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Green chemistry for sustainable waste management

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Abstract
Waste generation has grown rapidly alongside urbanization, industrial development, and modern consumption patterns, posing severe threats to the environment, public health, and climate stability. Traditional “end of pipe” approaches—collecting, treating, and disposing of waste—often shift pollution from one medium to another and create new environmental burdens. Green chemistry, guided by its 12 principles, offers a transformative framework for preventing waste at its source, designing safer materials, and converting unavoidable waste into valuable resources. This review explores the intersection of green chemistry and waste management, focusing on how strategies such as biocatalysis, catalytic conversion of waste into fuels and chemicals, solvent free and energy efficient processes, water treatment, bio refineries, and biodegradable product design can reduce the volume, toxicity, and persistence of waste. Real world case studies from India including rice straw to ethanol bio refineries, biogas plants for rural energy, catalytic plastic to fuel conversion, treatment of textile effluents, and compostable packaging demonstrate the practical application and benefits of these approaches.

Keywords: Waste generation, green chemistry, waste management, biocatalysis, catalytic conversion, bio refineries

Introduction
The growth of population, urbanization, and industrial activity has led to a sharp rise in the volume and diversity of waste produced worldwide. In India, millions of tones of municipal solid waste, agricultural residues, industrial effluents, and plastic waste are generated each year. Much of this waste ends up in open dumps, landfills, or incinerators. These practices not only occupy land but also release greenhouse gases such as methane and carbon dioxide, contributing to global warming [1]. Leachate from poorly managed landfills contaminates groundwater, while open burning emits toxic gases, worsening air quality and public health. Climate change exacerbates waste management challenges: floods spread untreated waste; extreme heat accelerates decomposition and odour, and energy demands for waste treatment rise. This vicious cycle between waste generation and climate impacts underscores the urgency for cleaner and more sustainable waste solutions.
Green chemistry is often described as chemistry that prevents pollution rather than treating it after it occurs [2]. It focuses on designing chemical processes and products that minimize the use and generation of hazardous substances, reduce waste at the source, save energy, and use renewable raw materials wherever possible. Instead of relying on toxic solvents or harsh reactions, green chemistry promotes safer alternatives like using water or plant based solvents, energy efficient catalysts, and biodegradable materials. In essence, it is a problem preventing approach rather than a problem fixing one.
Traditional waste management methods such as incineration, land filling, and chemical heavy treatments often create new environmental problems while trying to solve existing ones. For example, burning waste releases harmful emissions, while using strong oxidizing agents to treat effluents leaves behind toxic by products [3]. Green chemistry offers a shift in mindset: instead of merely disposing of waste, it seeks to transform waste into a resource.
By adopting green chemistry principles, industries can reduce their raw material use, lower energy consumption, and produce less waste in the first place. Waste that is unavoidable such as agricultural residues or plastic scrap can be converted into fuels, fertilizers, or value added chemicals using cleaner, more efficient processes. This approach not only cuts pollution but also supports a circular economy, where materials are reused and recycled rather than discarded. This review aims to bring together current knowledge and practical insights on how green chemistry can make waste management safer, cleaner, and more sustainable.

Principles of Green Chemistry

Green chemistry was introduced by Paul Anastas and John Warner in 1998 [2] as a framework for designing chemical products and processes that prevent pollution at its source rather than dealing with it after it forms. The 12 principles they proposed act like a checklist for scientists, engineers, and industries striving to make chemistry safer for people and the planet.

- **Prevention:** The first principle states: "It is better to prevent waste than to treat or clean it up after it has been created." By redesigning reactions to avoid by products, industries can cut waste before it exists saving energy, raw materials, and disposal costs.
- **Atom Economy:** A reaction with high atom economy converts most reactant atoms into the desired product, leaving little waste behind. For example, catalytic hydrogenation often has better atom economy than traditional reduction reactions that create large salt residues.
- **Less Hazardous Chemical Syntheses:** Green chemistry encourages processes that generate minimal toxicity for workers, consumers, and the environment. Using milder oxidants or avoiding carcinogenic intermediates reduces the risk of hazardous waste streams.
- **Designing Safer Chemicals:** This principle reminds chemists to think about a product's hazard profile throughout its life cycle. A detergent that biodegrades easily and does not bio accumulate reduces long term pollution.
- **Safer Solvents and Auxiliaries:** Traditional chemistry frequently relies on volatile organic solvents that are flammable, toxic, or difficult to recover. Green chemistry promotes the use of water, supercritical CO_2, ionic liquids, or bio based solvents, or even eliminating solvents entirely where possible reducing solvent waste and worker exposure.
- **Design for Energy Efficiency:** Processes that run at lower temperature or pressure, or use renewable energy sources such as solar or microwaves, save energy and cut the emissions tied to energy generation. Energy efficient processes also reduce the indirect waste of fuel and associated by products.
- **Use of Renewable Feedstock:** Instead of relying exclusively on petroleum based raw materials, green chemistry makes a case for the use of renewable, plant or waste derived feedstock for example, converting agricultural residues into bio ethanol or bioplastics. This not only conserves resources but also turns organic waste into a resource.
- **Reduce Derivatives:** when a protecting or blocking groups are added to a molecule and later removed, extra reagents and waste are generated. By avoiding unnecessary derivatization, reactions become shorter, cleaner, and cheaper.
- **Catalysis:** Catalysts whether metal based or biological like enzymes speed up reactions without being consumed, allowing smaller quantities of reactants and milder conditions. Catalytic processes typically produce less waste than reactions using stoichiometric reagents that end up as by products.
- **Design for Degradation:** Products should be designed in a way that they break down into harmless substances after their useful life. Biodegradable plastics that decompose into CO_2 and water prevent persistent waste such as microplastics in soil and oceans.
- **Real Time Analysis for Pollution Prevention:** Monitoring reactions as they occur using sensors or in line analytical tools helps detect unwanted by products early, allowing operators to adjust conditions and prevent the formation of hazardous waste.
- **Safer Chemical for Accident Prevention:** Choosing non volatile, non explosive, or less reactive chemicals lowers the risk of industrial accidents like leaks, fires, or spills events that often generate large amounts of contaminated waste during clean up.

Relevance to Waste Management

These 12 principles contribute to reducing the volume, toxicity, and persistence of waste or to reusing waste as a resource. Prevention, atom economy, catalysis, and reduced derivatives limit how much waste is created. Safer chemicals, safer solvents, and design for degradation ensure the remaining waste is less harmful. Energy efficiency and renewable feedstock cut the indirect waste linked to fossil fuel use. Real time analysis and inherently safer chemistry reduce the chance of accidents that generate emergency waste. By using these principles in industrial and municipal practices, societies move closer to a circular economy where materials flow in loops rather than end up in landfills or the atmosphere.

Current Waste Management Challenges

Modern waste management is more than just a technical task it is tied to human habits, economic priorities, and environmental limits. To understand why green chemistry matters, we first need to look closely at the problems facing existing waste management systems. These challenges vary across sectors, but together they showcase as to why traditional approaches are no longer enough [5].

Municipal Solid Waste: Cities and towns generate mountains of mixed waste food scraps, plastics, paper, packaging, textiles, and e waste.

Unsegregated collection: In many cities, households do not separate biodegradable waste from recyclables. As a result, plastics are mixed with organic waste, making both harder to recycle or compost.

Landfills under stress: Open dumps and overfilled landfills leak toxic leachate into soil and water, while decomposing food waste releases methane, a potent greenhouse gas.

Open burning: Where landfill space is scarce, waste is often burned in the open, producing fine particulate matter ($PM_{2.5}$), dioxins, and other harmful pollutants.

Recycling gaps: Informal recycling workers do recover some plastics and metals, but much recyclable material still ends up in dumps because of poor infrastructure and markets.

Agricultural Residues and Biomass

Farming leaves behind large volumes of straw, husks, and stalks. Traditionally, these residues were ploughed back into the soil or used as animal fodder, but large scale mechanized harvesting and shrinking storage space have changed practices [5].

Stubble burning: Farmers often burn leftover crop stubble to clear fields quickly, releasing smoke, soot, and greenhouse

gases, which worsen air quality and climate change.
Loss of potential resource: Instead of becoming bio fertilizer, compost, or bio fuel feedstock, this valuable biomass is wasted.
Seasonal surges: Residue production is seasonal, causing peaks that local waste systems cannot handle.

Industrial Waste
Industrial activity from textile dyeing to tanneries, from fertilizer plants to metal finishing units produces a mix of liquid effluents, chemical sludge, solvent vapours, and solid by products [6].
Toxic effluents: Many factories still discharge untreated or partially treated wastewater into rivers, harming aquatic life and public health.
Hazardous residues: Sludges often contain heavy metals or persistent organic pollutants that require specialized disposal.
Resource loss: Valuable metals, solvents, and energy embedded in this waste are often discarded rather than recovered.

Plastic and Packaging Waste
Plastic has transformed modern life but has also become one of the most visible environmental challenges [7].
Single use plastics: Bags, straws, multilayer packaging, and Styrofoam items are difficult to collect and recycle.
Microplastic pollution: Over time, plastic waste breaks into microscopic fragments that contaminate soil, water bodies, and even food chains.
Recycling bottlenecks: Mixed polymers and contamination by food waste reduce recyclability, leading to more incineration or land filling.

Electronic and Hazardous Waste
The rapid turnover of gadgets creates e waste containing lead, cadmium, mercury, brominated flame retardants, and rare earth metals[8].
Informal recycling: Much of the dismantling is done by informal workers without safety gear, releasing toxic fumes and creating new hazardous waste.
Lost resources: Precious metals like gold, palladium, and copper are often not efficiently recovered, representing both an environmental and economic loss.

Health and Climate Impacts
Air and water pollution: Poorly managed waste contaminates rivers, lakes, and groundwater while contributing to urban smog.
Greenhouse gas emissions: Methane from landfills, nitrous oxide from composting, and CO_2 from burning waste all add to climate change.
Public health burden: Outbreaks of vector borne diseases like dengue or cholera often spike where waste piles up in open spaces.

Systemic Barriers
Limited awareness: Communities may lack knowledge about segregation or sustainable disposal practices.
Inadequate infrastructure: Waste collection trucks, treatment plants, and segregation facilities are often insufficient for growing populations.
Economic pressures: Short term cost saving frequently outweighs investment in long term sustainable systems.

Traditional methods collect, treat, and dump cannot keep up with the sheer volume and complexity of modern waste. They often shift pollution from one medium (solid) to another (air or water). Green chemistry offers a different mindset: redesigning products and processes to reduce or eliminate waste before it is created and making unavoidable waste easier to treat or reuse [9].

Green Chemistry Approaches to Waste Management
Several approaches are emerging that reduce the volume, toxicity, and persistence of waste while recovering valuable materials. One of the most promising strategies is biocatalysis and enzymatic treatment. These methods use enzymes or whole microorganisms as natural catalysts to transform waste under mild conditions often at room temperature and in water [10]. Enzymes break down food scraps, textile dyes, and crop residues into compostable materials or smaller, less harmful molecules. Anaerobic digestion in rural biogas plants converts animal manure and kitchen waste into methane rich gas for energy and a nutrient rich slurry that serves as fertilizer. Such biological processes cut dependence on harsh chemicals and lower greenhouse gas emissions.
Another major approach is catalytic conversion of waste into fuels and chemicals. Instead of burning or dumping plastics and agricultural residues, industries can use metal or chemical catalysts to depolymerize or “crack” these materials into useful products. Plastic to fuel units produce liquid hydrocarbons that substitute for diesel; biomass gasification yields syngas for energy or as feedstock for bio based fuels and chemicals. Catalytic depolymerization of polyethylene terephthalate (PET) can regenerate its building blocks, enabling plastics to be recycled back into high quality materials [11].
Conventional industrial reactions often require large amounts of volatile organic solvents and intense heat, both of which create waste and drive up energy use. Green chemistry encourages replacing these with solvent free reactions, water based systems, or alternatives like supercritical carbon dioxide that can be recovered and reused. Processes that run at lower temperature and pressure also reduce greenhouse gas emissions. For example, supercritical CO_2 extraction is widely used in the food and cosmetics industries to recover essential oils and fragrances from plant waste without leaving solvent residues[12].
Emerging photocatalytic and electrochemical treatments offer further opportunities. Photocatalysis harnesses light activated catalysts often titanium dioxide to break down persistent pollutants such as textile dyes, pesticides, or pharmaceutical residues in wastewater into harmless end products like carbon dioxide and water. Electrochemical oxidation similarly treats contaminated effluents or disinfects hospital wastewater without adding chlorine or other reagents that generate toxic by products. These advanced oxidation processes provide chemical free routes for cleaner water treatment [13].
A broader systems approach comes from bio refineries and circular economy models. Bio refineries process organic waste such as crop husks, sugarcane bagasse, or algae to produce multiple outputs including bio ethanol, bioplastics, animal feed, and soil enhancers [15]. By extracting several products from one feedstock, these facilities minimize landfill needs and create renewable raw materials for other industries. Green chemistry extends upstream by designing

products for degradation and reuse. Biodegradable packaging made from starch, sugarcane bagasse, or algae, compostable cutlery, and eco friendly inks reduce the persistence of plastic litter and make future waste easier to manage. This proactive design complements downstream treatment technologies by ensuring that materials at the end of their life break down safely or can be recovered.

No single technology can solve all waste problems. Integrated solutions for example, combining biocatalysis for organic waste, catalytic depolymerization for plastics, and bio refinery methods for agricultural residues create closed loop systems where resources flow continuously back into production rather than ending up as pollution. Together, these approaches demonstrate that green chemistry is not merely a set of laboratory concepts but a practical framework for transforming waste management into a cleaner, resource conserving enterprise.

Policy, Regulations, and Frameworks

Effective waste management depends not only on technology but also on strong laws, policies, and community participation. In India, a combination of national rules, state initiatives, and global commitments shapes the shift toward greener and safer waste practices.

India's Plastic Waste Management Rules, introduced in 2016 and strengthened afterwards in 2021–2022, have been a turning point in tackling plastic pollution. These rules banned single use plastic products like straws, Styrofoam cutlery, and thin plastic carry bags. A key feature of these rules is Extended Producer Responsibility (EPR), which makes manufacturers and brand owners responsible for collecting and recycling the plastic they produce. This approach encourages companies to design packaging that is easier to recycle or compost, aligning with the green chemistry goals of waste prevention and design for degradation. Hazardous and Other Wastes Rules (2016) regulate the safe handling of industrial sludge, solvents, and chemical by products. These rules ensure that hazardous materials are stored, transported, treated, and disposed of in ways that prevent soil and water contamination. Similarly, E Waste Rules (2022) and Battery Waste Management Rules (2022) extend the idea of EPR to electronics and used batteries, ensuring that valuable metals like copper and lithium are recovered rather than discarded. These policies reflect the circular economy principle of turning waste into a resource. Several state level actions complement national policies. Sikkim has banned bags and promoting compostable packaging made from sugarcane bagasse and starch. Kerala and Himachal Pradesh have imposed strict controls on plastic use, while Punjab and Haryana support bio refineries that convert rice stubble into ethanol to curb stubble burning. At the grassroots level, Panchayati Raj Institutions (PRIs) play an important role in encouraging waste segregation, composting, and local recycling initiatives. Empowering these local bodies with funding, training, and simple technology is a key to achieving sustainable results.

India's policies are also influenced by international commitments. The country is a signatory to the Basel Convention, which controls the movement of hazardous waste across borders to prevent illegal dumping. Under the Paris Agreement (2015), India has pledged to reduce greenhouse gas emissions and expand renewable energy goals that encourage waste to energy solutions and energy efficient processes. The United Nations Sustainable Development Goals (SDGs), especially SDG 6 (Clean Water), SDG 7 (Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), serve as global benchmarks for integrating green chemistry into waste policies.

Despite strong frameworks, implementation remains a challenge. Many municipalities lack the infrastructure for proper waste segregation, collection, and treatment. Enforcement of EPR is uneven across regions, and informal recycling workers who play a significant role in recovering plastics and metals often remain excluded from financial and policy support. Bridging these gaps requires better monitoring, transparent financing, and collaboration between government agencies, industries, researchers, and local communities. Regulations set clear goals and create incentives, while green chemistry offers practical tools to achieve them. The success of bio refineries for crop residues, catalytic plastic to fuel plants, and compostable packaging shows that well crafted policies can accelerate the adoption of cleaner technologies, and innovation can make compliance more affordable for industries. Together, they can pave a way for a waste management system that is not only effective but also environmentally responsible.

Challenges and Barriers

While green chemistry offers practical and cleaner solutions for waste management, its large scale adoption faces several technical, economic, social, and policy related challenges. Understanding these barriers is critical to developing strategies that can make greener practices mainstream. A major challenge is the limited availability of affordable technology. Many green chemistry innovations such as catalytic plastic to fuel plants, photo catalytic wastewater reactors, or bio refineries are confined to research laboratories or small pilot projects. Scaling them up requires reliable supply chains for catalysts, enzymes, and renewable feedstock's, as well as specialized infrastructure. In rural areas, poor electricity supply and lack of skilled technicians make it even harder to operate advanced systems. Without robust technical support and maintenance services, many installations struggle to stay functional in the long term.

Economic barriers also slow down progress. The cost of setting up green technologies is often higher than traditional disposal methods like land filling or incineration [15]. Many small and medium enterprises cannot afford these investments without subsidies or low interest loans. In some cases, markets for recovered products such as biofuels, compost, or recycled plastics are unstable, making it difficult for industries to recover their costs. This lack of strong financial incentives discourages innovation and widespread adoption. Lack of social awareness, creates challenges like low levels of community participation in segregation, recycling, and sustainable consumption. Public understanding of concepts like compostable packaging or renewable feedstock's remains limited, leading to low demand for greener alternatives. Informal waste workers, who play a crucial role in collecting and sorting materials, lack training, safety gear, and access to fair prices for recovered materials. Their exclusion from the formal systems makes it harder to integrate them into circular economy models. Policy and institutional gaps present huge obstacles. While India has progressive rules such as the Plastic Waste Management Rules and Extended Producer

Responsibility frameworks, enforcement is inconsistent across states and municipalities. Many local bodies lack the manpower, funds, or technical expertise to ensure compliance. Moreover, overlapping regulations between agencies sometimes create confusion and slow decision making. Coordinating efforts between government departments, industries, research institutions, and local communities remains a work in progress. Another key obstacle is the lack of investment in research and development. Many green chemistry solutions require continuous innovation like designing cheaper catalysts, improving biodegradable materials, or finding efficient enzyme blends for bio refineries. Limited funding for long term research and insufficient collaboration between academia and industry restrict the growth of such technologies. Cultural and behavioral resistances pose significant resistance to change. Industries accustomed to conventional processes often hesitate to adopt greener alternatives due to uncertainty about performance or fear of disrupting existing production lines. Similarly, consumers can also resist switching to compostable packaging if it costs more or behaves differently than plastic. Overcoming these challenges will require integrated actions by improving access to affordable technologies, offering financial incentives and markets for recycled products, expanding training and public awareness campaigns, strengthening policy enforcement, and investing in collaborative research. Without overcoming these barriers, even the most promising green chemistry innovations will be unable to deliver their full environmental and social benefits.

Conclusion

Waste management today is one of the most pressing environmental and social challenges, deeply connected to climate change, resource scarcity, and public health. Traditional approaches that focus on collecting, treating, and disposing of waste are no longer enough. They shift pollution from one place to another such as from land to air or rely on processes that they generate new forms of waste. Green chemistry offers a new way of thinking: preventing pollution at its source, designing safer materials, and turning waste into a valuable resource. This review showed that the 12 principles of green chemistry from waste prevention and atom economy to catalysis, renewable feedstock, and design for degradation provide a strong foundation for creating cleaner industrial processes and more resilient waste management systems. Technical barriers, high initial costs, inconsistent policy enforcement, and lack of public awareness continue to slow down adoption. Overcoming these obstacles requires coordinated efforts among scientists, policymakers, industries, and local communities, backed by robust funding for research, fair markets for recycled products, and education programs to change consumption habits. Looking ahead, the future of waste management will depend on innovation and collaboration towards a circular economy where waste is minimized and resources flow in closed loops. Green chemistry is not merely a technical tool; it is a guiding philosophy that aligns environmental protection with economic progress and social well being. By embracing these principles, India and other nations can transform their waste systems into engines of sustainability reducing pollution, conserving natural resources, and building resilience against climate change. The path is challenging but achievable, and the time to act is now.

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