A REVIEW ON GREEN CHEMISTRY APPROACHES FOR BETTER WASTE-TO-ENERGY OUTCOMES FOR SUSTAINABILITY

[1]Barkha Shrivastava, [3]Dharmendra Hariyani, [1]Rekha Vijay, [2]Poonam Hariyani

[1]Professor Department of Chemistry, Jaipur Engineering College & Research Centre, Jaipur,
barkhasrivastva.chem@jecrc.ac.in

[3] Swami Keshvanand Institute of Technology, Management and Gramothan, Jaipur-302017 (Rajasthan), INDIA

[2]Associate Professor Department of Chemistry, JECRC University, Jaipur-303905,
poonamgck.09@gmail.com

[1]Assistant Professor Department of Chemistry, Jaipur Engineering College & Research Centre, Jaipur,
rekhavijay.chem@jecrc.ac.in

ABSTRACT

The growing global need for sustainable energy solutions has emphasized the significance of waste-to-energy (WtE) operations. Green chemistry has considerable promise for improving the efficiency and environmental performance of these processes. This research investigates alternative green chemistry techniques to improve WtE outcomes, with an emphasis on waste minimization, hazardous chemical reduction, and the promotion of renewable feedstock. It provides useful ways for improving processes, making them more efficient, sustainable, and ecologically friendly. By following green chemistry principles, we may improve the combustion, gasification, pyrolysis, and anaerobic digestion processes. This leads to improved energy recovery, lower emissions, and more environmentally friendly waste management solutions. Continued research and development, together with supporting laws and regulations, will be critical to progressing these technologies and meeting sustainable energy targets.

Keywords: Efficiency; Waste minimization; Sustainable; Energy recovery; WtE.

I. INTRODUCTION

Green chemistry has significant role to address the environmental and health consequences of chemical production and use in the recent decades having the emphasis on developing products and methods that reduce the use and production of harmful compounds. Green chemistry is being used to decrease or eliminate the negative consequences of chemical production and usage on human health and the environment unlike traditional chemistry, which generally focuses on the efficiency and yield of chemical processes. It is often referred to as the process of creating chemical products and processes that minimize or completely do away with the usage and production of hazardous materials, that is essential to the development of waste-to-energy (WtE) technology. The relevance of this strategy increases as the pollution, resource depletion, and climate change issues create sustainability issues on the globe. These concepts help scientists and engineers to develop more ecologically friendly chemical products and processes. Paul Anastas and John Warner developed the twelve principles of green chemistry (1) kicking off the green chemistry movement. Key themes include waste avoidance, the development of safer chemicals, the use of renewable feedstocks, and the deployment of energy-efficient procedures. The use of these ideas resulted in important advances and acted as a spark for future study and development in a variety of sectors, including medicines, agriculture, and materials research. Subsequent papers focused on particular applications such as catalysis, synthesis, and process design (2). The literature also emphasized the significance of developing safer chemicals and materials to reduce environmental and health concerns. This strategy, which seeks to maximize energy recovery while minimizing the environmental effect of waste conversion operations, is in line with sustainability standards. Green chemistry provides creative ways to convert waste materials into useful energy resources in the context of the world's growing waste creation and the pressing demand for sustainable energy solutions. Green chemistry improves the sustainability and efficiency of WtE processes by incorporating eco-friendly practices, such as the use of eco-friendly solvents and green catalysts. This paper examines the numerous green chemistry strategies being used to enhance WtE results, emphasizing how they might operate as a window into sustainability in contemporary waste management techniques.

Industries may lessen their environmental impact, promote safer consumer goods, and help to create a more sustainable economy by implementing green chemistry concepts. It also plays a critical role in tackling global environmental concerns by fostering the creation of novel technologies that provide more effective resource utilization and waste management.

The transition to green chemistry has been fueled by a mix of governmental pressure, commercial demand, and scientific discovery. Governments all across the world have passed stronger environmental restrictions, encouraging firms to embrace greener methods. Consumers are also growing more conscious of the environmental effect of the items they use, driving up demand for sustainable alternatives. Furthermore, technological developments and a greater knowledge of chemical processes have enabled scientists to create new methods and materials that are consistent with the aims of green chemistry.

Several examples in the literature demonstrate the effective implementation of green chemistry concepts in a variety of sectors. *e.g.* the pharmaceutical sector (3) has implemented green chemistry to increase the sustainability of medication manufacturing. In materials science, green chemistry has been used to create safer and more sustainable materials. Researchers have developed biodegradable polymers and green composites from renewable resources, providing ecologically acceptable alternatives to traditional plastics.

Paul Anastas and Nicolas Eghbali explained the green chemistry framework including designs, nature of the chemical products with processes and cohesive system in 2010 (4).

Design concept encompasses innovation, planning, and methodical conceptualization as well as is distinguished by meticulous planning of chemical synthesis and molecular design to minimize negative effects. Molecular sustainability feature of green chemistry (5) implies

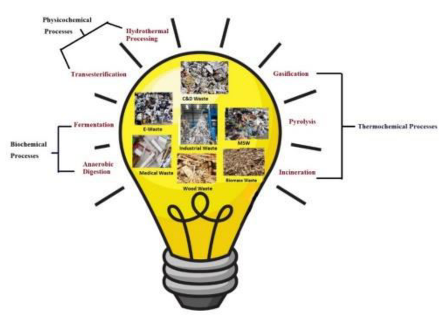

Figure 1. Waste and Recovery Methods

the role in industry sectors including agriculture, automobiles, cosmetics, domestic stuffs and pharmaceuticals (6).

Green chemistry principles drive the effective conversion of waste to energy, which is an important part of current chemical processes. This strategy seeks to decrease environmental adverse effect, waste, and use sustainable resources. By concentrating on green chemistry, we may improve the efficiency of waste-to-energy operations while being ecologically conscious. Different types of wastes, their characteristics and recovery methods have been discussed in Table 1 & Figure 1.

II. LITERATURE REVIEW & EXPERIMENTAL DETAILS

The objective of this review is to present state-of-the-art green chemistry techniques for practitioners to improve waste-to-energy (WtE) results, with an emphasis on contribution to sustainability. The review specifically attempts to assess the productivity and environmental impact of several WtE processes, including fermentation, anaerobic digestion, gasification, pyrolysis, incineration, and landfill gas recovery that may be enhanced using the green concept. It aims to showcase cutting-edge green chemical methods and materials that have been effectively incorporated into WtE technologies, offering a thorough analysis of case studies and real-world uses.

The scope of this review covers a broad spectrum of waste kinds, such as industrial, municipal, electronic, medical, and agricultural waste. It will discuss developments in environmentally acceptable solvents, green catalysts, and energy-saving procedures that follow the guidelines of green chemistry (Table 2). The evaluation will also cover the possible benefits and challenges of integrating green chemistry into WtE procedures, as well as the effects on

Table 1. Classification of waste and their recovery methods

Organic Waste	**Biomass Waste**	**Municipal Solid Waste (MSW)**	**Industrial Waste**	**Construction and Demolition (CandD) Waste**	**Electronic Waste (E-Waste)**	**Wood Waste**	**Medical and Hazardous Waste**
Description and Types:							
Organic waste originates from living organisms and includes materials that decompose naturally. It is primarily derived from food and agricultural activities, e.g., Food waste, agricultural residues, and yard waste.	Biomass waste comes from plant and animal materials that can be used as a renewable energy source, e.g. Wood chips, sawdust, crop residues, and other plant-based materials.	Waste generated from residential, commercial, and institutional sources, often including a mix of various materials, e.g. Mixed household waste, including paper, plastics, textiles, and non-recyclable materials.	Waste generated from industrial processes and manufacturing operations, e.g., Waste from manufacturing processes, including plastics, chemicals, and metal residues.	Waste resulting from construction, renovation, and demolition activities, e.g., Concrete, wood, metals, and drywall.	Waste generated from discarded electronic devices and equipment. e.g. computers, smartphones, and televisions	Waste generated from wood processing and use in construction and manufacturing, e.g., Sawdust, wood chips, and scrap wood from construction or furniture manufacturing.	Waste generated from healthcare facilities and industrial processes involving hazardous substances, e.g., Pharmaceuticals, contaminated materials, and industrial chemicals.
Characteristics:							

Rich in biodegradable organic matter that can be converted into energy through anaerobic digestion or composting.	High energy content and often used in direct combustion, gasification, or pyrolysis.	Variable energy content depending on composition, with a significant proportion of organic and combustible materials.	Often contains high energy content or valuable byproducts that can be utilized in energy recovery.	Generally, not suitable for traditional energy recovery but may be used as alternative fuels in cement kilns or processed for recovery of metals and other materials.	Contains valuable metals and components, with some energy content from plastics and batteries.	High in calorific value and suitable for energy recovery.	Requires careful handling due to potential toxicity and safety concerns.
Recovery Methods:							
Anaerobic Digestion: Converts organic waste into biogas and digestate, providing energy and a nutrient-rich byproduct. **Composting**: Biological process that transforms organic waste into compost, which can be used as a soil amendment.	**Direct Combustion**: Burned to produce heat and electricity. **Gasification**: Converts biomass into syngas (synthetic gas) for power generation. **Pyrolysis**: Thermochemical process that	**Incineration**: Burns waste to generate electricity and heat, often used to reduce volume and manage non-recyclable waste. **Mechanical Biological Treatment (MBT)**: Sorts	**Incineration**: For waste that cannot be recycled, with energy recovery and emission controls. **Recycling**: Recovery of metals, plastics, and other valuable materials. **Chemical**	**Recycling**: Sorting and processing materials like metals, wood, and concrete for reuse or repurposing. **Reuse**: Salvaging and repurposing building materials for new	**Shredding and Sorting**: For separating valuable metals and components from plastics and other materials. **Hydrometallurgical Processing**: Extracts precious metals from electronic components. **Pyrolysis**: Converts some e-waste into recoverable	**Direct Combustion**: Used in boilers or power plants to generate heat and electricity. **Palletization**: Compressed into pellets for use as a biofuel. **Gasification**: Converts wood waste	**High-Temperature Incineration**: For safe destruction of medical and hazardous waste with energy recovery. **Chemical Treatment**: Neutralizes hazardous substances to make them safer

Vermicomposting: Uses worms to decompose organic waste, producing nutrient-rich vermicompost.	converts biomass into bio-oil, char, and gas.	and processes waste to recover recyclables and produce compost or refuse-derived fuel (RDF). **Recycling and Composting**: Separates and processes recyclable materials and organic waste for further use.	**Treatment**: For hazardous waste, to neutralize or convert it into less harmful substances.	construction projects. **Energy Recovery**: Using some materials as alternative fuels in cement kilns or other industrial processes.	materials and energy.	into syngas for energy production.	for disposal. **Specialized Recycling**: For materials like batteries and electronic waste, involving processes to recover valuable components safely.

Table 2. 12 Principles of green chemistry and Applications

Principle	**Applications in waste-to-energy processes**
Prevention (7)	
	By creating mechanisms that minimize the production of hazardous byproducts and lower the amount of trash handled. This entails adjusting reaction parameters to guarantee total waste conversion to energy, minimizing the requirement for post-processing treatments and residual waste.
Atom Economy (8)	
	Creating reactions that guarantee the bulk of waste materials are transformed into energy products rather than undesirable byproducts is essential to maximizing atom economy in WtE.
Less Hazardous Chemical Syntheses (9)	
	The dangers connected with waste treatment for the environment and human health can be decreased by using lesser hazardous chemicals in WtE operations.
Designing Safer Chemicals (10)	
	It is possible to lessen possible environmental effects and guarantee safer handling and disposal of chemicals by engineering them to break down into benign components after usage.
Safer Solvents and Auxiliaries (11)	
	The environmental effect of WtE processes can be decreased by minimizing or doing away with the usage of auxiliary materials and harmful solvents. Such as employing environmentally friendly solvents in bio-digestion processes or streamlining procedures to reduce their usage might make an operation more sustainable.
Design for Energy Efficiency (12)	
	Optimizing conditions to lower energy consumption and improve energy recovery is a necessary part of constructing WtE processes to be energy-efficient. Energy consumption may be reduced and process efficiency raised by employing strategies like utilizing sophisticated energy recovery systems or enhancing heat integration in incineration.
Use of Renewable Feedstocks (13,14)	
	The idea of using renewable resources is supported by the incorporation of renewable raw materials, such as organic waste from municipal or agricultural sources. By converting garbage into useful energy resources, this strategy helps the growth of a circular economy and lessens dependency on non-renewable resources.

Reduce Derivatives (15)	
	Reducing waste and improving workflows are achieved by minimizing needless degradation in WtE procedures. Such as refining chemical reactions to eliminate extra stages in the reaction or intermediate products can result in more effective waste conversion and a smaller environmental impact.
Catalysis (16)	
	In WtE processes, the use of catalysis improves reaction efficiency and lowers the requirement for surplus chemicals. In procedures like gasification or anaerobic digestion, the use of efficient, non-toxic catalysts can increase conversion rates and decrease the production of unwanted byproducts.
Design for Degradation (17)	
	Environmental sustainability is supported by designing WtE processes such that any leftover trash or byproducts break down into non-toxic materials. Long-term environmental consequences can be decreased, for example, by making sure that waste products from incineration or other operations are managed in a way that minimizes their persistence in the environment.
Real-time Analysis for Pollution Prevention (18)	
	Real-time monitoring enables prompt identification and mitigation of possible sources of contamination in WtE processes. Sophisticated analytical methods are able to track waste composition, process efficiency, and emission levels, allowing for proactive modifications to reduce environmental effect.
Inherently Safer Chemistry for Accident Prevention (19)	
	Safety-conscious process design lowers the possibility of mishaps like explosions or leaks. To make sure that the operation continues to be safe for the employees and the community at large, this involves utilizing stronger process controls, stable materials, and safer reaction conditions.

the environment and the economy. This assessment attempts to be a useful tool for academics, business people, and legislators who are interested in supporting sustainable waste management and energy generation by providing a comprehensive grasp of the existing state of affairs and potential future developments.

Green Chemistry Approaches for Waste to Energy Conversion

The goal of WtE systems is to capture waste energy and decrease landfill waste by converting waste materials into useful energy sources like fuel, heat, or electricity. Anaerobic digestion, which uses microorganisms to break down organic waste into digestate and biogas, pyrolysis and gasification, which thermally decompose waste in low or partial oxygen conditions to generate syngas, bio-oil, and char, and incineration, which burns waste to produce heat for electricity or district heating, are important WtE techniques. While landfill gas recovery extracts methane from decaying trash in landfills for use as energy, fermentation transforms biomass into bioethanol and other biofuels. These procedures not only lessen trash creation and lessen their negative effects on the environment, but they also help recover resources and produce renewable energy, which promotes a circular economy and improves sustainability.

Green chemistry, which encourages ecologically acceptable and sustainable methods for converting trash into energy, is essential to improving WtE results. WtE procedures can minimize the use and production of hazardous compounds, lowering their total environmental effect, by following the guidelines of green chemistry. Green chemistry, for example, promotes the use of renewable and non-toxic catalysts, which can increase the effectiveness of chemical reactions involved in WtE processes including anaerobic digestion, gasification, and pyrolysis. Green chemistry also encourages the use of renewable feedstocks and energy-efficient procedures, which lowers the carbon footprint of WtE activities. Adopting green chemistry principles can also result in the creation of novel technologies that minimize the formation of hazardous byproducts while increasing the quantity and quality of energy products generated from waste. In general, green chemistry contributes to a cleaner and more sustainable energy future by increasing the sustainability and efficiency of WtE processes as well as aligning with larger environmental and economic goals.

Various chemical processes *viz.* combustion, gasification, pyrolysis (20), and anaerobic digestion (21) are used to convert waste materials into useable energy sources, such as heat, electricity, or fuels.

Catalysis process is critical in increasing the efficiency and selectivity of chemical reactions in waste-to-energy operations. Catalysts allow reactions to occur at lower temperatures and pressures, saving energy and boosting overall process efficiency. Catalysts can also improve the yield of desirable products while reducing the development of detrimental byproducts (22–24).

Designing Safer and More Efficient Processes

Safety, efficiency, and the environment should be on top priority in the designing of WtE operations. Green chemistry concepts can help to drive the creation of processes that utilize fewer hazardous ingredients, consume less energy, and emit fewer toxic byproducts (Figure 2).

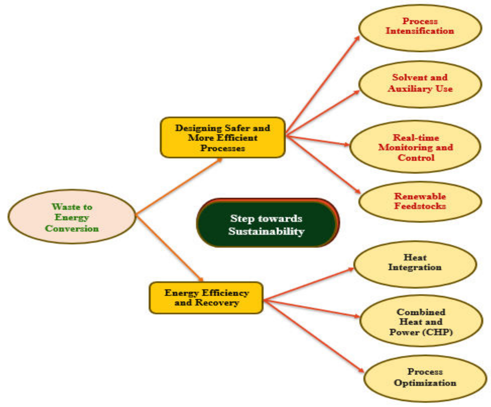

Figure 2. Sustainability by Conversion of Waste to Energy

1. Process Intensification

Process intensification entails developing more efficient and compact chemical processes, eliminating the demand for large-scale equipment and lowering energy usage (Figure 3). This can be accomplished through a variety of methods, including combining numerous reaction stages into a single unit, using sophisticated heat and mass transfer techniques, and using high-performance materials. We can minimize our overall environmental footprint and increase economic viability by intensifying waste-to-energy activities (25).

2. Solvent and Auxiliary Use

The type and amount of solvents have the great challenge to the environment and human health during work exposure. Green chemistry promotes the reduction or removal of these chemicals whenever feasible. Solvent-free or benign solvents (26) can be used in waste-to-energy processes to limit waste creation and toxicity. Aqueous and biobased solvents, ionic liquids and super critical liquids are the alternative solution for the chemical processes mainly in separation and purification during the synthesis.

3. Real-time Monitoring and Control

Implementing real-time monitoring and control systems can improve the efficiency and safety of waste-to-energy operations. Automated sorting and separation systems, advanced control and continually monitoring process parameters such as temperature, pressure, and composition, robotic systems, and data analytics help in this process. Advanced analytical methods, including as spectroscopy and chromatography (27), can be utilized for in-process monitoring, allowing for fast modifications to avoid the development of undesirable byproducts.

4. Renewable Feedstocks

Green chemistry relies heavily on renewable feedstocks such as agricultural wastes, forestry waste, and municipal solid waste. Using these feedstocks allows us to lessen our dependency on fossil fuels while also reducing the environmental effect of waste disposal (28).

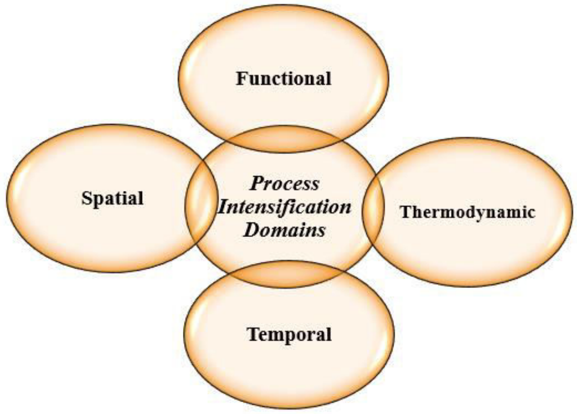

Figure 3. Process Intensification domains (29)

Energy Efficiency and Recovery

Improving principles and increasing energy recovery are critical to the success of waste-to-energy technologies. Green chemistry principles (30) can help drive the development of products and practices that improve energy efficiency and minimize waste.

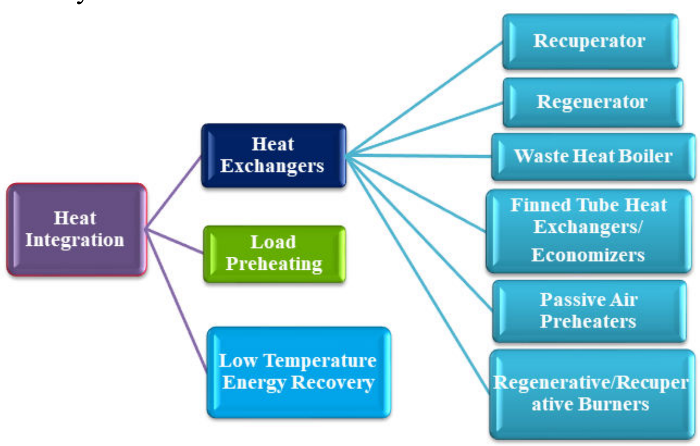

Figure 4. Waste Heat Recovery Options and Technologies (31)

1. ***Heat Integration***

Heat integration [Figure 4] is the recovery and reuse of heat inside a process to reduce energy consumption. Heat generated by combustion or gasification in waste-to-energy operations can be recovered (32) and utilized to warm feedstocks, create steam, or power other processes (33). By optimizing heat integration, we may minimize total energy consumption while increasing process efficiency.

2. ***Combined Heat and Power (CHP)***

CHP systems, referred to as cogeneration, generate electricity and usable heat from the same energy source. CHP systems may considerably enhance energy efficiency (34) in waste-to-energy applications by using heat generated during the waste conversion process. This strategy maximizes energy efficiency while lowering greenhouse gas emissions.

3. ***Process Optimization***

Process optimization entails fine-tuning operational parameters to maximize efficiency and yield (35). This can be accomplished in a variety of ways, including altering temperature, pressure, and residence time or utilizing complex control systems. By optimizing waste-to-energy systems, we can boost energy recovery, minimize trash creation, and improve overall sustainability.

Challenges and barriers

While green chemistry offers many benefits, there are also some potential adverse effects and challenges associated with its implementation.

1. **High Upfront Cost**: The transition to green chemistry can involve significant upfront costs, such as investing in new technologies, equipment, and training. This can be a barrier for small and medium-sized enterprises (SMEs) with limited financial resources.
2. **Technological Challenges**: Developing green chemistry solutions often requires advanced scientific knowledge and technological innovation. This can be challenging for industries that rely on traditional chemical processes and lack the expertise to implement greener alternatives.
3. **Limited Availability of Green Alternatives**: In some cases, green chemistry solutions may not yet be available or fully developed for certain applications. This can limit the ability of industries to adopt greener practices and achieve their sustainability goals.
4. **Regulatory Uncertainty**: The regulatory landscape for green chemistry is still evolving, and there can be uncertainty about the requirements and standards for green products and processes. This can create challenges for companies trying to navigate the regulatory environment and ensure compliance.
5. **Potential Trade-Offs**: In some cases, green chemistry solutions may involve trade-offs, such as higher costs or lower performance compared to conventional alternatives. Balancing these trade-offs can be challenging and may require careful consideration of the overall benefits and drawbacks.

Transitioning to green chemistry can be especially difficult for small and medium-sized businesses (SMEs) due to limited resources and knowledge. Furthermore, the availability of green alternatives for certain applications remains an issue. In some circumstances, green chemical solutions may not be as successful or cost-efficient as traditional approaches. The literature advocates for ongoing research and development to close these gaps and increase the viability of green chemistry in all areas (36).

The future of green chemistry looks promising, with several trends and developments likely to shape its evolution in the coming years.

***1. Technological advancements**:* Technological advances are required to increase the efficiency and scalability of waste-to-energy operations. Research and development efforts should be directed on optimizing reaction conditions, improving catalyst performance, and creating innovative materials. Furthermore, improvements in real-time monitoring and control systems can boost process stability and safety. Ongoing research and development in domains such as biotechnology (37), materials science, and nanotechnology (38) are likely to drive additional progress in green chemistry. These technologies can help to create new, more sustainable chemical processes and products.

***2. Economic Viability**:* The economic feasibility of waste-to-energy systems (39,40) is determined by factors such as feedstock availability, capital and operational expenses, and market demand for energy output. Developing cost-effective methods and ensuring consistent feedstock sources are critical to commercial success. Policy incentives and regulatory assistance can also help promote the use of waste-to-energy systems (41).

***3. Increased Collaboration and Partnerships**:* Collaboration among business, academia, and government will be critical to advance green chemistry. Partnerships and collaborative projects (42) can allow the exchange of information, resources, and best practices, hastening the adoption of greener solutions.

***4. Education and Awareness**:* Raising awareness and giving training on green chemistry will be critical to its broad adoption. Efforts to incorporate green chemistry ideas into academic curriculum and professional training programs can assist to develop a workforce that is aware and experienced in sustainable practices (43).

***5. Stronger Regulatory Support**:* Compliance with environmental legislation and standards is critical for waste-to-energy systems. Environmental protection necessitates strict emission limitations and waste management standards. Collaboration between business, government, and research institutions can help to create policies and technology that promote sustainable waste-to-energy practices. As governments prioritize environmental preservation and sustainability, green chemistry is projected to get increased legislative backing. This might include incentives for green behaviors, tighter environmental regulations, and more money for research and development (44).

***6. Consumer Demand for Sustainability**:* Growing customer awareness and demand (45) for environmentally friendly products will encourage businesses to use green chemistry. Companies that prioritize sustainability might gain a competitive edge by satisfying consumer expectations and increasing brand loyalty.

III. RESULT & DISCUSSION

Green chemistry has several advantages over traditional chemistry in view of economy, environment, and social perspectives [Figure 5].

Economic Benefits

1. **Cost Savings**: By reducing waste and improving resource efficiency, green chemistry can lower the costs associated with raw materials, waste disposal, and energy consumption (46). This can lead to significant savings for businesses.
2. **Innovation and Competitiveness**: Adopting green chemistry can drive innovation, leading to the development of new products and technologies. Companies that embrace green chemistry can gain a competitive edge in the market by offering sustainable solutions (47) that meet consumer demand.
3. **Regulatory Compliance**: Green chemistry helps companies comply with increasingly stringent environmental regulations, reducing the risk of fines and legal issues. This can also enhance a company's reputation and build trust with stakeholders.

Social Benefits

1. **Health and Safety**: Green chemistry promotes worker, consumer, and community health and safety by developing safer chemicals and eliminating the usage of harmful compounds. This can result in better public health performance and an improved standard of life.
2. **Sustainable Development**: Green chemistry promotes ecologically benign processes that may be continued over time, so contributing to sustainable development (48,49). This is consistent with worldwide efforts to fulfil the United Nations' Sustainable Development Goals (SDG).

Environmental Benefits

1. **Pollution Reduction**: Cleaner environment and better ecosystems can be achieved by minimizing air, water, and soil pollution using lesser harmful ingredients and producing less waste.
2. **Resource Efficacy:** The depletion of nonrenewable resources and the environmental impact of chemical operations can be reduced by using renewable resources and the effective use of basic materials.
3. **Energy Conservation**: Green methods are energy-efficient, which reduces the overall energy consumption of chemical manufacturing as well as reduces greenhouse gas

emissions and conserves precious energy resources.

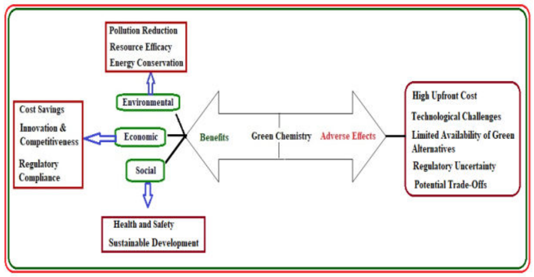

Figure 5. Opportunities and Obstacles of Green Chemistry

IV. CONCLUSION

Green chemistry is a disruptive approach to chemical research and engineering that provides a sustainable alternative to traditional chemistry. Green chemistry tackles many of the environmental, economic, and social issues involved with chemical manufacture and usage by emphasizing the creation of safer compounds, waste reduction, and resource efficiency.

Green chemistry has several benefits, including decreased pollution, cost savings, innovation, and increased health and safety. However, the move to green chemistry is fraught with difficulties, including high initial prices, technological problems, and regulatory uncertainties. Despite these hurdles, the future of green chemistry seems promising, with technological improvements, more cooperation, and rising consumer demand driving its continuing progress.

Green chemistry will play an important part in developing a healthier and more sustainable society as the global community is working on conversion of waste to energy. Scientists, engineers, and enterprises may help to clean up the environment, strengthen the economy, and improve everyone's quality of life by adopting green chemistry concepts.

The labelling, emphasis, and attention associated with green chemistry will be superfluous when the 12 Principles of Green Chemistry are simply integrated into routine chemistry. While problems persist, continuing improvements and collaborative efforts offer hope for a future in which green chemistry becomes the norm, resulting in a healthier and more sustainable planet.

Theoretical Implications

WtE and green combination can advance sustainable waste management *via* innovative and efficient technologies with environmental impact in a sustainable mode. This type of review helps to elucidate the role of green chemistry principles in reducing pollutants and enhance the energy efficiency of WtE processes as well as it can foster a deeper understanding of the potential for integrating renewable energy sources and sustainable practices within the WtE framework, ultimately contributing to the development of more sustainable and eco-friendly energy systems. This knowledge can guide future research and policy-making, promoting a circular economy and reducing the carbon footprint of energy production.

Practical implications

The study can guide industries for more sustainable and efficient waste management practices, reducing dependance on landfills and enhancing energy yield from waste materials and ultimately result in significant cost reductions and more economically feasible. It can also provide valuable insights for policymakers, leading to the development of supportive regulations and standards for green WtE initiatives. Thus, the assessment can be quite helpful in advancing a more environmentally friendly and sustainable method of producing energy and managing wastes.

Future Prospects and Research Directions

New Directions in Green Chemistry for WtE

More and more, the focus of emerging developments in green chemistry for WtE is on improving environmental performance, sustainability, and efficiency. A significant development in waste conversion processes is the combination of cutting-edge nanotechnology and material science to create more selective and effective catalysts that reduce the production of undesired byproducts. Furthermore, the use of waste-derived feedstocks and bio-based materials to produce more sustainable WtE solutions is gaining popularity. The creation of environmentally friendly reagents and solvents is also becoming more popular as these substitutes enhance process safety and lessen their negative effects on the environment. Using AI and machine learning to optimize WtE operations is another new trend that is starting to take off. This allows for real-time monitoring and control, which lowers costs and increases operational efficiency. These patterns are part of a larger movement in green chemistry towards creative and sustainable methods of energy recovery and waste management.

Prospect of Innovations and New Technologies

Waste-to-energy has enormous and significant possibilities for new technology and advancements in green chemistry. The creation of synthetic microbes and enzymes that can effectively transform complicated waste materials into biofuels and chemicals is being made possible by advancements in biotechnology. The creation of smart materials and high-performance nano catalysts, among other innovations in materials science, is increasing the effectiveness of waste conversion processes. Additionally, there are chances to maximize resource recovery and energy output through the use of hybrid and integrated technologies that combine several WtE processes, including gasification with bioenergy production. Supercritical water gasification and plasma arc like developments might increase the adaptability and efficiency of WtE systems. The efficiency and sustainability of waste-to-energy operations are expected to increase further with the further investigation and application of these innovative technologies.

REFERENCES

1. Paul Anastas and John Warner. Green Chemistry: Theory and Practice. 1998. 14821–14842 p.
2. Sheldon RA. Fundamentals of green chemistry: efficiency in reaction design. Chem Soc Rev [Internet]. 2012;41(4):1437–51. Available from: https://xlink.rsc.org/?DOI=C1CS15219J
3. David J. C. Constable, Peter J. Dunn, John D. Hayler, Guy R. Humphrey, Johnnie L. Leazer, Jr., Russell J. Linderman, Kurt Lorenz, Julie Manley, Bruce A. Pearlman, Andrew Wells AZ and TYZ. Key green chemistry research areas—a perspective from pharmaceutical manufacturers. Green Chem. 2007;9:411–20.
4. Anastas P, Eghbali N. Green Chemistry: Principles and Practice. Chem Soc Rev [Internet]. 2010;39(1):301–12. Available from: https://xlink.rsc.org/?DOI=B918763B
5. Sheldon RA. The E factor 25 years on: the rise of green chemistry and sustainability. Green Chem [Internet]. 2017;19(1):18–43. Available from: https://xlink.rsc.org/?DOI=C6GC02157C
6. Sheldon RA. The E Factor: fifteen years on. Green Chem [Internet]. 2007;9(12):1273. Available from: https://xlink.rsc.org/?DOI=b713736m
7. Ivanković A. Review of 12 Principles of Green Chemistry in Practice. Int J Sustain Green Energy [Internet]. 2017;6(3):39. Available from: http://www.sciencepublishinggroup.com/journal/paperinfo?journalid=169&doi=10.11648/j.ijrse.20170603.12
8. Brunner PH, Rechberger H. Waste to energy – key element for sustainable waste management. Waste Manag [Internet]. 2015 Mar;37:3–12. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0956053X14000543

9. M. Koh, M. Yahayu, S. Ramli, S. Z. Hanapi, D. J. Dailin, E. S. Lim HAEE. Recent Development in Biological Production of 1, 3-Propanediol. Chem Methodol. 2024;8(6):439–61.
10. Gao X, Abdul Raman AA, Hizaddin HF, Bello MM, Buthiyappan A. Review on the Inherently Safer Design for chemical processes: Past, present and future. J Clean Prod [Internet]. 2021 Jul;305:127154. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0959652621013731
11. Wahyuningsih AS, Multazam MT, Nandiyanto ABD, Abdullah AG, Widiaty I. Green Chemistry Principles: An Alternative Approach to Practice Laboratory Safety and Health. IOP Conf Ser Mater Sci Eng [Internet]. 2018 Jan;288:012001. Available from: https://iopscience.iop.org/article/10.1088/1757-899X/288/1/012001
12. Sheldon RA. Green chemistry and resource efficiency: towards a green economy. Green Chem [Internet]. 2016;18(11):3180–3. Available from: https://xlink.rsc.org/?DOI=C6GC90040B
13. Salladini A, Agostini E, Borgogna A, Iaquaniello G. Waste feedstocks for sustainable chemicals and fuels. In 2020. p. 193–213. Available from: https://linkinghub.elsevier.com/retrieve/pii/B9780444643377000112
14. Skaggs RL, Coleman AM, Seiple TE, Milbrandt AR. Waste-to-Energy biofuel production potential for selected feedstocks in the conterminous United States. Renew Sustain Energy Rev [Internet]. 2018 Feb;82:2640–51. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1364032117313631
15. Vandeponseele A, Draye M, Piot C, Chatel G. Subcritical water and supercritical carbon dioxide: efficient and selective eco-compatible solvents for coffee and coffee by-products valorization. Green Chem [Internet]. 2020;22(24):8544–71. Available from: https://xlink.rsc.org/?DOI=D0GC03146A
16. Enache DI, Edwards JK, Landon P, Solsona-Espriu B, Carley AF, Herzing AA, et al. Solvent-Free Oxidation of Primary Alcohols to Aldehydes Using Au-Pd/TiO 2 Catalysts. Science (80-) [Internet]. 2006 Jan 20;311(5759):362–5. Available from: https://www.science.org/doi/10.1126/science.1120560
17. Concepción Jiménez-González DJC. Green Chemistry and Engineering: A Practical Design Approach. John Wiley & Sons; 2011.
18. Yayayürük AE, Yayayürük O. Applications of Green Chemistry Approaches in Environmental Analysis. Curr Anal Chem [Internet]. 2019 Oct 15;15(7):745–58. Available from: http://www.eurekaselect.com/170747/article
19. Anastas PT, Hammond DG. Accident Vulnerability and Terrorist Threats to the Chemical and Related Industries. In: Inherent Safety At Chemical Sites [Internet]. Elsevier; 2016. p. 11–6. Available from: https://linkinghub.elsevier.com/retrieve/pii/B9780128041901000021
20. Kalogirou EN. Waste-to-Energy Technologies and Global Applications [Internet]. Boca Raton, FL : CRC Press, 2018.: CRC Press; 2017. 21–82 p. Available from: https://www.taylorfrancis.com/books/9781351977920
21. Hussain Z, Mishra J, Vanacore E. Waste to energy and circular economy: the case of anaerobic digestion. J Enterp Inf Manag [Internet]. 2020 Aug 18;33(4):817–38. Available from: https://www.emerald.com/insight/content/doi/10.1108/JEIM-02-2019-0049/full/html
22. R. A. Sheldon, Isabella Arends UH. Green Chemistry and Catalysis. 2007.
23. Hoelderich WF. 'One-pot' reactions: a contribution to environmental protection. Appl Catal A Gen [Internet]. 2000 Mar;194–195:487–96. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0926860X99003956

24. Sharma VK, Binder TP, Allgeier AM. Conceptual Process Design and Techno-Economic Analysis of Biocatalytic Furfural Hydrogenation Using Ethanol as the Terminal Reductant. ACS Sustain Chem Eng [Internet]. 2024 Jul 9; Available from: https://pubs.acs.org/doi/10.1021/acssuschemeng.4c01718
25. Soltani A, Sadiq R, Hewage K. Selecting sustainable waste-to-energy technologies for municipal solid waste treatment: a game theory approach for group decision-making. J Clean Prod [Internet]. 2016 Feb;113:388–99. Available from: https://linkinghub.elsevier.com/retrieve/pii/S095965261501865X
26. Gu Y, Jérôme F. Glycerol as a sustainable solvent for green chemistry. Green Chem [Internet]. 2010;12(7):1127. Available from: https://xlink.rsc.org/?DOI=c001628d
27. Armenta S, Garrigues S, de la Guardia M. Green Analytical Chemistry. TrAC Trends Anal Chem [Internet]. 2008 Jun;27(6):497–511. Available from: https://linkinghub.elsevier.com/retrieve/pii/S016599360800109X
28. Sharma S, Basu S, Shetti NP, Aminabhavi TM. Waste-to-energy nexus for circular economy and environmental protection: Recent trends in hydrogen energy. Sci Total Environ [Internet]. 2020 Apr;713:136633. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0048969720301431
29. Cogswell Chris. Process intensification: The key to sustainability in chemical engineering [Internet]. 2024. Available from: https://www.elsevier.com/en-in/connect/process-intensification-the-key-to-sustainability-in-chemical-engineering
30. Gałuszka A, Migaszewski Z, Namieśnik J. The 12 principles of green analytical chemistry and the SIGNIFICANCE mnemonic of green analytical practices. TrAC Trends Anal Chem [Internet]. 2013 Oct;50:78–84. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0165993613001234
31. A F. Waste Heat Recovery: - Technology and Opportunities in U.S. Industry. J Chem Inf Model [Internet]. 2013;53(9):1689–99. Available from: https://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/waste_heat_recovery.pdf
32. Brückner S, Liu S, Miró L, Radspieler M, Cabeza LF, Lävemann E. Industrial waste heat recovery technologies: An economic analysis of heat transformation technologies. Appl Energy [Internet]. 2015 Aug;151:157–67. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0306261915004584
33. Jouhara H, Khordehgah N, Almahmoud S, Delpech B, Chauhan A, Tassou SA. Waste heat recovery technologies and applications. Therm Sci Eng Prog [Internet]. 2018 Jun;6:268–89. Available from: https://linkinghub.elsevier.com/retrieve/pii/S2451904918300015
34. Wu DW, Wang RZ. Combined cooling, heating and power: A review. Prog Energy Combust Sci [Internet]. 2006 Sep;32(5–6):459–95. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0360128506000244
35. Méndez CA, Cerdá J, Grossmann IE, Harjunkoski I, Fahl M. State-of-the-art review of optimization methods for short-term scheduling of batch processes. Comput Chem Eng [Internet]. 2006 May;30(6–7):913–46. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0098135406000287
36. Dunn PJ. The importance of Green Chemistry in Process Research and Development. Chem Soc Rev [Internet]. 2012;41(4):1452–61. Available from: https://xlink.rsc.org/?DOI=C1CS15041C
37. Sheldon RA. Green and sustainable manufacture of chemicals from biomass: state of the art.

Green Chem [Internet]. 2014;16(3):950–63. Available from: https://xlink.rsc.org/?DOI=C3GC41935E

38. Iravani S. Green synthesis of metal nanoparticles using plants. Green Chem [Internet]. 2011;13(10):2638. Available from: https://xlink.rsc.org/?DOI=c1gc15386b
39. Xiong J, Ng TSA, Wang S. An optimization model for economic feasibility analysis and design of decentralized waste-to-energy systems. Energy [Internet]. 2016 Apr;101:239–51. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0360544216300044
40. Morero B, Lorenzon AB, Cafaro DC. Integrated management of urban and rural wastes with energy recovery and low carbon emissions. J Clean Prod [Internet]. 2024 Jan;434:139729. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0959652623038878
41. Liu J, Kua HW, Wang C-H, Tong YW, Zhang J, Peng Y. Improving urban ecosystem holistic sustainability of municipal solid waste-to-energy strategy using extended exergy accounting analysis. Sci Total Environ [Internet]. 2023 Dec;904:166730. Available from: https://linkinghub.elsevier.com/retrieve/pii/S004896972305355X
42. Huang J, Liu S, Plaza A, Zhou W. Creating an Enabling Environment for Public–Private Partnerships in Waste-to-Energy Projects [Internet]. Manila, Philippines; 2018 Dec. Available from: https://www.adb.org/publications/ppp-waste-to-energy-projects
43. Anastas PT, Kirchhoff MM. Origins, Current Status, and Future Challenges of Green Chemistry. Acc Chem Res [Internet]. 2002 Sep 1;35(9):686–94. Available from: https://pubs.acs.org/doi/10.1021/ar010065m
44. Clark JH. Green chemistry: today (and tomorrow). Green Chem [Internet]. 2006;8(1):17–21. Available from: https://xlink.rsc.org/?DOI=B516637N
45. Yaraş A, Bayram M, Ustaoğlu A, Erdoğmuş E, Hekimoğlu G, Sarı A, et al. Advancing thermal control in buildings with innovative cementitious mortar and recycled expanded glass/n-octadecane phase change material composites. Renew Sustain Energy Rev [Internet]. 2024 Sep;202:114680. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1364032124004064
46. Clark JH, Matharu AS. Waste to Wealth using Green Chemistry. In: Waste as a Resource [Internet]. The Royal Society of Chemistry; 2013. p. 66–82. Available from: https://books.rsc.org/books/book/1060/chapter/879881/Waste-to-Wealth-using-Green-Chemistry
47. Sheldon RA, Brady D. Green Chemistry, Biocatalysis, and the Chemical Industry of the Future. ChemSusChem [Internet]. 2022 May 6;15(9). Available from: https://chemistry-europe.onlinelibrary.wiley.com/doi/10.1002/cssc.202102628
48. Bjelić D, Markić DN, Prokić D, Malinović BN, Panić AA. “Waste to energy” as a driver towards a sustainable and circular energy future for the Balkan countries. Energy Sustain Soc [Internet]. 2024 Jan 2;14(1):3. Available from: https://energsustainsoc.biomedcentral.com/articles/10.1186/s13705-023-00435-y
49. Kalair AR, Seyedmahmoudian M, Stojcevski A, Abas N, Khan N. Waste to energy conversion for a sustainable future. Heliyon [Internet]. 2021 Oct;7(10):e08155. Available from: https://linkinghub.elsevier.com/retrieve/pii/S2405844021022581