pathways. First, waste-to-energy technologies operate to prevent waste from entering landfills which serve as primary environmental pollution sources through their emissions of greenhouse gases and their production of groundwater contamination. Waste-to-energy technologies create an environmentally friendly waste management solution which transforms waste products into energy through the waste-to-energy process, thereby decreasing the amount of waste that will end up in landfills. Waste-to-energy technologies enable the extraction of essential resources from waste material through their capacity to process waste.

The incineration process generates ash which contains metals and other valuable materials that can be extracted as reusable resources. The acquired resources enter production processes as reusable materials which create a system that enables organizations to manage resources through circular resource management practices. Waste-to-energy systems generate renewable energy through their ability to convert waste energy output into usable energy resources. The process enables users to decrease their fossil fuel dependence, which results in environmental advantages through climate change mitigation and energy security advancement. Waste-to-energy systems provide a less harmful environmental solution since they generate lower greenhouse gas emissions and environmental effects than traditional waste disposal methods which use landfills. Waste-to-energy systems enable organizations to decrease their environmental impact through their capability to extract energy from waste materials.

Waste-to-energy systems operate as standalone systems, which organizations can combine with other circular economy systems that focus on waste reduction and material reuse and recycling. The implementation of successful waste separation and recycling programs enables waste management systems to reduce their processing needs for waste conversion operations which results in increased system performance. The industrial sector of India which generates substantial GDP revenue acts as a major natural resource consumer and produces significant waste and pollution. Patil et al. (2024) emphasized on the principle of circular economy that waste can be a resource through practices like sharing, reusing, and recycling. Circularity offers benefits such as waste management, decarbonization, and resource conservation. However, challenges remain in scaling up industrial waste circularity. By diverting waste from landfills, waste to energy technologies mitigate greenhouse gas emissions and groundwater contamination. Table 2 compares the environmental impacts of various waste to energy technologies.

Table 2: Environmental impacts of various waste to energy technologies.

Technology	GHG Emissions Reduction	Energy Recovery Efficiency	Residual Waste
Incineration	High	20–30%	Ash (~10%)
Anaerobic Digestion	Moderate	50–60%	Digestate
Gasification	High	60–80%	Minimal

The challenges of waste to energy technologies are high capital cost, waste segregation and policy gaps. It costs a lot of money to build a waste-to-energy plant. Not separating sources makes waste-to-energy processes less effective. Though, not having clear rules and incentives is also a problem. The government has put in place market-based Extended Producer Responsibility (EPR) rules to deal with trash from plastic packaging, batteries, e-waste, used tires, and used oil. These rules set clear goals for incorporating recycled materials, reusing, recycling, and refurbishing, which all support a circular economy. India is a member of the Global Alliance for Circular Economy and Resource Efficiency (GACERE). This group works with both government and non-governmental organizations to push for a fair global shift to a circular economy and better resource management. India is also a member of the International Resource Panel (IRP) Steering Committee which gives us authoritative scientific assessments. These assessments help us make policies for natural resource use. Waste, to energy technologies are very useful. They can really help us achieve the Sustainable Development Goals (SDGs). These technologies are related to five SDG goals which are SDG 7, SDG 9, SDG 11, SDG 12, and SDG 13 as shown in Figure 5 (Alam et al., 2022).

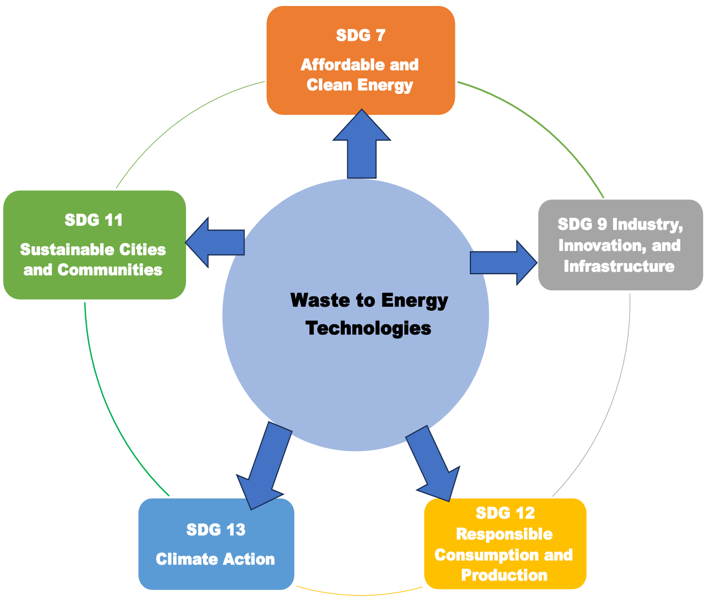

Figure 5: Contribution of waste to energy technologies in SDG goals.

The nexus of waste to energy technologies and these SDG goals are discussed as follows:

- SDG 7 (Affordable and Clean Energy): Waste to energy technologies can generate electricity and heat from waste, thereby reducing dependence on fossil fuels and promoting a cleaner energy mix. Rural communities that are located in areas that are distant from power grids can benefit from the decentralized power waste to energy plants can provide. By using this technology, rural India can have increased access to electricity. Waste to energy is helping to create a better world by decreasing our use of fossil fuels and increasing accessibility to energy.
- SDG 9 (Industry, Innovation, and Infrastructure): Waste to energy technologies have the potential to transform the waste management and renewable energy sectors through innovation, new technologies, and creation of job opportunities. Establishing waste to energy plants can help in building sustainable infrastructure in both urban and rural areas. Therefore, waste to energy technologies contribute by advancing technologies and building infrastructures.
- SDG 11 (Sustainable Cities and Communities): Waste to energy technologies not only address the issue of rapidly growing municipal solid waste by offering a sustainable solution for Indian cities but also reduce the volume of landfills and their environmental impacts. By converting waste into energy, these technologies could help in reducing air and water pollution that result from the indiscriminate dumping of waste. Thus, waste to energy is contributing by improving waste management and reducing pollution.
- SDG 12 (Responsible Consumption and Production): Waste to energy technologies is in line with the circular economy concept, as they turn waste from something to be disposed of into a valuable resource while also reducing the amount of waste generated and encouraging the efficient use of resources. Besides, it extracts valuable materials from waste through recycling or reuse, indicating promotion of waste circularity.
- SDG 13 (Climate Action): Waste-to-energy technologies can greatly cut down on the greenhouse gases that landfills release, which is a big source of methane emissions. These technologies help the renewable energy sector by reducing our dependence on fossil fuels, which helps to fight climate change. So, waste-to-energy technologies are helping the environment by cutting down on greenhouse gas emissions and providing a source of renewable energy.

Waste-to-energy technologies have a lot of potential, but they are hard to put into practice because they are expensive at first, need new technology, and people need to be willing to accept them. To overcome these challenges, it is recommended to:

- Invest in research and development to improve the efficiency and cost-effectiveness of waste to energy technologies.
- Develop policies and incentives to encourage the adoption of waste to energy technologies in waste management systems.
- Educate the public and stakeholders about the environmental and economic benefits of waste to energy technologies.

4. Conclusion

Waste to energy technologies can be a sustainable solution for MSW management. Although there are barriers to its implementation on a larger scale, the technology provides many environmental benefits and could help to increase renewable energy production in the future.

It will need more focus and governmental policies supporting its use. Waste to energy technologies can benefit India and allow them to reach their goals. Hence, India should focus on waste to energy technologies to help them reach their SDGs and create a sustainable future.

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