

Review

Towards Circular Economy: Integrating Waste Management for Renewable Energy Optimization in Zimbabwe

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Abstract: Many countries across the globe are not yet exploiting the full potential energy that is inherent in waste to solve their energy and waste management crisis. This review critically examines the intersection of waste management and renewable energy optimization within the context of Zimbabwe's transition towards a circular economy. This review explores the integration of waste management practices into renewable energy initiatives to foster a circular economy in Zimbabwe. Therefore, by assessing the feasibility and benefits of incorporating waste-to-energy technologies, this study elucidates the potential for synergistic resource utilization and environmental sustainability. Through a comprehensive analysis of existing waste management frameworks and renewable energy strategies, this paper highlights opportunities for optimizing energy production while addressing pressing waste management challenges. Ultimately, the findings underscore the importance of adopting a comprehensive approach to renewable energy development that leverages waste as a valuable resource in Zimbabwe's transition towards a circular economy paradigm.

Keywords: energy management; circular economy; waste management; renewable energy



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1. Introduction

The transition towards a circular economy represents a crucial paradigm shift in sustainable development, particularly in the context of addressing energy and waste management issues [1,2]. In Zimbabwe, the government seeks to enhance its sustainability efforts, and incorporating the potential synergies between waste management and renewable energy is a paramount part of its vision for the 2030 middle economy.

This concept of the circular economy is based on and applied from the 5R, which implies re-using, re-making, recovering, recycling, and rethinking, with the aim of producing no waste in the manufacturing sectors. This paper aims to explore the opportunities and challenges experienced by integrating waste management into renewable energy initiatives in Zimbabwe, highlighting the significance of this approach for achieving environmental sustainability and resource efficiency.

Effective waste management is crucial in developing countries. Unfortunately, the current situation in many of these nations is far from ideal. Inadequate waste collection rates, low recycling levels, littering, and improper final disposal are major challenges that must be addressed urgently. These challenges pose significant obstacles to achieving a circular economy in these countries. However, it is important to note that implementing integrated waste management systems can be expensive and slow, making it difficult for developing countries lacking waste management infrastructure to implement such complex systems right away.

A recent study by Shabani et al. [3] states that implementing circular economy principles in waste management in Zimbabwe is very important for optimizing renewable energy utilization in the country. Integrating sustainable management practices, such as life cycle assessment models, can transform the country towards a sustainable future. The shift does not align with or promote the United Nations Sustainable Development Goals [4] only but also promotes economic growth and social benefits for the people of Zimbabwe [3]. Empowering the communities in the different parts of the country can help pave the way to renewable energy optimization and environmental efficiency. Therefore, integrating waste management techniques can optimize the use of renewable energy.

The convergence of waste management and renewable energy optimization holds significant aspects for both environmental sustainability and public well-being across the globe. According to Sithole et al. [5], Zimbabwe has notably committed to reducing its greenhouse gas emissions by 40% by 2030 across all sectors. The researchers highlighted that the energy sector alone contributes approximately 34% of the country's total emissions. Zimbabwe is also a signatory of the Paris Climate Change Agreement [6]. To achieve this target, Zimbabwe has developed a comprehensive climate action plan that includes specific policies and measures. The actions in the plan include the expansion of renewable electricity generation and energy efficiency improvements.

Research on waste management and the circular economy in Zimbabwe has highlighted a range of challenges and potential solutions [7]. New research on solid waste management issues states that the problem is growing, especially in schools where open dumping persists, causing environmental pollution, and there is a scarcity of research on waste management in Zimbabwean educational institutions [8]. Waste management plays an important role in the reduction of emissions, and Zimbabwe can explore waste-to-energy solutions, converting waste into usable energy.

Therefore, an extract from the United Nations Framework Convention on Climate Change (UNFCCC) [9] states that prioritizing the steps outlined below can enhance both waste management and renewable energy optimization:

- (1) Reduce: Minimize waste generation.
- (2) Re-use: Encourage the re-use of materials.
- (3) Recycle: Promote recycling practices.
- (4) Recover Value: Extract energy from waste.
- (5) Disposal: Landfill only when no alternative is available.

However, in many cities in Zimbabwe such as Harare and Bulawayo and other small towns, there are challenges such as illegal dumping, inefficient collection, and a lack of integrated solid waste management systems [10]. In terms of waste management, the country faces issues such as inadequate infrastructure and low public awareness, leading to poor waste management. Zimbabwe's waste-to-energy landscape is dominated by biomass, with traditional methods still being used in the process. Makonese [11] also pointed out that the country has significant potential for renewable energy but faces challenges in its development and adoption. In terms of waste management, Harare and Bulawayo, to name a few of these cities, are still grappling with significant challenges, including pollution and inadequate infrastructure. The potential for energy generation from waste is highlighted, suggesting a shift towards decentralized waste management systems. Addressing these issues through integrated waste management systems and renewable energy technologies can mitigate energy poverty, environmental impact, and health hazards in Zimbabwe.

The circular economy paradigm emphasizes resource efficiency, waste reduction, and sustainable practices [12,13]. In Zimbabwe, where waste management and renewable energy play critical roles, integrating these two domains can yield significant benefits. Therefore, integrating waste management into renewable energy strategies is crucial for fostering a circular economy in Zimbabwe. This approach not only addresses waste problems or energy poverty but also aligns with sustainable development goals.

Hence, the integration of waste management into renewable energy strategies is crucial to fostering a circular economy in Zimbabwe. Mukhlis et al. [14] emphasized the need for

long-term planning and community engagement in waste management, with research on village results showing a feasible implementation of a circular economy model consisting of reducing, re-using, and recycling. At the same time, other researchers highlighted the importance of waste minimization strategies in the informal sector [7]. These studies collectively underscore the significance of integrating waste management into renewable energy strategies as a key component of a circular economy in Zimbabwe.

Circular economy initiatives offer various benefits [15,16]:

1. Resource Recovery: Processes like waste-to-energy extract value from organic waste.
2. Landfill Reduction: Implementing waste-to-energy methods minimizes the burden on landfills.
3. Synergy with Biomass Energy: Converting biomass into energy aligns waste management with renewable energy goals.
4. Job Creation: Circular economy initiatives foster employment opportunities.

Consequently, incorporating waste management into renewable energy approaches can enable Zimbabwe to progress towards a more sustainable and circular economic system. Moreover, social and cultural factors may influence community acceptance of and participation in waste management and renewable energy initiatives. Thus, while the concept of a circular economy offers a compelling vision for sustainability, careful consideration of these challenges is essential to ensure the successful implementation and realization of its benefits in Zimbabwe. Nonetheless, with strategic planning, collaborative efforts, and innovative solutions, Zimbabwe has the potential to overcome these obstacles and emerge as a leader in sustainable development within the region.

The main objective of this research was to explore the opportunities and challenges of integrating waste management into renewable energy initiatives in Zimbabwe, with a focus on the potential for waste-to-energy technologies. Through the examination of existing waste management frameworks and renewable energy strategies in the country, this study aims to highlight the potential for synergistic resource utilization and environmental sustainability. This research seeks to contribute to the field of study by providing a comprehensive analysis of the feasibility and benefits of incorporating waste-to-energy technologies in Zimbabwe's transition towards a circular economy. The findings of this study will inform policymakers and stakeholders of the potential for waste-to-energy technologies in addressing energy poverty and environmental impact in Zimbabwe. Additionally, this research will provide insights into the social and cultural factors that may influence community acceptance and participation in waste management and renewable energy initiatives in Zimbabwe.

Methodology

A comprehensive search was conducted on Scopus, Web of Science, and Google Scholar to identify relevant articles. The search terms used included "waste management", "renewable energy", "waste-to-energy", "circular economy", and "Zimbabwe". The inclusion criteria for the studies were articles published in English since 2010 focusing on waste management and renewable energy initiatives in Zimbabwe. All article types, including research articles, review articles, and conference papers, were included. Studies were excluded if they were not relevant to the research question, not published in English, or not focused on Zimbabwe.

The data synthesis and analysis were conducted using a thematic approach. The studies were categorized according to the type of waste management and renewable energy initiatives. The themes that emerged from the data were analyzed, and the findings were synthesized. The synthesized findings were used to identify the opportunities and challenges of integrating waste management into renewable energy initiatives in Zimbabwe. The strengths and limitations of the studies were also considered in the analysis. The limitations of this study include the exclusion of non-English articles and the focus on Zimbabwe only. Future research may consider a broader scope of geographical locations and languages to provide a more comprehensive understanding of the topic.

2. Waste-to-Energy Technologies: Potentials and Challenges

Energy is the key to sustainable development. Rapid urbanization and industrialization have caused an increase in waste generation in developing countries across the globe [17]. However, waste-to-energy solutions offer significant assistance in addressing waste management challenges around the world. Waste-to-energy technologies play a crucial role in sustainable waste management and energy production [18]. These technologies encompass a diverse array of processes aimed at converting various waste forms into usable energy sources. These technologies typically involve thermal or biological processes to extract energy from waste materials, including municipal solid waste, agricultural residues, biomass, and industrial by-products.

Waste-to-energy technologies offer a sustainable solution to waste management challenges while contributing to renewable energy production and reducing greenhouse gas emissions.

2.1. Review of Various Waste-to-Energy Technologies and Their Feasibility

Several researchers have reviewed various waste-to-energy technologies (Table 1). These technologies include pyrolysis, incineration, gasification, anaerobic digestion, and landfilling with gas recovery; these all contribute to the sustainable development goals of the globe. Municipal waste incineration has been used in many cities and municipalities all over the world and offers sustainable waste management. A recent study by Zafar et al. [19] highlights the importance of solid waste incineration in Pakistan's major cities, proving the feasibility of using this technology, which will be beneficial to the country. The study proposes the use of thermal energy-based municipal solid waste incineration technology for electricity generation and waste volume reduction in Pakistan. However, a comprehensive review study by Mayer et al. [20] showed that anaerobic digestion and gasification emerged as more competitive or better than incineration in waste conversion, with proven results across the globe.

A range of waste-to-energy technologies have been reviewed, with a focus on their feasibility and potential in various contexts. Afrane et al. [21] analyzed four waste-to-energy alternatives (anaerobic digestion, gasification, pyrolysis, and plasma arc gasification) in Ghana and highlighted the techno-feasibility results of these technologies for investment. They found that gasification emerged as the optimal waste-to-energy technology in Ghana, followed by anaerobic digestion, pyrolysis, and plasma arc gasification.

To counter-argue this, another recent study by Ahmed et al. [22] compared the feasibility of three waste-to-energy technologies, namely, incineration, landfill gas recovery, and anaerobic digestion in Bangladesh, Egypt, Afghanistan, Ghana, and Indonesia and analyzed the electricity generation potential, economic viability, and socio-environmental dimensions; however, the results showed that incineration was the best method. Dhar et al. [23] reviewed the use of organic waste to produce energy in India, and the review presents a sustainable approach to reduce volumes and pollution, offering various economic and social benefits.

To elucidate these technologies, Kumar and Samadder [24] emphasized the capacity of waste to energy to serve as a renewable energy resource. The study reviewed technologies such as incineration, pyrolysis, gasification, anaerobic digestion, and landfilling, with landfilling emerging as the most practiced method across developing countries. Waste-to-energy technologies like incineration and anaerobic digestion are crucial for sustainable development, addressing United Nations Sustainable Development Goals 7 and 11 [25].

Waste-to-energy technologies offer significant potential in terms of energy generation, economic viability, and environmental impact. Anaerobic digestion and incineration are the leading most used technologies from different parts of the world. Therefore, tracing the developments across the globe underscores the importance of waste-to-energy technologies as integral components of sustainable waste management and renewable energy strategies. Despite these technologies offering several benefits in addressing waste and

energy challenges, they should be part of a broader, integrated approach to sustainability that prioritizes waste prevention and minimization [26].

Table 1. Various waste-to-energy technologies and their feasibility.

Technology	Waste	Feasibility	Key Findings	Ref.
Anaerobic digestion	Municipal solid waste (organic fraction)	High	The research findings demonstrated that anaerobic digestion emerged as the most effective approach for treating and managing the biodegradable portion of municipal solid waste in Harare and its surrounding urban and peri-urban areas. As a result, it is crucial to consider anaerobic digestion as a comprehensive waste management strategy. This approach not only contributes to the enhancement of renewable energy supply but also facilitates agricultural and horticultural productivity through the utilization of biofertilizers in the form of digestate or compost. Furthermore, adopting anaerobic digestion helps in mitigating greenhouse gas emissions, in alignment with the National Low Emission Development strategy, while preserving the quality of both surface and groundwater resources.	[27]
Pyrolysis	Pine sawdust waste	High	The bio-oil produced from the process primarily consists of phenolics, furan, carboxylic acids, and aromatics, with phenols being the predominant chemical identified. These phenolic compounds can be extracted using solvent methods and find applications in various industries, including in chemical production, antioxidants, and antimicrobials. Additionally, the inclusion of phenols in biofuels improves their properties and helps prevent degradation during storage. Furthermore, the study revealed the potential for upgrading bio-oil to biodiesel through a transesterification process. The properties of the resulting biodiesel were found to meet the requirements specified by EN 14214 [28].	[29]
Gasification	Coal water slurry	High	The practical potential of light-induced conversion for industrial waste-to-syngas conversion is promising. Through the utilization of light-induced gasification, waste-derived fuel could be efficiently converted into syngas, with a conversion efficiency of over 30%. This process generated carbon monoxide and hydrogen gases. Notably, light-induced gasification enabled “cold” processing without the need for conventional fire-based methods, making it a safer option. Moreover, this approach demonstrated good practical potential for industrial applications, as it does not require expensive components, thereby enhancing its economic feasibility.	[30]
Incineration	Municipal solid waste	Moderate	According to the study, an incinerator with a capacity of 32,500 kg/h has the capability to handle all the anticipated waste generated in Malta over the next 20 years. The evaluation of waste combustion enthalpy was carried out using data on the composition of municipal solid waste. Among the various scenarios considered, the study identified that incineration coupled with combined heat and power (CHP) offered the greatest potential for optimizing revenue generation. This approach involves efficiently combining the production of heat and electricity. Through the implementation of incineration and CHP together, the process can maximize revenue by simultaneously generating electric power and producing desalinated water.	[31]
Landfilling with gas recovery	Municipal solid waste	Low	The study’s main finding suggests that combined heat and power (CHP) production from case landfills provides the highest greenhouse gas (GHG) emission savings. As a result, the study recommended CHP production as a suitable option for utilizing the gas generated from landfills. Through the implementation of CHP, the waste gases produced by landfills can be efficiently utilized to generate both heat and power. This approach helps to minimize the release of GHG emissions into the atmosphere, contributing to environmental sustainability and mitigating climate change.	[32]

2.2. Applicability to Zimbabwean Context and Case Study

Various waste-to-energy technologies applicable to the Zimbabwean context, including anaerobic digestion, incineration, gasification, and landfill gas energy, have been reviewed by researchers. Nhubu et al. [33] estimated the production of energy from waste in Zimbabwe's urban centers. The study highlighted the potential of various waste-to-energy technologies that can be applied to the country; however, it failed to provide details of the exploration of the analysis. Incineration and gasification contribute 5% and 2%, respectively, to national electricity consumption, with energy generation potentials of 415.8 GWh and 168.5 GWh [33]. Landfill gas to energy, with estimated electrical power potentials of 43.1 GWh and 66.8 GWh for different temporal scales, contributes 2.5% to national electricity consumption [33]. These technologies provide substantial energy recovery from waste, mitigating energy poverty and environmental impacts in Zimbabwe, which is in line with the nation's sustainable development objectives of Vision 2030. Another study examined the potential of energy recovery from municipal waste in Harare [34]. The results prove the feasibility of extracting energy from waste, reducing landfill waste by up to 40% and increasing the electrical energy production of the waste. An ever-increasing body of literature findings advocates for waste-to-energy technologies as viable waste disposal options in African cities, for example, Harare, Zimbabwe [35,36].

Case Study: Pomona Waste-to-Energy Project in Harare

Like many big cities around the world, Harare has also suffered from sustainable waste management due to increased urbanization and population growth. However, to curb this problem, Harare City Council, with funding from the government, came up with the introduction of the Pomona dumpsite.

The Pomona dumpsite project in Harare aims to address the city's waste management challenges by transforming the existing landfill into a modern waste management facility. The project involves upgrading infrastructure, implementing advanced waste treatment technologies, and incorporating sustainable practices to minimize environmental impact and improve public health. By modernizing waste management processes, the Pomona dumpsite project seeks to enhance waste collection, recycling, and disposal practices in Harare, promoting a cleaner and healthier urban environment for residents. All waste collected in Harare is transported to the Pomona dumpsite, which is a central location for solid waste disposal.

Although the Pomona dumpsite in Harare, Zimbabwe, serves as a major destination for solid waste (Figure 1), a significant portion comprises household waste. The plant is intended to produce or generate 16 to 22 MW. However, the integration of the informal recycling sector with the waste management system at the dumpsite has been found to be incomplete, leading to missed opportunities for poverty alleviation and improved waste management [37].



Figure 1. The Pomona waste management plant.

The management of the dumpsite has also raised concerns about groundwater contamination, with the potential for future risks if a properly engineered landfill is not constructed. These issues are further compounded by the lack of accurate and reliable data on waste generation and composition, which hinders effective planning for sustainable waste management [10].

2.3. Challenges of Waste-to-Energy Technologies in Zimbabwe

The potential for waste-to-energy technologies in Zimbabwe is significant; however, this potential is hindered by policy limitations and the need to explore other commercially available options. The challenges of waste-to-energy technologies in Zimbabwe include the following:

- (1) **Limited Infrastructure:** Zimbabwe faces constraints in infrastructure development, including inadequate waste collection and disposal systems, which hinder the implementation of these projects.
- (2) **Technological Feasibility:** Many of these technologies require advanced infrastructure and expertise, which may not be readily available in Zimbabwe, leading to feasibility concerns.
- (3) **Financial Constraints:** Funding for waste-to-energy projects is limited, and there are challenges in securing investment due to economic instability and limited access to financing.
- (4) **Regulatory Frameworks:** The lack of comprehensive waste management policies and regulations specific to waste-to-energy technologies complicates project development and implementation.

Addressing these challenges will require coordinated efforts from the government, the private sector, and civil society stakeholders to create an environment that is conducive to the success of these projects. The next section will discuss the implementation of policy and regulatory frameworks.

3. Policy and Regulatory Frameworks

3.1. Energy Policies and Legal Frameworks in Zimbabwe

3.1.1. The National Energy Policy

The National Energy Policy (NEP) of Zimbabwe plays a pivotal role in the country's transition towards a circular economy by integrating waste management for renewable energy optimization. The policy was established in 2002 and was subsequently updated. It provides a comprehensive framework for the country's energy sector development, sustainability, and efficiency. The main aim of the NEP is to ensure the country's energy security, affordability, accessibility, and sustainability. The NEP emphasizes the diversification of energy sources to enhance resilience and reduce the dependency on fossil fuels. The key objectives of the NEP include promoting energy efficiency across all sectors; improving access to energy, particularly in rural areas; and prioritizing environmental sustainability [38].

Moreover, the NEP recognizes the role of energy in socio-economic development. It aims to stimulate economic growth, create jobs, and alleviate poverty. This enhances the quality of life for people across the country. The NEP also aims to leverage energy resources efficiently and sustainably for inclusive and equitable development nationwide. It does this while promoting the stimulation of economic growth, job creation, poverty alleviation, and quality of life [38].

Various studies have undertaken a comprehensive analysis of the energy policy landscape in Zimbabwe. For instance, Dzobo et al. [39] pointed out the potential for energy savings within the manufacturing sector and proposed a collaborative policy framework involving government entities, the energy regulator, and research institutions. Similarly, Samu et al. [40] projected a moderate rise in energy demand by 2030, stressing the need for a well-defined policy framework to achieve widespread access to modern energy technologies. Davidson and Mwakasonda [41] conducted a comparative analysis of power sector reforms, focusing on the impact on vulnerable populations in South Africa and Zimbabwe.

The findings of their research underscored Zimbabwe's initiatives aimed at increasing electricity access through both grid expansion and off-grid electrification. The findings of these studies collectively highlight the critical need for a comprehensive and inclusive national energy policy in Zimbabwe that addresses energy efficiency, sustainability, universal access, and economic considerations.

3.1.2. The National Renewable Energy Policy

The National Renewable Energy Policy of Zimbabwe is significant in aligning with the concept of a circular economy by integrating waste management for renewable energy optimization. This policy was established in 2019, and it strategically aims to transition Zimbabwe's energy sector towards sustainable and renewable sources. The policy emphasizes diversifying energy sources by promoting a range of renewable energy sources like solar, wind, hydro, biomass, and geothermal energy. This shift to renewable energy sources reduces the reliance on fossil fuels, improves energy resilience, and fosters innovation in renewable technologies. It also focuses on enhancing energy security and affordability, with an aim to stabilize energy prices and reduce the dependency on fossil imports. Environmental sustainability is paramount, targeting the reduction of emissions and the promotion of clean energy technologies and sustainable practices [38].

The policy also focuses on efficiency improvements across sectors to reduce waste and lower costs. The policy also prioritizes rural energy access through infrastructure and technological solutions. The role of renewable energy in socio-economic development is highlighted in this policy, with a focus on job creation, economic growth, poverty alleviation, and better living standards. The policy supports capacity-building and research initiatives through training, knowledge sharing, and partnerships [38].

The conceptual framework for evaluating renewable energy policy in Oman aligns with the broader discourse on renewable energy development in Africa (Figure 2). The renewable energy potential in Africa, including Zimbabwe, is substantial, driven primarily by the need for sustainable energy sources [42]. However, challenges such as market failures, limited information, and difficulties in accessing raw materials hinder the development of renewable energy systems, as noted by Owusu et al. [42]. A similar call for action is echoed in Nigeria, where Oyedepo [43] advocated for governmental initiatives to diversify energy sources and embrace new technologies to curb energy wastage and reduce costs. Additionally, Shaaban and Petinrin's [44] analysis of renewable energy prospects in Nigeria emphasized the significance of decentralized renewable energy resources in enhancing the well-being of rural communities. These findings collectively underscore the importance of leveraging renewable energy opportunities and addressing associated challenges in crafting a robust national renewable energy policy for Zimbabwe.

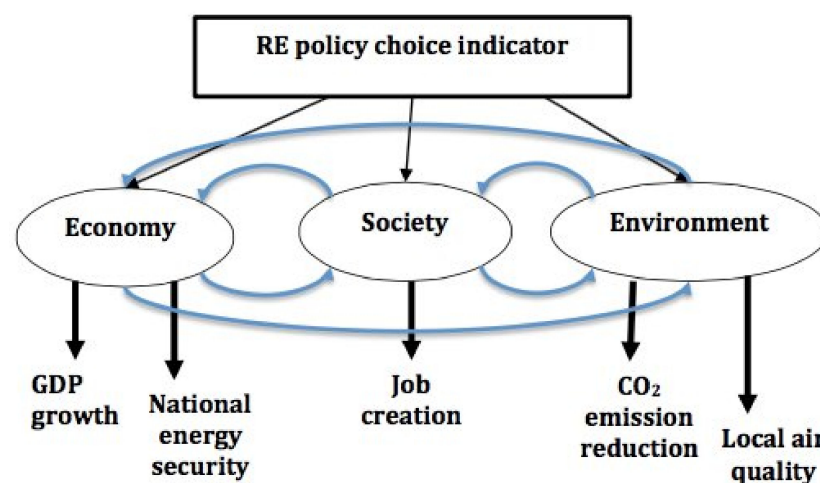


Figure 2. Alignment of renewable energy policy evaluation framework in Oman with African context [45].

3.1.3. The Biofuels Policy

The Biofuels Policy in Zimbabwe was established in 2019 with the aim of steering the sustainable development of the biofuel industry by creating a conducive environment. This policy ensures that all activities related to biofuel production, processing, distribution, and marketing adhere to the principles of economic, environmental, and social sustainability. It emphasizes the importance of having a clear policy framework to avoid inconsistent and fragmented efforts that may not yield the desired outcomes. The benefits of establishing a domestic biofuel sector are significant, including reduced dependence on imported petroleum products, stabilized fuel prices, enhanced energy security, rural development, poverty reduction, and job creation. The policy scope covers the period up to 2030, focusing on the production of liquid biofuels like ethanol from sugar cane and biodiesel from *Jatropha curcas*, with room for exploring other feedstocks. Structured around economic, agricultural, environmental, and social pillars, the policy aims to achieve specific targets such as a 20% ethanol blending ratio with petrol and a 2% biodiesel blending ratio with diesel by 2030 while fostering sector growth, maintaining product quality, enhancing feedstock productivity, and ensuring environmental sustainability. Additionally, the policy seeks to maximize community benefits from biofuel investments through institutional cooperation and coordination [38].

The lack of a national biofuel policy in Zimbabwe in past years has impeded the effectiveness of biofuel initiatives [46]. Although the country possesses significant potential for biomass energy, there is a pressing need to shift towards modern biomass energy technologies [47]. However, existing legal and institutional frameworks may not be robust enough to attract investors and mitigate potential negative impacts [48]. Additionally, the socio-economic implications of biofuel development, particularly concerning land acquisition and local livelihoods, have not received sufficient attention [49]. This highlights the critical importance of developing a comprehensive biofuel policy that addresses regulatory, technological, and socio-economic challenges to unlock the full potential of biofuel programs in Zimbabwe.

3.2. Waste Management Policies and Legal Frameworks in Zimbabwe

The Environmental Management Act

The Environmental Management Act of 2002 is the principal legislation governing waste management and environmental protection in Zimbabwe. The Act provides the legal framework for integrated waste management and the utilization of waste as a resource through recycling and waste-to-energy schemes. It establishes principles of environmental impact assessment, pollution control, and waste standards. The act also mandates local authorities to provide waste management services and designate waste disposal sites. In 2008, Zimbabwe adopted a National Waste Management Strategy and Action Plan to address gaps in waste management infrastructure and regulation. The strategy aims to promote recycling, re-use, and waste minimization [50]. However, deficiencies exist in implementing the act effectively due to a lack of financial and technical capacity at local government levels. While the act aims to promote sustainable waste practices, on-ground progress has been slow, with little coordination between various stakeholders.

Several statutory instruments have been enacted to complement and strengthen the framework established by the Environmental Management Act of 2002 in Zimbabwe.

These subsidiary legislations aid implementation by providing specific regulations and standards for different types of waste streams and sectors. Statutory Instrument 6 of 2007 addresses the disposal of effluent and solid waste from industrial operations. Statutory Instrument 10 of 2007 creates rules for managing hazardous waste. Statutory Instrument 98 of 2010 focuses on minimizing plastic pollution by regulating plastic packaging and bottles [51]. Together, these statutory instruments expand upon the parent Environmental Management Act by developing detailed guidelines. They assist various waste generators and handlers in applying appropriate management practices. While these statutory instru-

ments aim to operationalize waste policies, a lack of enforcement continues to undermine their effective implementation on the ground.

3.3. Harnessing Zimbabwe's Waste Resources through an Enabling Policy Framework

Zimbabwe has an enabling policy framework for integrated waste management and waste-to-resource recovery that is set on the platform, according to the Environmental Management Act of 2002. To complement this act, additional statutory instruments have been set down to give standards and guidelines to manage different types of waste, including industrial, municipal, hazardous, and plastic, to ensure that such waste is managed in an environmentally responsible manner.

With this in place, the framework classifies waste as a resource, thus pushing and driving its re-use, recycling, and recovery using technologies for waste valorization. Technologies include anaerobic digestion, combustion, and gasification, which are considered very promising pathways for the conversion of many waste biomass streams into energy. As a result, the enabling regulatory environment is articulated through policies like the National Energy Policy and National Renewable Energy Policy. The implantation of waste valorization projects and the penetration of renewable technologies can thus fall in line with diversification sources, an issue supported by the enabling regulatory environment coupled with sustainable practices.

The Biofuels Policy specifically targets the bioenergy sector and sets a basis for producing liquid fuels from appropriate waste biomass residues by implementing targets and incentives. By supporting and reinforcing such coordinated policies, waste management can create jobs and promote further socio-economic development, reinforcing support and protection for the construction of local waste valorization facilities. These strong policies, with enforcement measures, can further optimize these practices and supply waste-fed renewable technologies. The department has policies in place to mandate research support and capacity development for evolving suitable options based on the availability of feedstock resources in the country.

In this respect, Zimbabwe's integrated policy framework presents very effective main-lining platforms, such as waste-to-energy projects. To realize the vision, the country needs to investigate the potentiality of various wastes, including municipal, industrial, and agricultural wastes, that the nation can recover and convert into valuable renewable fuels and power.

4. Economic and Environmental Implications

4.1. Environmental Implications

Energy recovery from waste has proven to be an effective way of regulating the environmental impacts caused by the disposal of municipal waste [52]. It not only reduces negative impacts but also aids in producing clean and sustainable energy [34]. Currently, the research focus, in both academia and industry, is on finding innovative ways of how waste management can provide energy and secondary raw materials to the economy [53]. Hence, there is a need to integrate waste management practices and renewable energy initiatives.

Waste disposal poses public health risks to people residing near waste sites (breeding sites for flies, etc., which spread various ailments, infectious diseases, or radiation effects to pregnant women) and many environmental challenges such as land degradation, air pollution (since landfills without gas outlets pollute air by methane or odors from incomplete combustion), and water contamination by incineration residues, among other things [3]. Since waste generation is expected to increase in developing countries, to address these issues, waste-to-energy (WtE) technologies must be designed to produce clean energy [52].

The integration of waste management practices and renewable energy initiatives enables the burning of solid waste inside incinerators with combustion engines. This allows for the conversion of flue gases into electricity and, thus, energy generation, reductions in air pollution, and acceleration towards a circular economy, thus promoting sustainable resource management [3]. According to [54], incineration can potentially reduce more than

80% of disposed solid waste, though a way of eliminating heavy metals in air pollutants is required [54]. In this regard, advanced emission control systems are being installed in current incineration facilities, but the ash produced must be properly controlled to avoid contaminating soil and water [34]. Thus, eliminating gaseous emissions to the environment and leachate to the groundwater must be achieved [55].

The energy generated can be used in industries, homes, transportation systems, etc., and is clean, as opposed to conventional resources like fossil fuels. This can help reduce non-renewable resource dependence and eliminate greenhouse gas emissions [34]. This shows how beneficial the integration of waste management practices and renewable energy initiatives is since energy output is boosted while waste is managed at the same time [3]. To curb the risks of the improper disposal of hazardous waste, WtE processes can be implemented. This not only resolves these issues but also affects the amount of land required for disposal since landfill sites require more land compared to WtE facilities. Also, WtE technologies cater to various types of waste. Instead of sending waste to landfills, much of it is converted into energy, thus reducing the emission of greenhouse gases like methane and reducing landfilling by almost 90%. This makes WtE a very effective and reliable waste management tool [34].

4.2. Economic Implications

In developing countries, particularly African countries, the implementation of WtE technologies significantly contributes to electricity generation and sustainable waste management. This also accelerates the shift towards renewable energy, a circular economy, and a green environment through limited environmental pollution and a diversified energy mix [54]. Given the current energy crisis and poor solid waste management practices in Zimbabwe, the adoption of WtE technologies is the way to go. The power output from incineration is used in heat exchangers and/or steam turbines to turn on or heat several industrial machines/processes [54].

According to [53], integrating waste management practices with renewable energy initiatives, i.e., generating energy from thermal solid waste treatment, to be specific, can potentially increase the share of biofuels and waste to electricity production from 1.3% to not less than 2.2% in Zimbabwe [53]. Enhancing this integration further helps address the infrastructural shortages of waste management systems, thus eliminating inefficient waste management services not only in Zimbabwe but in Africa as a whole [54]. Most importantly, it enables economic activities, for example, the creation of employment in, but not limited to, the renewable energy and waste management sectors during the construction and implementation stages [34]. Once a very effective integration of renewable energy initiatives and waste management practices is set, through energy sales and/or the sale of by-products, the renewable energy initiatives can generate revenue while in operation, whilst the effective management of waste can help reduce the operational costs of such initiatives [34].

4.3. Cost–Benefit Analysis and Assessment of Potential Socio-Economic Impacts

A huge benefit of integrating renewable energy technologies and waste management is the drive towards a circular and sustainable use of resources through locally produced waste resources and by-products. This reduces dependence on fossil fuels, thus achieving one of the SDGs [55]. Since the capability of renewable energy initiatives to produce energy lies within the waste's composition and economies, various factors must be considered for the successful integration of these initiatives and waste management practices [54].

In most African countries, there is plenty of organic waste being generated, meaning that the generation of bio-methane is highly probable. For example, according to [55], South Africa produces organic waste with a large inherent energy value. Therefore, around 104463TJ/year can be recovered through incineration and around 22710TJ/year through landfill gas in South Africa [55]. However, updated data regarding the chemical characteristics of the waste are still lacking in most African cities, hence the slow adoption

of these initiatives [53]. In the case of renewable energy initiatives, the capital required to set up the facilities is very high. The need to incorporate advanced technologies into such systems also contributes to these costs since, in the case of African countries, the technologies are imported from outside Africa [52]. The procurement of machines to obtain gas from landfills and the respective engines for cooling these gases before conversion to energy must also be considered during the planning stage [54]. However, given that WtE technologies convert waste into various forms of energy and fuel, these advantages identify thermal solid waste treatment as a convenient method for disposing of waste in African cities [53].

Another challenge in the integration of renewable energy initiatives and waste management practices is the lack of highly skilled technical personnel. This affects both the construction and operation stages of these initiatives [52]. Encouraging WtE policies also contributes to successful integration; however, in most cases, such policies are lacking, and where they do exist, their implementation is challenging [54]. An additional requirement that is costly but necessary for successful integration is devising innovative but efficient ways of tapping flared gas at landfills [54]. To mitigate the potential social impacts, methods to win public trust like awareness campaigns must be applied to obtain support from local communities, since this is also a major factor, and the facilities must be properly engineered to avoid issues like noise and air pollution [34]. The increasing population increases the daily waste generation, which, in turn, has adverse effects on the environment and human health [52]; it would be worthwhile, not only for Zimbabwe but for all developing countries, to integrate renewable energy initiatives and waste management practices.

Examples of successful projects in Africa include one through incineration in South Africa at the Bisasar, Mariannhill, and La Mercy landfill sites in the eThekweni municipality with a capacity of generating 7.5 MW of electricity, which is expected to increase to between 20 MW and 50 MW within its 30-year lifetime. Whilst generating ZAR 48 million through carbon credit sales, this figure is expected to rise to around ZAR 400 million within its lifetime [54]. In Accra, Ghana, around 10,000 tons of solid waste have been processed daily since 2014, generating more than 10 MW of electricity through WtE projects. In Abijan, Cote d'Ivoire, 30 MW of electricity has been generated via the anaerobic treatment of Akouedo landfill waste [54]. These examples prove that though high startup, construction, and operational costs, etc., are so demanding, in the long run, benefits such as effective waste management, revenue and energy generation, resource recovery, the creation of employment, and greenhouse gas emission control can potentially compensate for these costs [34].

5. Discussion

This study identified several waste-to-energy technologies, including anaerobic digestion, incineration, gasification, and landfill gas energy, that have the potential to contribute to sustainable waste management and energy production in Zimbabwe. The findings of this study support the hypothesis that waste-to-energy technologies have the potential to contribute to sustainable waste management and energy production in Zimbabwe. However, the feasibility of these technologies in different contexts varies, and there are several challenges to their implementation, partially refuting the hypothesis.

This study found that anaerobic digestion has the potential to produce biogas and fertilizer, contributing to energy generation and waste management in Zimbabwe. However, there are several challenges to its implementation, including the lack of appropriate feedstock, high capital costs, and limited technical expertise. These findings align with previous studies that have highlighted the potential for anaerobic digestion in Zimbabwe [27,47,56]. Regarding incineration, this study found that it has the potential to produce electricity and heat, contributing to energy generation and waste management in Zimbabwe. However, there are several challenges to its implementation, including high capital costs, limited technical expertise, and concerns regarding emissions and public health [57]. These findings align with previous studies that have highlighted the potential for incineration in

Zimbabwe [34,58]. This study also found that gasification and landfill gas energy have the potential to contribute to sustainable waste management and energy production in Zimbabwe. However, there are several challenges to their implementation, including the limited technical expertise and concerns regarding emissions and public health. These findings align with previous studies that have highlighted the potential for gasification and landfill gas energy in Zimbabwe [33,47].

Regarding the applicability of these technologies in the Zimbabwean context, this study found that there are several opportunities for waste-to-energy technologies in Zimbabwe, including the potential for energy generation and waste management. However, there are also several challenges, including the lack of appropriate policies and regulations, limited technical expertise, and high capital costs. These findings align with previous studies that have highlighted the need for appropriate policies and regulations, technical expertise, and financial support to ensure the successful implementation of waste-to-energy technologies in Zimbabwe [33,34,47,59].

The findings of this review contribute to the existing literature on waste-to-energy technologies in Zimbabwe and provide insights into the opportunities and challenges of integrating these technologies into Zimbabwe's transition towards a circular economy. The findings of this study can inform policymakers and stakeholders about the potential for waste-to-energy technologies in addressing energy poverty, environmental impacts, and health hazards in Zimbabwe. Additionally, this research provides insights into the social and cultural factors that may influence community acceptance and participation in waste management and renewable energy initiatives in Zimbabwe.

6. Conclusions

This review highlighted the potential of various waste-to-energy technologies to contribute to sustainable waste management and energy production in Zimbabwe. The findings support the hypothesis that waste-to-energy technologies have the potential to address energy poverty and environmental impacts in the country. However, the feasibility of these technologies in different contexts varies, and there are several challenges to their implementation, partially refuting the hypothesis.

Anaerobic digestion, incineration, gasification, and landfill gas energy are all promising waste-to-energy technologies for Zimbabwe, with the potential to produce biogas, electricity, heat, and fertilizer. However, the successful implementation of these technologies requires addressing several challenges, including the lack of appropriate feedstock, high capital costs, limited technical expertise, limited policies and regulations, and concerns regarding emissions and public health.

The findings of this review have important implications for policymakers and stakeholders in Zimbabwe, providing insights into the opportunities and challenges of integrating waste-to-energy technologies into the country's transition towards a circular economy. This review also highlights the need for further research on the social and cultural factors that may influence community acceptance and participation in waste management and renewable energy initiatives in Zimbabwe.

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