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Advanced Waste-to-Energy Technologies: A Review on Pathway to Sustainable Energy Recovery in a Circular Economy

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ABSTRACT

In the face of the rapid rise in global waste production and the pressing need to shift towards sustainable energy options, advanced Waste-to-Energy (WtE) technologies have emerged as a highly promising solution. These innovative technologies effectively utilize waste as a valuable resource, presenting a viable pathway for sustainable energy recovery and making a substantial contribution to the principles of the circular economy paradigm. This review provides a comprehensive overview of advanced WtE technologies, including thermal, biological, and chemical methods, such as gasification, pyrolysis, plasma arc gasification, anaerobic digestion, fermentation, transesterification, and hydrothermal carbonization. The efficiency of these technologies is evaluated based on their energy recovery potential, environmental impact, and economic feasibility. Case studies on successful implementations of advanced WtE technologies are analyzed to highlight their practicality and effectiveness. Finally, the paper addresses technical, regulatory, and policy challenges in this field and provides future perspectives. The objective is to underscore the role of advanced WtE technologies in achieving a sustainable and resource-efficient circular economy.

INTRODUCTION

The consistent and rapid increase in global waste generation and the pressing need to shift towards sustainable energy sources present significant challenges for society. According to the World Bank, global waste generation could increase by 70% from 2016 levels to 3.40 billion tonnes per year by 2050, driven by rapid urbanization and growing populations (Kaza et al. 2018). Simultaneously, the growing impacts of climate change and the depletion of finite fossil fuel reserves demand a transition towards renewable and sustainable energy sources. In this context, waste-to-energy (WtE) technologies, particularly advanced systems, have emerged as a promising solution based on the need to adopt policies that will enhance the affordability, reliability, and sustainability of energy (IEA 2022). These WtE technologies have the potential to transform vast amounts of waste into valuable energy resources, such as heat and electricity, thereby providing a pathway toward sustainable energy recovery. By converting waste into energy, these technologies not only help manage waste but also contribute to the diversification of energy sources and the reduction of greenhouse gas emissions.

Additionally, WtE technologies align with the principles of a circular economy, an economic system aimed at eliminating waste through the continual use of resources (Boloy et al. 2021). In a circular economy, waste is viewed not as a problem but as a resource that can be harnessed for value creation (Hari Bhakta et al. 2021). Advanced WtE technologies exemplify this strategy by converting waste into energy, thereby contributing to a more sustainable and resource-efficient economy. This convergence of waste management, energy recovery, and circular economy principles presents a compelling rationale for a deeper examination of advanced WtE technologies. Understanding their potential, efficiency, and the challenges they face is crucial for their successful implementation and for realizing a sustainable circular economy.

Research Questions, Objectives, and Scope of the Review

These research questions guided this study

(a) How does the principle of circular economy intersect with waste management and energy recovery?

(b) What criteria should be adopted in evaluating advanced waste-to-energy technologies in conformity with the principles of sustainability within the circular economy model?

(c) What are the technical, regulatory, and policy challenges faced by these advanced WtE technologies?

Following these research questions, the primary objective of this review is to provide a comprehensive understanding of advanced Waste-to-Energy (WtE) technologies and their role within the context of a circular economy. We aim to analyze the potential and viability of these technologies as solutions for sustainable energy recovery and waste management and evaluate their alignment with circular economy principles. In accordance with the preceding discussion, the specific objectives of the review were to (i) Explore the principles of a circular economy and how it intersects with waste management and energy recovery (ii) Provide an in-depth understanding of various thermal, biological, and chemical WtE technologies such as gasification, pyrolysis, plasma arc gasification, anaerobic digestion, fermentation, transesterification, and hydrothermal carbonization (iii) Summarize the important criteria for evaluating the efficiency of Advanced WtE technologies based on the principles compatible with the circular economy model and (iv) Present Case Studies, highlighting practical examples of successful implementations of advanced WtE technologies around the world, providing insights into their practicality and effectiveness.

The scope of the review is global, considering advanced WtE technologies and their implementations across various countries and regions. However, the specific context of each case may vary, given the influence of local factors, such as waste composition, regulatory frameworks, and socio-economic conditions.

MATERIALS AND METHODS

Methodology and Structure of the Paper

Based on a comprehensive literature review, this review paper draws on both theoretical and empirical sources to critically explore the subject of advanced Waste-to-Energy (WtE) technologies and their role in a circular economy. The literature review involved critical searches of several academic databases, including Google Scholar, Scopus, Web of Science, JSTOR, and Science Direct, using a combination of keywords such as "waste-to-energy," "advanced waste-to-energy technologies," "circular economy," and "sustainable energy recovery."

The paper is organized into seven main sections: Section 1 provides the background, rationale, objectives, and scope of the review, including the methodology and structure of the paper. Section 2 introduces the concept of a circular economy, discussing its principles, benefits, and how it intersects with waste management and energy recovery. Section 3 Gives an in-depth description of various thermal, biological, and chemical WtE technologies, while Section 4 Evaluates the Efficiency of Advanced WtE Technologies. Section 5 Presents Case Studies of Successful Implementations. Section 6 Discusses the technical, regulatory, and policy challenges faced by advanced WtE technologies, as well as future trends and research directions in this field. And finally Section 7: Summarizes the key findings of the review, discussing their implications for research and practice in the field of advanced WtE technologies and circular economy.

The Concept of a Circular Economy

The concept of Circular Economy (CE) is currently being promoted by the European Union (EU), as well as by several national governments, including Japan, France, China, the United Kingdom, Canada, the Netherlands, Sweden, and Finland. Additionally, several businesses around the world are also promoting the concept of a Circular Economy (EMAF, 2012, EMAF 2013, Jouni et al. 2018). The CE is a model of production and consumption that involves sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended, waste generation is minimized, and the value of products and materials is maintained. This is a significant shift away from the traditional linear economy, which follows a 'take-make-dispose' model of production (EMAF 2013, WEF 2014, Gustavo et al. 2017).

Principles of a Circular Economy

The circular economy operates on the foundation of three fundamental principles: the elimination of waste and pollution through design, the continuous utilization of products and materials, and the restoration of natural systems (EMAF 2013, Velenturf & Purnell 2021). Fig. 1 summarises these key principles.

Design out waste and pollution: Design plays a pivotal role in shaping production methods, consumption patterns, and disposal systems, with early decisions in product, service, and system development having a significant impact on both environmental and social outcomes (EEA 2016, Reichel et al. 2016). In a circular economy, products are designed and optimized for a cycle of disassembly and reuse, which significantly reduces waste and pollution. This principle involves rethinking product design to eliminate waste, considering the entire lifecycle of a product, and using materials that can be reused or safely returned to the environment. In recent years, various studies have focused on designs that focus on eliminating waste. To sustain principles of CE where there is high potential for

Fig 1: Principles of circular economy.

circularity, the European Union action plan focuses on those sectors that use the most resources, such as electronics and ICT, batteries and vehicles, packaging, plastics, textile construction and buildings, food, water, and nutrients. Tayebi-Khorami et al. (2019) identified various integrative approaches for rethinking mining wastes framed around the circular economy, which includes social dimensions, geo-environmental aspects, geo-metallurgy specifications, economic drivers, and legal implications. For instance, in textile production, (Zhang et al. 2018) focused on improving the design for the textile production process based on life cycle assessment. Similarly (Othman & Elsawaf 2021) applied the principle of "design out waste" in Public House Projects as a strategy to achieve sustainability. Bofylatos (2022) exemplified the principle of designing out waste" by the use of simple materials such as plywood, Plexiglas, and other local materials in an iterative research-through-design process that combines experiential and tacit knowledge from local case studies. The principle of designing out waste and pollution is at the heart of a circular economy. This principle entails rethinking and redesigning products and processes to prevent waste and pollution from being created in the first place.

The key strategies for implementing the principle of 'Design out Waste and Pollution" are Eco-Design, Business Models, Industrial Symbiosis, and Regulations and Standards.

Eco-Design: This involves designing products to reduce their environmental impact throughout their lifecycle, from raw material extraction to end-of-life disposal. This could include using less material, choosing renewable or recyclable materials, designing for easy disassembly, and minimizing energy use during production and use. Eco-design, as defined in ISO 14062 (ISO/TR 14062, 2002), is "*a design approach aiming to reduce the environmental impacts of products and services throughout the whole life cycle while assuring similar or improved services to the end customer*." More recently, the concept of eco-design has been applied to the manufacture of nanomaterials (Ilaria et al. 2023) and in the design of polymer matrix composite. (Lazar et al. 2023) with composite materials with a polymer matrix increasingly being used in various components of modern automobiles, including the body, seats, upholstery, electrical and electronic components, and many others (Lazar et al. 2023). In general, eco-design as a key strategy for "designing out waste" contributes to environmental and human health protection, as well as efficient resource utilization.

Business models: Businesses can adopt models that reduce waste and pollution. For example, product-as-a-service models allow companies to retain ownership of a product while customers pay for the service it provides. This incentivizes companies to design durable, reusable, and recyclable products, as they retain the responsibility for the product at the end of its service life (Miying et al. 2018, Salwin et al. 2022).

Industrial symbiosis: This involves sharing resources among different industries to minimize waste. For example, the waste product from one process can be used as a raw material in another process. This not only reduces waste but also reduces the need for virgin raw materials. Industrial symbiosis has proved to be a strong ally for the achievement of environmental, economic, and social objectives (Angela et al. 2020).

Regulations and standards: Governments have the power to establish regulations and standards mandating waste and pollution reduction in corporate practices. One such example is the implementation of extended producer responsibility (EPR) regulations, which compel producers to manage the disposal of their products at the end of their lifecycle (Ramasubramanian et al. 2023, Jenkins et al. 2023, Leclerc & Badami 2023). By proactively addressing waste and pollution in design, the circular economy not only mitigates the environmental consequences of production and consumption but also fosters economic prospects. Companies can reduce expenses by conserving materials and energy, while novel business prospects can emerge in sectors like recycling and product refurbishment.

Keep Products and Materials in Use

This principle centers on establishing a closed-loop system for all products, ensuring that resources are not discarded but are instead recycled repeatedly. It encompasses a range of strategies, including repair, remanufacturing, refurbishing, product sharing, leasing, and recycling, all aimed at maintaining these items within the economic cycle. The second core principle of the circular economy emphasizes the prolongation of product and material lifecycles to their fullest extent. The goal is to optimize the value of products and materials, decrease the need for fresh raw materials, and minimize waste generation. Here are some examples of how this principle has been put into practice:

Repair and maintenance: Regular repair and maintenance can extend the lifespan of products, delaying the point at which they become waste. This can involve traditional repair services, as well as innovative models like repair cafés, where community members can learn to fix their own items. The principles of repair and maintenance have been applied in many sectors, such as automobile, electrical, and more recently in healthcare equipment. Samenjo et al. (2023) extensively discussed various strategies and the extent to which the circular economy principle of repair and maintenance has been applied in the design of medical equipment for low-resource settings in Sub-Saharan Africa.

Reuse and redistribution: Products that are no longer needed by one person can often be used by others. This can be facilitated through second-hand markets, swapping platforms, and charitable donations.

Remanufacturing and refurbishing: Products can often be brought back to like-new condition through remanufacturing or refurbishing. This involves disassembling the product, repairing or replacing worn-out components, and then reassembling it. This can significantly extend the product's lifespan and reduce the need for new products to be manufactured (Ijomah 2010, Soloman et al. 2020, Coker et al. 2021, Oturu et al. 2021).

Recycling: When a product can no longer be repaired, reused, or remanufactured, the materials it is made from can often be recycled. This involves breaking down the product into its constituent materials, which can then be used to manufacture new products.

Product-as-a-service models: In these models, customers pay to use a product without owning it outright. This encourages manufacturers to design durable products and offer services to maintain and upgrade them, as they retain ownership of the product throughout its lifecycle.

By keeping products and materials in use, a circular economy can significantly reduce environmental impacts, create new business opportunities, and generate cost savings for consumers and businesses…

Regenerate Natural Systems

The circular economy promotes the use of renewable energy and materials and encourages systems that regenerate and restore. This means moving away from practices that harm the environment and depleting resources towards systems that improve the quality of the environment and increase resource security. (EMAF 2018, Geissdoerfer et al. 2017) These principles differentiate a circular economy from the traditional linear 'take-make-dispose' model. Instead of viewing the production process as a one-way street, the circular economy sees it as a loop that reuses and recycles materials minimizes waste, and creates sustainable patterns of consumption and production. The principle of regenerating natural systems is the third principle of a circular economy, focusing on enhancing and supporting the natural world. The idea is to go beyond just reducing harm and strive to create systems that have a positive impact on the environment. This principle is implemented through a variety of methods:

Use of renewable resources: Prioritizing the use of renewable resources, such as wind, solar, and geothermal energy, helps reduce dependence on finite, non-renewable resources and minimizes environmental degradation.

Restorative practices: Implementing practices that restore natural environments, such as reforestation and regenerative agriculture, can help rebuild ecosystems, increase biodiversity, and sequester carbon.

Biomimicry: This approach involves learning from and emulating nature's time-tested patterns and strategies to create sustainable solutions. For example, designing products or systems that mimic natural processes can help reduce waste and energy use. The nuances and relationship between biomimicry and sustainability were discussed extensively by (Ilieva et al. 2022), with biomimicry playing a critical role as a sustainable design methodology with a great potential to cultivate more sustainable human-nature relations (Taylor Buck et al. 2017, Lebdioui 2022).

Biodegradability: Using materials that can safely decompose back into the environment at the end of their life can help reduce waste and pollution and contribute to the nutrient cycle.

Carbon sequestration: Implementing methods to capture

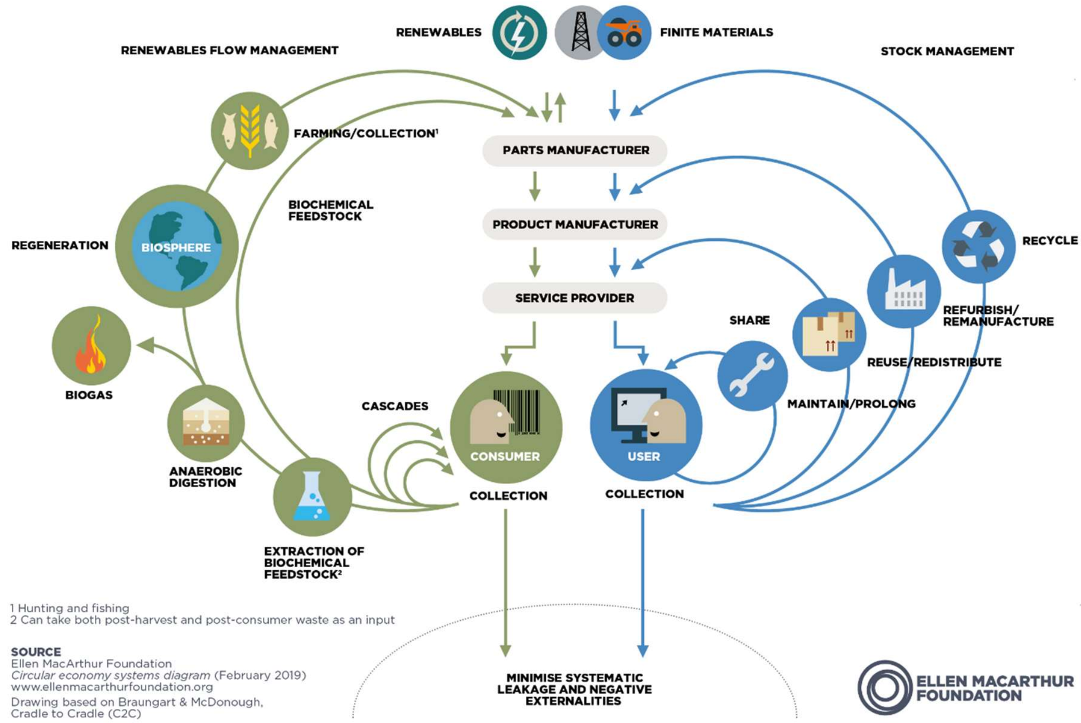

Fig. 2: Material flow in a circular economy source Ellen MacArthur Foundation (EMAF 2019).

and store carbon dioxide can help reduce greenhouse gas emissions and mitigate climate change. This can involve natural processes, such as reforestation, or technological solutions, such as carbon capture and storage.

Through the revitalization of natural systems, a circular economy supports the long-term well-being of our planet, safeguarding its capacity to provide the resources essential for human survival. This perspective acknowledges that the economy is intricately interconnected with the environment. It underscores the imperative for human society to collaborate harmoniously with nature, striving for a sustainable future instead of working at odds with it.

Circular Economy and Waste Management

Within the framework of a circular economy, waste is not regarded as a problem but as a valuable resource that can be harnessed. The overarching concept is to 'close the loop' within product lifecycles, achieved through enhanced recycling and re-manufacturing processes that curtail waste production. This approach is universally applicable, spanning diverse waste streams such as solid municipal waste, industrial by-products, agricultural residues, and more. Given the escalating volumes of waste generated by our expanding population and consumption patterns, waste management has emerged as a formidable global challenge. A circular economy presents a holistic strategy for addressing this issue, converting waste from a terminal outcome within a linear system into a precious resource within a circular system. The significance of a circular economy in waste management can be elucidated in multiple ways. Find below in Fig. 2 the diagrammatic representation of material flow within a circular economy according to the Ellen and MacArthur Foundation (EMAF).

Waste Reduction

By extending the utilization of materials and incorporating waste reduction measures from the inception, a circular economy can substantially curtail the volume of waste produced. This not only eases the burden on waste management systems but also mitigates the environmental repercussions tied to waste disposal, including the emission of greenhouse gases from landfill sites. Waste reduction, alternately referred to as waste prevention or waste minimization, entails the systematic reduction of waste generation by individuals, enterprises, or communities. It stands as a pivotal element within the waste management hierarchy and constitutes a fundamental tenet of a circular economy. The pursuit of waste reduction can be realized through a diverse array of strategies, such as (EMAF 2019)

- **Source Reduction**: This entails the reduction of waste at its origin by designing products that require fewer materials in manufacturing, have extended lifespans, and are easy and straightforward to repair, remanufacture, or recycle (Guo et al. 2021, Hajam et al. 2023).

- **Reuse**: Rather than disposing of items after use, there is an opportunity for their reuse. This might involve basic practices like opting for refillable water bottles and reusable shopping bags, or it might entail businesses engineering products with reusability in mind, such as refillable packaging.
- **Recycling and composting**: Recycling involves converting waste materials into new products, reducing the demand for virgin materials. Composting is a form of recycling where organic waste is broken down into a nutrient-rich soil conditioner.

Waste reduction has numerous environmental, economic, and social benefits. Environmental benefits include conserving materials and resources, reducing the demand for raw materials, decreasing pollution and greenhouse gas emissions associated with waste disposal, and the production of new goods. Economic benefits include preventing the costs associated with waste disposal and the purchase of new goods. Social benefits include reducing pollution and health impacts associated with raw material extraction (EMAF 2019). An established policy promoting the transition to a circular economy is the European Union's five-step waste hierarchy, introduced in the 2008 EU Waste Framework Directive, with a primary focus on waste generation prevention. EU Member States were mandated to implement waste prevention programs by December 2013, with numerous countries incorporating measures to encourage innovative business models, repair, reuse, and eco-design in their programs. (EEA 2016). In many African countries, with high levels of unemployment, poverty and inequality, with high demand for energy and resources, the principle of circular economy has been applied in many informal sectors. End-of-life products and equipment are often repaired, recycled, and reused. In South Africa, with high energy demands (DOE 2019a) and water scarcity challenges, grey water has been recycled and reused for decades, with returns of about 13% of South Africa's available water supply (Godfrey 2021).

Similarly, in the energy sector, with the increasing energy crisis, various forms of renewable energies have been adopted. Government policies and initiatives play a crucial role in promoting and institutionalizing the vision of a circular economy (Wills et al. 2016).

Value Creation

Value creation is a fundamental concept in economics and business, referring to the process through which goods, services, or some form of value is produced for consumers. Within the context of a circular economy, value creation takes on a broader and more sustainable perspective, going beyond economic profits to include environmental and social benefits. In a circular economy, value creation can occur at various stages:

- **Design phase**: Value can be created by designing products to be durable, repairable, reusable, and recyclable, extending their lifespan and reducing waste.
- **Production phase**: Value is created by using efficient processes that minimize waste and energy use, and by using renewable or recycled materials.
- **Use phase**: Value is created by providing services that enable consumers to use products longer, share them, or use them more efficiently.
- **End-of-life phase**: Value is created by recovering materials from products at the end of their life so they can be used to make new products, reducing the need for virgin resources.

Value creation in a circular economy has numerous benefits:

- **Economic**: It can generate new revenue streams, reduce costs, and create competitive advantages for businesses. It can also contribute to economic growth and job creation.
- **Environmental**: It can reduce resource use, waste, and emissions, contributing to environmental sustainability.
- **Social**: It can contribute to social wellbeing by creating more sustainable products and services, promoting fair labor practices, and reducing the social impacts of waste and pollution.

In a circular economy, the goal is to maximize value and minimize waste, not just in terms of economic profits but also in terms of environmental sustainability and social well-being. It's about creating a system that is good for people, the planet, and the economy. However, the potential for cost reduction plays a key role in the level of acceptability and implementation of the circular economy. Following the report on an investigation into South Africa's industrial perspective regarding circular economy models, motivating factors, and sustainability considerations, with a specific emphasis on composite waste, the study revealed that cost reduction stood out as the predominant catalyst and facilitator for composite recycling (Mativenga et al. 2017), Consequently, prioritizing avenues for cost reduction emerges as a pivotal element in motivating South African enterprises to adopt circular economy principles, underscoring its significance in shaping suitable national frameworks for guiding the transition toward a circular economy.

Sustainability

A circular economy supports sustainability by reducing the extraction and consumption of finite natural resources, minimizing waste and pollution, and creating systems that can continue to function effectively over the long term. Sustainability is a broad concept that involves meeting our present needs without compromising the ability of future generations to meet their own needs. It encompasses three interconnected 'pillars' or 'dimensions': economic, environmental, and social sustainability - often referred to as 'profits, planet, and people.' Find below a summary of each of these aspects:

Economic sustainability: This involves creating long-term economic value and ensuring that economic growth and development are balanced and sustainable. It includes aspects like profitability, economic resilience, fair trade, and responsible consumption and production.

Environmental sustainability: This involves protecting and preserving the natural environment for future generations. It includes aspects like reducing pollution and waste, conserving natural resources, tackling climate change, and promoting biodiversity.

Social sustainability: This involves ensuring social wellbeing, equity, and justice for all people. It includes aspects like human rights, labor standards, community development, health and wellbeing, and social inclusion.

Sustainability is a key principle in a circular economy, which aims to decouple economic growth from environmental degradation by designing out waste, keeping products and materials in use, and regenerating natural systems. In a circular economy, sustainability is not just about reducing the harm we do to the planet but actively contributing to its restoration and regeneration. Sustainability requires systemic thinking and collaborative action across different sectors and disciplines. It's about finding a balance between economic growth, environmental health, and social well-being and creating a world that is resilient, equitable, and sustainable for all (Sachs 2012, SDG 2022, Agbedahin 2019, UNESCO 2014a, Mckeown 2002b).

Climate Change Mitigation

Mitigating climate change and implementing a circular economy are closely linked in many ways. For instance, heat and electricity generation from renewable energy sources is an important means of reducing Greenhouse Gas emissions (GHGs) (Hans 2021). By reducing the demand for new resources and minimizing waste, a circular economy can help to mitigate climate change. Climate change mitigation refers to efforts to reduce or prevent the emission of greenhouse gases. This is because the extraction, processing, and disposal of materials contribute significantly to greenhouse gas emissions. By implementing a circular economy approach in waste management, society can transition towards a more sustainable, efficient, and resilient system that not only addresses the waste crisis but also contributes to broader economic, social, and environmental goals. The ultimate goal is to limit the future warming of the planet and avoid the worst impacts of climate change. Mitigation strategies can range from making energy consumption more efficient, to increasing the share of clean energy to removing carbon dioxide from the atmosphere. Previous studies have suggested the following key strategies:

Energy efficiency: Improving energy efficiency entails getting more output from each unit of energy. This is achieved through a variety of measures, such as improving insulation in buildings (Lachheb et al. 2019, Allouhi et al. 2015), increasing fuel economy in vehicles (Aguilar et al. 2021), and designing more efficient appliances and industrial processes. Lachheb demonstrated the efficiency of Spent Coffee Grounds (SCGs), with results indicating that up to 20% of the cooling and heating loads of a building can be reduced if SCG material substitutes the conventional one.

Renewable energy: Shifting from fossil fuels to renewable sources of energy, such as wind, solar, hydropower, and geothermal, can significantly reduce greenhouse gas (GHG) emissions. This also includes the use of bioenergy, as long as it's sourced sustainably.

Carbon capture and storage (CCS): Carbon Capture and Storage involves capturing carbon dioxide emissions from power plants and industrial processes and storing them underground to prevent them from being released into the atmosphere.

Land use and forestry: Protecting and restoring forests, which absorb carbon dioxide, can help offset emissions. Other strategies include improving agricultural practices and managing land use to increase carbon sequestration and reduce deforestation and land degradation.

Behavioral changes: This involves changes in individual and societal behaviors, such as reducing energy use, choosing more sustainable transportation options, and adopting plant-based diets.

Climate change mitigation is a key aspect of sustainability and a circular economy. By designing out waste, keeping products and materials in use, and regenerating natural systems, a circular economy can help reduce greenhouse gas emissions and contribute to climate change mitigation. It's also crucial to transition to a low-carbon economy, where energy is sourced from renewable sources, and resources are used more efficiently and sustainably.

CIRCULAR ECONOMY AND ENERGY RECOVERY

Energy recovery from waste is a key component of a circular economy. Advanced WtE technologies convert various types of waste into heat, electricity, and fuel, thereby providing a pathway toward sustainable energy recovery. (IEA 2020, Tun et al. 2020) By transforming waste into energy, these technologies not only contribute to the diversification of energy sources and the reduction of greenhouse gas emissions but also help to close the loop of material cycles in a circular economy.

The Role of Waste-to-Energy in a Circular Economy

Waste-to-energy (WtE) technologies play a particular role in a circular economy. These technologies convert solid waste materials that would otherwise be destined for landfill into heat, electricity, or fuel. By doing so, waste-to-energy can reduce the volume of waste, generate energy, and save on traditional waste disposal costs. However, it's important to remember that in a truly circular economy, the goal is to keep materials in use as long as possible and reduce waste to a minimum. Therefore, waste-to-energy should be seen as a last resort for dealing with waste after options for reduction, reuse, repair, and recycling have been explored.

Waste-to-energy technologies can contribute to energy recovery and waste management in a circular economy, but they also have some drawbacks. For instance, they can produce greenhouse gases and other pollutants, and they often require a steady stream of waste for their operation, which can discourage waste reduction efforts. Therefore, while waste-to-energy has a role in a circular economy, it should not replace efforts to prevent waste and keep materials in circulation.

Overview of Waste-to-Energy Technologies

Waste-to-Energy (WtE) technologies involve the process of generating energy in the form of electricity, heat, or fuel from waste materials. These technologies play a crucial role in waste management, energy creation, and resource recovery. Fig. 3 below shows the categories and types of some key waste-to-energy technologies:

Traditional Waste-to-Energy Technologies

Traditional Waste-to-Energy (WtE) technologies involve the conversion of non-recyclable waste materials into usable heat, electricity, or fuel. These technologies can play a key role in waste management, reducing the volume of waste sent to landfills and generating energy. Here are some common traditional WtE technologies:

Incineration: Incineration is the most common form of WtE and involves the combustion of waste at high temperatures. The heat generated is used to produce steam, which in turn drives a turbine to generate electricity. Modern incineration plants are designed to reduce the emission of pollutants, but concerns about air quality and residual ash remain. Incineration is a waste-to-energy (WtE) method where solid waste is combusted at high temperatures to reduce its volume and convert it into energy. It's often used to manage municipal solid waste, industrial waste, and certain hazardous wastes. (Makarichi et al. 2018)

The incineration process involves burning waste materials at high temperatures, often above 850°C. The heat generated is used to produce steam, which drives a turbine connected to a generator, producing electricity. The residual ash, which is reduced to about 15 - 10% of the original waste

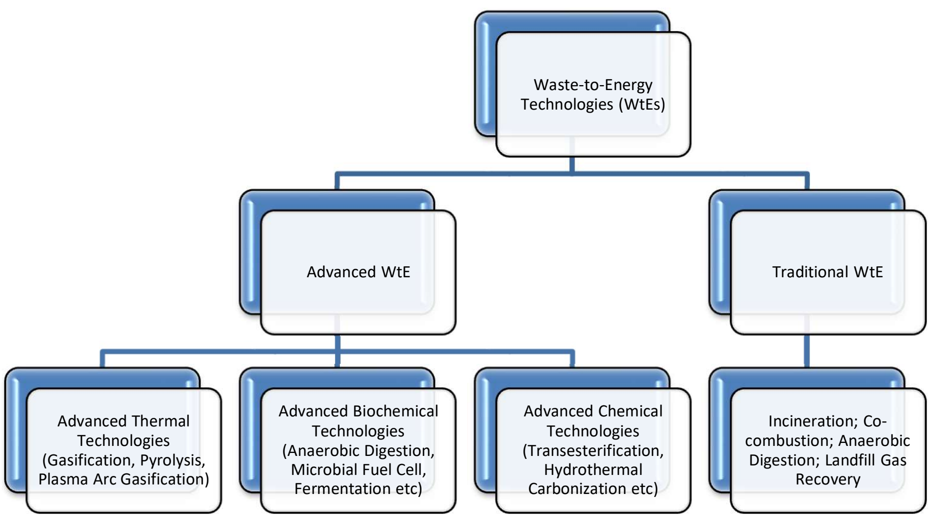

Fig. 3: Broad Categories of Waste-to-Energy Technologies.

volume, is often used in construction materials or disposed of in landfills.

Energy production: Incineration can generate significant amounts of energy. It's a reliable source of energy as it doesn't depend on weather conditions, unlike some renewable energy sources.

Waste reduction: Incineration reduces the volume of waste by about 90%, which can help save space in landfills and reduce the transportation and handling of waste (Đurđević et al. 2018, He et al. 2023).

However, there are some important considerations regarding incineration in a circular economy:

Air pollution and greenhouse gases: Incineration can produce pollutants like dioxins and furans, heavy metals, and particulates. Modern incinerators are equipped with pollution control equipment to reduce these emissions, but they are not eliminated. Incineration also releases carbon dioxide, a greenhouse gas, contributing to climate change.

Waste hierarchy: In a circular economy, the goal is to prevent waste and keep materials in use as long as possible. Therefore, incineration should only be used when waste cannot be prevented, reused, repaired, or recycled. It should not replace efforts to reduce waste and increase resource efficiency.

Energy efficiency: While incineration produces energy, it's less energy efficient compared to using those materials more directly. For example, recycling aluminum saves more than 90% of the energy needed to create new aluminum from raw materials, whereas incinerating aluminum waste to generate energy is far less efficient.

So, while incineration has a role in managing waste and producing energy in a circular economy, it should be used judiciously and not undermine efforts to prevent waste and recycle materials.

Co-combustion or co-firing: In co-combustion processes, waste materials are co-utilized with conventional fuels (such as coal) in industrial boilers or kilns, thereby contributing to a reduction in the consumption of fossil fuels and a decrease in emissions.

Anaerobic digestion (AD): Conventional anaerobic digestion processes primarily target the treatment of organic waste, including sewage sludge or agricultural residues. Within these processes, microorganisms decompose the waste in an oxygen-free environment, resulting in the generation of biogas, which comprises methane and carbon dioxide. This biogas can be harnessed for electricity or heat production. Anaerobic digestion is a biological process that entails the decomposition of organic waste materials, such as food waste, manure, or sewage sludge, through the activity of microorganisms in the absence of oxygen (Angelidaki et al. 2003, Ahring 2003). This waste-to-energy technology is a crucial component of the circular economy, especially in the management of organic waste and the production of sustainable energy. In a conventional anaerobic digestion system, organic waste is deposited into an enclosed anaerobic digester, creating an oxygen-free environment. Within this digester, microorganisms break down the organic matter, resulting in the production of biogas, composed mainly of methane and carbon dioxide, along with a nutrient-rich residue known as digestate. The biogas can serve as a versatile fuel source, powering applications like combined heat and power (CHP) plants to generate both electricity and heat. Alternatively, it can undergo purification and upgrading to become biomethane, a renewable natural gas. Meanwhile, the digestate remaining after the process can be repurposed as a soil conditioner or fertilizer, replenishing soil nutrients and diminishing the reliance on synthetic fertilizers (Samoraj et al. 2022).

Anaerobic digestion offers several benefits in a circular economy, such as **Waste Management**: It provides a way to manage organic waste, reducing the amount that goes to landfills and the associated methane emissions. **Renewable Energy**: It produces a renewable source of energy, contributing to the transition away from fossil fuels. **Soil Health**: It produces a nutrient-rich residue that can improve soil health and fertility. **Greenhouse Gas Reduction**: Capturing methane (a potent greenhouse gas) from organic waste, helps to reduce greenhouse gas emissions. However, some drawbacks and challenges with anaerobic digestion have been reported, such as the need for sorting and pre-treatment of waste, managing the digestate, and ensuring the system is economically viable. It's also important to remember that in a circular economy, the priority should still be to prevent waste in the first place, and anaerobic digestion should not replace efforts to reduce food waste and other forms of organic waste. **Landfill Gas Recovery (LGR)**: As waste decomposes in landfills, it produces a gas composed largely of methane and carbon dioxide. This gas is captured and used to generate electricity or heat or processed into a transportation fuel. This process helps to reduce greenhouse gas emissions and generate energy. When organic waste decomposes in a landfill, it produces landfill gas, which is approximately 50% methane (a potent greenhouse gas), 50% carbon dioxide, and a small amount of non-methane organic compounds.

Landfill gas recovery systems involve the installation of a series of wells and pipes throughout the landfill, which collect the gas as it's produced. This gas is then either flared (burned off), used on-site for heating or power generation, or processed and sold as a commercial energy source. The recovery and utilization of Landfill gases prevent methane, a potent greenhouse gas, from being released into the atmosphere, thereby helping to mitigate climate change. Additionally, using landfill gas as a source of energy reduces the demand for fossil fuels. Within the framework of circular economy, LGR has significant economic value as a cost-effective source of energy. By selling the gas or the electricity generated from it, landfill operators can generate additional revenue.

Additionally, the process of capturing LFG can create jobs and contribute to local economies. It can also reduce local air pollution by burning methane that would otherwise be released into the atmosphere. While landfill gas recovery is a valuable tool in waste management and energy production, it's important to remember that it's part of a broader waste management strategy. The priority should be on reducing waste, reusing materials, and recycling wherever possible to minimize the amount of waste going to landfills in the first place.

In general, traditional Waste-to-Energy (WtE) technologies, while valuable for waste management and energy generation, should be integrated into a comprehensive waste and resource management approach where the foremost emphasis lies on source waste reduction, product reuse, and material recycling, with WtE applications reserved for materials that cannot be feasibly reused or recycled and implemented with minimal environmental impact. Advanced WtE technologies emerged as a need to improve on the progress of the traditional WtE technologies.

ADVANCED WASTE-TO-ENERGY TECHNOLOGIES

Advanced Waste-to-Energy (WtE) technologies have evolved to provide more efficient and environmental-friendly methods for converting waste into energy. These technologies address some of the environmental concerns associated with traditional WtE methods, particularly around emissions and residues. Here are some examples:

Advanced Thermal Technologies (Gasification, pyrolysis, Plasma Arc Gasification)

These techniques involve heating waste in a low-oxygen or oxygen-free environment to produce a gas (syngas) that can be used to generate energy. These methods generally produce fewer emissions than traditional incineration and can handle a wide variety of waste types. Waste plastic, which poses a significant problem in terms of disposal, may be converted into energy through pyrolysis. Padmanabhan et al. (2022) investigated the possibility of recovering energy from waste plastics as a potential option to meet the circular economy as a fuel source. Plastic wastes were converted to diesel fuel through pyrolysis of High-Density Polyethylene (HDPE).

Gasification and pyrolysis are two related advanced thermal treatment technologies that convert waste into energy-rich fuels. They can be used to process a variety of waste materials, including municipal solid waste, industrial waste, biomass, and even certain hazardous wastes. Several studies have reported cases of energy recovery from other forms of waste, such as garden wastes through hydrothermal gasification (Ipiales et al. 2022), energy recovery for waste printed circuit boards using microwave pyrolysis (Huang et al. 2020), from pyrolysis of municipal solid waste (Husan et al. 2021) and waste tires (Abdallah et al. 2020).

The major difference between the process of gasification and pyrolysis lies in heating and process parameters.

Gasification: This is a process where waste is heated at high temperatures in a controlled, low-oxygen environment. This prevents combustion and instead produces a gas known as syngas (a combination of hydrogen, carbon monoxide, and sometimes carbon dioxide). Syngas is a versatile energy carrier that can be converted into electricity, heat, or transformed into other fuels (Padmanabhan et al. 2020).

Pyrolysis: is a process that entails heating waste in an oxygen-deprived environment, resulting in the decomposition of waste into three primary components: syngas, bio-oil, and a solid residue referred to as char. Syngas and bio-oil are versatile, finding applications in heat and electricity generation, as well as serving as chemical feedstocks. The potential use of char as a soil amendment depends on its specific properties and the presence of contaminants (Demirbas & Arin 2002, Soltes & Elder 2018).

Gasification and pyrolysis can process a variety of waste materials, including those that are difficult to recycle. They can generate energy and other valuable products, reducing the amount of waste that goes to landfills and the demand for virgin resources. However, gasification and pyrolysis also have some important considerations in a circular economy: Both processes require significant amounts of energy to heat the waste material (Jin et al. 2017). The net energy balance and resource efficiency depend on the type of waste, the specific technology used, and how the products are used. Gasification and pyrolysis can produce emissions and residues that need to be managed carefully. For example, syngas often need to be cleaned to remove impurities, and the char from pyrolysis may contain heavy metals or other contaminants Bernardo et al. 2010.

Plasma arc gasification: This advanced thermal treatment technology subjects waste to extremely high temperatures, reaching levels as elevated as 10,000 to 25,000 degrees Celsius, using a plasma torch (Pourali 2009, Yayalik et al. 2020). The intense heat triggers the transformation of waste into syngas and generates a minimal amount of solid residue known as slag, which, if uncontaminated, can be repurposed in construction projects. Plasma arc gasification is often lauded for its capacity to manage a wide array of waste types and its potential to significantly reduce waste volume.

While these thermal technologies offer a means to address waste that cannot be recycled or composted, they should be integrated into a comprehensive waste management strategy that prioritizes waste reduction, reuse, and recycling. Additionally, it's crucial to acknowledge that the energy efficiency, environmental impacts, and economic viability of these technologies can vary. Hence, adapting and optimizing them to suit local conditions and specific waste streams is of paramount importance.

Advanced Biochemical Technologies (Anaerobic Digestion, Microbial Fuel Cell, Fermentation)

Biochemical technologies involve the use of microorganisms to convert waste into usable products, including various forms of energy. Unlike conventional anaerobic digestion and fermentation, advanced AD systems continue to explore advanced techniques and processes to address the basic challenges in conventional AD systems:

Advanced anaerobic digestion: The Advanced Anaerobic digestion system employs an advanced biological process in which microorganisms break down organic materials in the absence of oxygen. These processes are harnessed and optimized to yield better results in terms of biogas production, comprising higher quality methane and less carbon dioxide, as well as a nutrient-rich digestate. The produced biogas can be harnessed for heat and electricity generation, while the digestate can serve as a beneficial soil conditioner or fertilizer. Enhanced Anaerobic digestion is a versatile method used for treating various organic waste streams, encompassing food waste, agricultural residues, and sewage sludge. Various advanced processes, including co-digestion and the use of additives and nanoparticles, have been applied to advanced AD to yield better results. (Hassanein 2019). Anaerobic Digestion (AD) technology holds a pivotal role in advancing the circular bioeconomy and contributes significantly to achieving carbon neutrality. It accomplishes this by converting organic materials into valuable bioenergy and biosolids. The production and reclamation of bioenergy from organic wastes through the stages of hydrolysis, acidogenesis, acetogenesis, and methanogenesis represent a cost-effective and sustainable approach for valorizing agricultural biomasses and food waste (Chibueze et al. 2021).

Microbial fuel cells (MFCs): These are bio-electrochemical devices that utilize the metabolic activity of microorganisms to generate electricity by oxidizing organic matter. These innovative devices have the potential to provide sustainable power generation while simultaneously treating wastewater or organic waste (Logan & Regan 2006, Franks & Nevin 2010, Slate et al. 2019).

Fermentation: Fermentation is a process where microorganisms, usually yeasts or bacteria, convert organic compounds - usually sugars and starches - into alcohols and gases. In a waste-to-energy context, it's often used to convert biomass or organic waste into bioethanol, a renewable fuel that can be used in transportation. The process also produces carbon dioxide and other by-products that can be captured and used.

The implementation of these technologies is currently being optimized for different waste streams and local conditions and should take into account the energy balance, environmental impacts, and economic feasibility.

Advanced Chemical Technologies (Transesterification, Hydrothermal Carbonization)

Chemical technologies involve reactions aimed at transforming waste into energy or other valuable products. Within the waste-to-energy (WtE) sector, two prominent technologies include transesterification and hydrothermal carbonization (Kumar & Samadder 2017).

Transesterification: This is a chemical process that converts fats and oils into biodiesel. It involves reacting lipids (fats and oils) with an alcohol (usually methanol or ethanol) in the presence of a catalyst (usually a strong alkali) to form esters (biodiesel) and glycerol. The biodiesel produced can be used as a fuel in diesel engines (Meher et al. 2006, Gandhi et al. 2011). Transesterification is commonly used to convert waste cooking oil and animal fats into biodiesel, providing a way to recycle these waste streams and produce renewable fuel. Recently, studies have focused on converting various plant-based materials to biodiesel through transesterification processes. Plant-based non-edible feedstock such as castor bean and jatropha were successfully converted to biodiesel (Baionie Silva et al. 2023), and using the nanocatalyst transesterification process, microalgae were converted to biodiesel (Akubude et al. 2019).

Hydrothermal carbonization (HTC): HTC is a process that converts organic waste into a coal-like substance known as hydrochar. The process involves treating the waste with water under high pressure and temperature (Djandja et al.

2023). The resulting hydrochar can be used as a solid fuel or as a soil amendment. HTC can be used to treat a wide variety of organic waste, including sewage sludge, food waste, and agricultural waste. While advanced WtE technologies offer promising solutions to waste management and energy production, the primary focus should always be on waste prevention, reduction, and recycling. WtE technologies should be utilized for waste that cannot be recycled or reused and implemented in ways that minimize environmental and health impacts.

Criteria for Evaluating the Efficiency of Advanced Waste-to-Energy Technologies

Assessing the effectiveness and efficiency of advanced Waste-to-Energy (WtE) technologies involves an evaluation encompassing both their technical proficiency and their environmental, economic, and social implications. In this review, the following key criteria were highlighted from all the relevant journal papers reviewed:

Energy efficiency: The overall energy efficiency of a WtE technology can be evaluated by comparing the energy content of the input waste to the usable energy output. This includes the heat and electricity generated or the energy content of any fuels produced.

In thermal WtE systems, such as gasification, the energy efficiency of gasification varies based on several factors, such as type of waste (feedstock), operating conditions, and the specific gasification technology. Many studies have reported a gasification energy efficiency between 60% - 80%. Zhang et al. (2011) conducted a thermodynamic evaluation of biomass gasification with air in auto-thermal gasifiers. They reported energy and exergy efficiencies of biomass gasification in the ranges of 52.38-77.41% and 36.5-50.19%, respectively. In a recent study, which integrated solar irradiation and gasification of municipal plastic wastes both energy and exergy efficiencies were obtained as 74% and 73%, respectively (Gungor & Dincer 2021, Aikalin & Dincer 2023). A higher efficiency can be achieved with advancements in gasification systems and energy optimization. In general, the efficiency of gasification processes depends on the ability to optimize the conversion of feedstock into valuable gases (e.g., syngas) while minimizing energy wastage. Variables affecting energy efficiency encompass the management of operational parameters (temperature, pressure, residence time), feedstock composition, the design of the gasification reactor, and the harnessing of waste heat for cogeneration applications. Additionally, it should be noted that energy efficiency can also be measured in terms of the overall system efficiency, considering the subsequent utilization of the produced syngas or other products. For example, if the syngas are efficiently used for combined heat and power (CHP) generation, the overall energy efficiency of the gasification system can be further improved.

The energy efficiency of biochemical systems, such as anaerobic digestion, and the energy efficiency of different biogas systems, which included single and co-digestion of multiple feedstocks, were evaluated. Pöschl et al. (2010) assessed the process energy efficiency using energy balance as the Primary Energy Input to Output (PEIO) ratio. They showed that PEIO corresponded to 10.5-64% and 34.1-55.0% for single feedstock digestion and co-digestion, respectively. When the feedstock used was transported from a distance of more than 22 km and 425 km for cattle manure and municipal solid waste, respectively, a negative energy efficiency was recorded. The overall energy input was influenced by the type and characteristics of feedstock and all other factors and processes that will contribute to energy input, such as pre-treatment of feedstock. Whereas energy balance depends on biogas yield, feedstock utilization efficiency, and energy value of intended fossil fuel substitution.

Transesterification is a chemical waste-to-energy process that involves the conversion of triglycerides, usually found in vegetable oils or animal fats, into acid alkyl esters known as biodiesels. This is usually done through a reaction with an alcohol. There are three broad types of transesterification processes – Base-catalyzed, Acid-Catalyzed, and Enzymatic Transesterification processes. The application of Ultrasound-assisted biodiesel production from waste-cotton seed cooking is gaining attention due to a lower reaction time and high energy efficiency. Sharma et al. (2020) investigated the application of Ultrasound-assisted KOH and CaO-catalyzed transesterification for biodiesel production from waste-cotton seed. They reported that the US-assisted transesterification process using KOH catalyst condition helped to reduce the mass transfer barrier and expedite the chemical reaction between non-miscible reactants. It also contributed to reducing the activation energy by allowing transesterification to be performed at lower temperatures.

Waste reduction: A key measure of the efficiency of WtE technologies is the degree to which they reduce the volume and mass of waste that would otherwise need to be disposed of in landfills. For instance, utilizing organic waste as a raw material, gasification, and pyrolysis systems can generate bio-oil, syngas, and thermal energy, all the while diminishing waste volume by up to 85-95% through the transformation into valuable biosolids and biochars (Srishti et al. 2021). Similarly, the waste reduction capacity from other biochemical processes, such as anaerobic digestion, will vary based on feedstock type, operating conditions,

Table 1: Classification of Waste based on WtE Technology and Energy potential.

Waste Category	Organic Waste	Municipal Solid Waste	Agricultural Waste	Waste Oils and Fats	Sewage Sludge
Energy Content (MJ/Kg)	15-20	10-15	10-20	35-40	5-10
WtE Technology	Anaerobic Digestion (AD), Gasification, pyrolysis	Incineration, AD, Gasification, pyrolysis	Direct Combustion, AD, gasification	Transesterification	AD, Gasification, combustion

detention time, and level of pre-treatment before utilization (Achi et al. 2020).

Environmental impact: The environmental impact of WtE technologies should be evaluated across their entire lifecycle, from the collection and preparation of waste to the end use of the energy produced. This includes the emissions produced during operation, the impacts of any residues that need to be disposed of, and the potential benefits of avoiding landfill disposal or fossil fuel consumption.

Economic feasibility: The economic feasibility of a WtE technology depends on the costs of building and operating the facility, the revenues from selling the energy produced or any valuable by-products, and the potential cost savings from reduced landfill disposal.

Social impact: The social impact of WtE technologies can include job creation, impacts on local communities (such as changes in traffic or noise levels), and potential health impacts from emissions.

Integration with waste management: Advanced WtE technologies should be evaluated as part of an integrated waste management strategy. This means considering how they fit with waste reduction, reuse, and recycling efforts and whether they are suitable for the local waste composition and quantities.

A thorough evaluation of advanced WtE technologies should consider all these aspects and involve a wide range of stakeholders, including local communities, waste management authorities, and environmental organizations. It should ideally be supported by detailed data and analysis, using tools such as life cycle assessment and cost-benefit analysis.

ENERGY RECOVERY POTENTIAL OF WASTE AND WTE TECHNOLOGIES

Energy recovery potential refers to the amount of usable energy that can be obtained from a waste material. This can vary greatly depending on the type of waste and the technology used to convert it into energy. Table 1 shows the energy recovery potential for different waste streams and technologies.

In all cases, the actual energy recovery will depend not only on the energy content of the waste but also on the efficiency of the conversion technology and the energy used in collecting, preparing, and processing the waste. Therefore, the overall energy balance and environmental impacts of waste-to-energy systems should be evaluated using a life cycle approach.

Environmental Impact

Waste-to-Energy (WtE) technologies can have significant environmental impacts, both positive and negative. Some of these impacts include:

Positive Impacts

Reduction in Landfill Use: By converting waste into energy, WtE technologies can significantly reduce the amount of waste that ends up in landfills. This can significantly help conserve land resources and reduce the environmental impacts associated with landfilling, such as the emission of methane, a potent greenhouse gas.

Renewable Energy Production: WtE technologies can produce renewable energy in the form of heat, electricity, or fuels. This can help replace fossil fuels and reduce greenhouse gas emissions.

Resource Recovery: Some WtE technologies can also recover valuable resources from waste, such as metals from incinerator bottom ash or nutrients from anaerobic digestion residues. This can help save natural resources and reduce the environmental impacts of mining and fertilizer production.

Negative Impacts

Air emissions: WtE technologies can produce air pollutants, such as particulate matter, nitrogen oxides, sulfur dioxide, and heavy metals, depending on the type of technology and the composition of the waste. Modern WtE facilities are equipped with advanced air pollution control systems to reduce these emissions, but they cannot eliminate them completely.

Greenhouse gas emissions: While WtE technologies can reduce greenhouse gas emissions by replacing fossil fuels and preventing landfill methane emissions, they can also produce carbon dioxide emissions, especially when they process waste containing fossil-derived materials like plastics.

Residues: WtE technologies can produce residues that need to be managed, such as incinerator bottom ash or residues from gas cleaning systems. These can sometimes contain contaminants that need to be treated or disposed of safely.

Energy and material use: The collection, preparation, and processing of waste for energy recovery can consume energy and materials, which can have additional environmental impacts.

In order to assess the overall environmental impacts of WtE technologies, a comprehensive life cycle assessment (LCA) should be conducted. This should take into account not only the operation of the WtE facility itself but also the upstream and downstream processes, such as waste collection and residue management.

Economic Feasibility

The economic feasibility of Waste-to-Energy (WtE) technologies depends on a variety of factors, including capital costs, operational costs, revenues, and policy support. Some of the key aspects to consider are:

1. **Capital costs:** The capital costs of WtE facilities can be substantial, especially for advanced technologies like gasification and pyrolysis. These costs include the design and construction of the facility, the purchase of equipment, and the installation of pollution control systems.
2. **Operational costs:** The operational costs of WtE facilities include labor, maintenance, fuel (if required), waste disposal, and other ongoing expenses. These can vary greatly depending on the technology, the scale of operation, and local conditions.
3. **Revenue streams:** The main revenue streams for WtE facilities are the sale of energy and any valuable by-products, such as metals recovered from incinerator ash or digestate from anaerobic digestion. The value of these products can depend on energy prices, commodity markets, and local demand.
4. **Policy support:** The economic feasibility of WtE technologies can be greatly influenced by policy support, such as renewable energy incentives, landfill taxes, or feed-in tariffs. These policies can help offset the costs of WtE technologies and make them more competitive with other forms of waste disposal and energy production.
5. **Waste Supply:** A reliable and sufficient supply of waste is necessary for the economic operation of a WtE facility. The costs of waste collection and preparation can also affect the economic feasibility.
6. **Life Cycle Costs:** To fully assess the economic feasibility of a WtE technology, it's important to consider the entire life cycle costs, from initial investment to decommissioning. This should also include the costs of managing any residues and potential future liabilities, such as environmental remediation.

A comprehensive economic evaluation should be undertaken to assess the viability of Waste-to-Energy (WtE) technologies, encompassing these factors and supported by realistic assumptions regarding future circumstances. Additionally, it is crucial to account for economic risks and uncertainties, such as fluctuations in energy prices or variations in waste composition.

CASE STUDIES OF SUCCESSFUL IMPLEMENTATION OF ADVANCED WASTE-TO-ENERGY TECHNOLOGIES

There are numerous examples of successful implementation of advanced Waste-to-Energy (WtE) technologies around the world. Here are only a few examples (Table 2):

These case studies demonstrate the feasibility of advanced WtE technologies and their potential benefits in terms of renewable energy production, waste reduction, and environmental protection. However, they also highlight the importance of careful planning, good design, and community engagement in ensuring the success of these projects.

For instance, Enerkem's facility in Edmonton, Alberta, is a prime example of advanced waste-to-energy technology in action. This facility uses gasification technology to convert municipal solid waste (MSW) into biofuels and chemicals. The Enerkem facility faced several challenges, including technical difficulties in scaling up the technology, delays in construction, and fluctuations in commodity prices. However, the project has demonstrated the technical feasibility of waste-to-biofuels technology and highlighted the importance of policy support and strong partnerships in bringing such projects to fruition. It also showcases the potential of advanced waste-to-energy technologies to contribute to a circular economy, where waste is viewed not as a problem to be disposed of but as a valuable resource.

Similarly, the Amager Bakke, also known as Copenhill, is a state-of-the-art waste-to-energy plant located in Copenhagen, Denmark. This facility is notable not only for its advanced technology but also for its creative approach to urban integration and multi-functionality. It plays a key role in Copenhagen's ambition to become a carbon-neutral city by 2025. It has been designed to be as efficient as possible, with a net energy efficiency of 107% due to its ability to utilize both heat and electricity from the waste.

In compliance with environmental policies, the plant also has a robust air pollution control system in place, ensuring that it complies with strict emission limits. Any

Table 2: Summary of case studies.

Case Studies	Type of Advanced WtE	Feedstock	Materials/Energy Recovery	Capacity/Scale
Enerkem, Edmonton, Canada (Enerkem, 2023)	Gasification	Municipal Solid Waste (MSW)	Methanol and Ethanol	Converts 100,000 Metric tons per year to $\approx$ 38 million litres of ethanol
Amager Bakke, Copenhagen, Denmark (Bjarke Ingels Group, 2019)	Advanced combustion/ Incinerator	MSW	Heat and Electricity	400,000 metric tons to provide heat for 160,000 households and electricity for 62,500 households
Powerhouse Energy Group, United Kingdom: (Powerhouse Energy Group (2023)	Gasification (Dual fluidized bed gasification)	Plastic waste	Synthetic Gas, hydrogen, and Electricity through combined Heat and Power systems	Large-scale
Ensyn, Canada and USA (Ensyn 20230)	Pyrolysis (Rapid Thermal Processing)	agricultural residues and biomasses	Bio-oil and bionased chemicals	Large Scale
Bristol BioEnergy Centre, UK; (Bristol Bioenergy Centre 2023)	Microbial Fuel Cells	Organic Waste	Electricity	Large scale/ Commercial
WasteMart, Western Cape South Africa (SA) (WasteMart 2023)	Gasification	Industrial and Municipal wastes	Syngas to Electricity and Heat	Commercial
Sasol, South Africa (Sasol 2023)	Plasma Gasification	Wastes	Synthetic fuels and Chemicals	Large Scale
EThekwini Municipality Biogas project, Durban, SA; (eThekwini Municipality 2019)	Anaerobic Digestion	Landfill Organic wastes	Biogas for electricity	3MW of electricity

residual ash from the incineration process is treated and, where possible, recycled as a substitute for natural aggregates in road construction. One of the most unique features of Amager Bakke is its multi-functional design. The roof of the plant has been designed to include a 400-meter-long ski slope, a climbing wall, and hiking trails. This creative approach to design not only helps integrate the facility into the urban landscape but also creates additional value for the community.

The success of Amager Bakke highlights the potential of waste-to-energy projects to contribute to urban sustainability and quality of life. It also underscores the importance of innovative design, community engagement, and political leadership in bringing such projects to fruition. The Amager Bakke case study demonstrates that waste-to-energy facilities can be more than just industrial plants. With thoughtful design and planning, they can become an integral part of the urban fabric, delivering multiple benefits and improving the quality of life in cities.

CHALLENGES AND FUTURE PERSPECTIVES

Waste-to-Energy technologies hold significant potential for managing waste and generating renewable energy. However, they also face several challenges:

1. **Technological Challenges:** Advanced WtE technologies, such as gasification and pyrolysis, are still evolving, and there can be challenges in scaling up these technologies and ensuring their operational reliability.
2. **Economic Challenges:** The high capital and operational costs of WtE facilities can be a barrier to their implementation, especially in the absence of policy support or favorable market conditions.
3. **Environmental Impacts:** While WtE technologies can have significant environmental benefits, they can also have negative impacts, such as air emissions and residues, which need to be carefully managed.
4. **Public Acceptance:** Public acceptance can be a challenge for WtE projects, especially for incineration-based technologies, due to concerns about emissions and health impacts.

With the future in perspective, there are several key areas of focus to overcome these challenges:

Technological Innovation: Ongoing research and development can help improve the performance and reliability of WtE technologies and reduce their costs and environmental impacts.

Public Engagement: Engaging with local communities and stakeholders is crucial for gaining public acceptance and ensuring the success of WtE projects.

Policy Support: Greater policy support, such as renewable energy incentives or landfill taxes, can help improve the economics of WtE projects.

Sustainability Assessment: Conducting comprehensive sustainability assessments, including life cycle assessments and socio-economic impact assessments, can help guide the planning and implementation of WtE projects to ensure they deliver net positive impacts. Although there are challenges to be overcome, the future of WtE technologies is promising, as they offer a potential solution to the dual problems of waste management and renewable energy generation.

Technical Challenges in Waste-to-Energy Technologies

Implementing Waste-to-Energy (WtE) technologies presents several technical challenges due to the complex nature of waste and the technologies themselves. The following key technical challenges were highlighted from the reviewed literature:

Variability of waste: Municipal solid waste is highly heterogeneous, with its composition varying significantly over time and geographical location. This variability can affect the operation of WtE technologies, particularly those like gasification, pyrolysis, and Anaerobic Digestion systems, which require a consistent feedstock.

Scale-up: Many advanced WtE technologies have been proven at a small scale, but scaling up to a commercial size can be challenging. This is due to the complex physical and chemical processes involved, which may not scale linearly.

Emission control: WtE technologies can generate emissions, such as particulates, heavy metals, dioxins, and furans, which need to be carefully controlled to meet environmental regulations. Developing and maintaining effective emission control systems can be technically challenging.

Energy recovery: Improving the efficiency of energy recovery from waste is a continual challenge. This includes optimizing the conversion process and integrating the WtE facility with other energy systems, such as district heating networks or electricity grids.

Residue management: WtE processes can produce residues, such as ash or char, which need to be treated and disposed of safely. Managing these residues, particularly those from incineration-based technologies can be technically challenging, especially if they contain hazardous substances.

Plant reliability and maintenance: Like any industrial facility, WtE plants need regular maintenance to ensure reliable operation. Given the harsh operating conditions, including high temperatures and the corrosive nature of waste, maintaining the reliability of WtE plants can be technically challenging.

Future research and development efforts will need to continue addressing these technical challenges to further improve the performance and viability of WtE technologies. This will likely involve a combination of technological innovation, process optimization, and system integration.

Regulatory and Policy Challenges in Waste-to-Energy Technologies

Implementing Waste-to-Energy (WtE) technologies can also face significant regulatory and policy challenges. The following are some of the key issues:

Regulatory complexity: The WtE projects often fall under the jurisdiction of multiple regulatory authorities, covering areas such as waste management, energy generation, and environmental protection. Navigating this regulatory landscape can be complex and time-consuming, and inconsistencies or uncertainties in regulations can pose significant challenges.

Policy support: The WtE projects typically require significant upfront investment and may not be economically viable without policy support, such as renewable energy subsidies, feed-in tariffs, or carbon pricing. The absence of such support or uncertainty about future policy direction can be a significant barrier to the development of WtE projects.

Waste hierarchy: Many jurisdictions follow a waste hierarchy that prioritizes waste prevention, reduction, reuse, and recycling over energy recovery and disposal. While this hierarchy is important for promoting sustainable waste management, it can also pose challenges for WtE projects, particularly if they are perceived as competing with recycling or waste reduction efforts.

Emission standards: Many WtE facilities are subject to strict emission standards to protect air quality and public health. Complying with these standards can be challenging, particularly for emerging technologies that may not yet have proven emission control systems.

Permitting and approval processes: Obtaining the necessary permits and approvals for a WtE facility can be a complex and lengthy process involving environmental impact assessments, public consultations, and detailed technical reviews. Delays or complications in this process can pose significant challenges.

Overcoming these regulatory and policy challenges requires a combination of proactive engagement with regulators and policymakers, careful project planning and design, and ongoing efforts to demonstrate the environmental and economic benefits of WtE technologies. It also underscores the importance of a stable and supportive policy environment for advancing sustainable waste management and energy recovery solutions.

Future Directions in Advanced Waste-to-Energy Technologies

The field of Waste-to-Energy (WtE) is subject to continuous innovation, growth, and development, with several promising trends, prospects, and directions for the future:

Advanced thermal technologies: While incineration remains the most common WtE technology, advanced thermal technologies like gasification and pyrolysis are gaining interest. These technologies can offer higher energy efficiency and potentially lower emissions compared to incineration, though they also come with their own challenges.

Biochemical technologies: The use of biochemical technologies like anaerobic digestion and fermentation for producing biogas and biofuels from organic waste is another promising area. These technologies can contribute to a circular economy by turning waste into valuable products.

Hybrid systems: Combining different WtE technologies in a hybrid system can offer advantages in terms of flexibility, efficiency, and environmental performance. For example, a system might use mechanical and biological treatment to pre-treat waste and extract recyclables, followed by thermal treatment for energy recovery from the residual waste.

Integration with other systems: There is growing interest in integrating WtE facilities with other systems, such as district heating networks or carbon capture and storage facilities, to improve overall efficiency and sustainability.

Circular economy approaches: The concept of a circular economy, where waste is viewed as a resource and kept in use for as long as possible, is influencing the development of WtE technologies. This includes technologies that can recover valuable materials from waste, as well as those that can convert waste into a variety of products, not just energy.

Digitalization and automation: The use of digital technologies, such as sensors, data analytics, and automation, can help improve the operation and maintenance of WtE facilities, enhance their efficiency, and reduce their environmental impact.

These future directions highlight the potential for continued innovation and improvement in WtE technologies. However, realizing this potential will require ongoing research and development, supportive policies, and collaboration among various stakeholders, including researchers, policymakers, industry, and communities.

CONCLUSION

Waste-to-energy (WtE) technologies hold significant potential to address two critical global challenges: managing increasing amounts of waste and reducing reliance on fossil fuels for energy generation. By converting waste into valuable energy, these technologies contribute to a more sustainable and circular economy. The case study of the Himiko plant in Tokyo, Japan, provided a detailed view of the practical implementation and potential benefits of advanced WtE technologies. However, it also highlighted the challenges involved, including managing waste variability, maintaining high energy efficiency, and ensuring public acceptance.

Several technical, regulatory, and policy challenges must be addressed to further the adoption of WtE technologies. These include the variability of waste, the difficulty of scaling up technologies, emission control, the need for policy support, and the complexity of regulatory environments. Looking to the future, promising trends include the development of advanced thermal and biochemical technologies, the integration of WtE facilities with other systems, the application of circular economy principles, and the digitalization and automation of WtE operations. Addressing these challenges and seizing these opportunities will require concerted efforts across multiple sectors and disciplines. It will necessitate ongoing research and development, supportive policy frameworks, and proactive engagement with stakeholders, including local communities.

In conclusion, while WtE technologies face significant challenges, they also offer considerable opportunities. If these challenges can be successfully addressed, WtE technologies can play an important role in transitioning towards a more sustainable and resilient energy system while also contributing to effective waste management.

Summary of Key Findings

Through the analysis and case study of Waste-to-Energy (WtE) technologies, several key findings emerged:

1. **Value of WtE technologies:** WtE technologies can play a significant role in sustainable waste management and renewable energy generation, contributing to a circular economy by turning waste into valuable resources.
2. **Performance of advanced WtE technologies:** Advanced WtE technologies, such as gasification, as seen in the Himiko plant, can offer high energy efficiency and low emissions. However, they also pose challenges, including managing waste variability and maintaining high energy efficiency.
3. **Importance of regulatory and policy support:** Regulatory and policy support is crucial for the implementation and operation of WtE projects. This includes clear and consistent regulations, financial

incentives for renewable energy, and supportive planning and permitting processes.

4 **Challenges in WtE implementation:** There are significant technical, regulatory, and policy challenges in implementing WtE technologies. These range from the technical challenges of handling varied waste to the regulatory challenges of navigating complex environmental regulations.

5. **Future directions in WtE:** The future of WtE includes areas like advanced thermal and biochemical technologies, hybrid systems, integration with other systems, circular economy approaches, and the use of digital technologies to improve WtE operations.

These findings underscore the potential of WtE technologies to contribute to sustainable waste management and renewable energy generation. However, they also highlight the complexity and challenges involved in implementing and operating these technologies, and the need for ongoing research, development, and policy support to advance this field.

Implications for Policy and Practice

The key findings of this analysis have several important implications for policy and practice in the field of Waste-to-Energy (WtE):

1. **Policy support:** Given the significant upfront costs and technical challenges associated with WtE projects, policy support is crucial. This can take various forms, including financial incentives for renewable energy, simplified permitting processes, and stable, long-term policy frameworks that provide certainty for investors.
2. **Integrated waste management:** WtE should be considered as part of an integrated waste management strategy that also includes waste prevention, reduction, reuse, and recycling. Policies and practices should aim to optimize the entire waste management system rather than focusing solely on energy recovery.
3. **Stakeholder engagement:** Given the potential environmental and health impacts of WtE facilities and the public concern these can generate, proactive and transparent engagement with local communities and other stakeholders is crucial. This can help build understanding and acceptance of WtE projects and ensure that their benefits are equitably shared.
4. **Research and development:** Ongoing research and development is needed to improve WtE technologies, address technical challenges, and develop innovative solutions. This should be supported by funding and collaboration opportunities, as well as mechanisms for sharing knowledge and best practices.
5. **Regulatory harmonization:** Efforts should be made to harmonize and streamline the regulatory frameworks that apply to WtE projects. This can help reduce the complexity and uncertainty that project developers face while maintaining robust environmental and health protections.
6. **Sustainability metrics:** The development and use of comprehensive sustainability metrics can help assess the overall performance of WtE projects, taking into account not just energy output and emissions but also factors like waste reduction, resource recovery, and social impacts.

By addressing these implications, policymakers, practitioners, and other stakeholders can help advance the development and adoption of WtE technologies and maximize their contributions to sustainable waste management and renewable energy generation.

Areas for Further Research

The findings of this study also highlight several areas for further research in the field of Waste-to-Energy (WtE):

1. **Advanced WtE technologies:** There is a need for more research into advanced thermal and biochemical WtE technologies, including their technical performance, environmental impacts, and economic viability. This can help address the current challenges faced by these technologies and unlock their full potential.
2. **Hybrid systems and system integration:** The potential benefits of combining different WtE technologies into hybrid systems or integrating WtE facilities with other energy systems are promising areas for further research.
3. **Sustainability assessment:** More research is needed to develop comprehensive sustainability assessment methods for WtE projects, taking into account not just energy output and emissions but also other environmental, economic, and social impacts.
4. **Waste variability:** Given the significant variability of waste, research is needed to better understand its impacts on WtE operations and how these can be managed. This may involve developing more flexible technologies or improving waste sorting and pre-processing methods.
5. **Policy analysis:** Further research is needed to understand the impacts of different policies on the development and operation of WtE projects. This can inform the design of more effective policy frameworks and support mechanisms.

6. **Public acceptance:** Understanding the factors that influence public acceptance of WtE projects and how these can be addressed is another important area for research.

By pursuing these research areas, we can deepen our understanding of WtE technologies, address their current challenges, and better harness their potential to contribute to sustainable waste management and renewable energy generation.

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