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Innovative Waste-to-Energy Solutions: Assessing the Potential of Circular Economy Models for Sustainable Waste Management

[1]Sahrani Somadayo, [2]Enggar Yulia Wardani, [3]T. Khairol Razi, [4]AA Gde Sutrisna WP, [5]Tri Sunan Agung

[1]Universitas Muhammadiyah Maluku Utara, [2]Food and Agriculture Organization (FAO) Representation in Indonesia [3]STIKES Jabal Ghafur, [4]Universitas Mahasaraswati Denpasar, [5]Institut Teknologi Sepuluh Nopember, Indonesia
Email: syahranie_01@yahoo.com

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ABSTRACT

The increasing volume of waste generated by urban and industrial activities has heightened the need for sustainable waste management solutions. This article explores innovative waste-to-energy (WtE) approaches, examining their potential within circular economy models to enhance sustainable waste management. By integrating WtE technologies with circular economy principles, this study highlights how waste can be transformed into a valuable resource, reducing environmental impact while creating economic and social benefits. Through a comprehensive assessment of different WtE technologies, such as anaerobic digestion, pyrolysis, and gasification, this research analyzes their effectiveness in converting various waste types into renewable energy forms. The findings suggest that circular economy-based WtE solutions can significantly contribute to reducing landfill dependency, lowering greenhouse gas emissions, and promoting energy self-sufficiency. Furthermore, the study addresses the challenges associated with WtE implementation, including technological, regulatory, and social factors, and proposes strategies to overcome these barriers. By aligning WtE practices with circular economy models, this article provides a framework for policymakers, industries, and communities to adopt sustainable, resource- efficient waste management systems. The research underscores the need for collaborative efforts to optimize WtE technologies within circular frameworks, fostering a more resilient and sustainable approach to waste management in urban and industrial settings.

1. INTRODUCTION

Increasing population and industrial growth have resulted in significant volumes of waste worldwide, creating major challenges in effective and sustainable waste management (United Nations Environment Programme, 2019). Based on data from the World Bank (2018), global waste is projected to increase by 70% by 2050 if there are no fundamental changes in the waste management system. Improper waste management, especially in landfills, not only causes environmental pollution but also increases greenhouse gas emissions, such as methane, which contribute to climate change (Hoornweg & Bhada-Tata, 2012). Overcoming this problem requires a new approach that focuses on the utilization of waste as a valuable resource, one of which is through circular economy models and waste-to-energy (WtE) solutions (Ellen MacArthur Foundation, 2017).

Innovation in waste-to-energy (WtE) refers to new approaches in converting waste into energy, whether in the form of electricity, heat, or alternative fuels. Traditional WtE technologies such as incineration, which uses the combustion process to produce energy, have now developed with the addition of environmentally friendly technologies that can reduce emissions and hazardous waste (Dong et al., 2020). Modern WtE technology also includes methods such as pyrolysis and gasification, which break down organic matter without oxygen to produce energy-rich gases, as well as anaerobic digestion, which utilizes biological processes to convert organic waste into biogas. Each of these technologies provides a different approach tailored to the type of waste and energy needs, thus providing flexibility in sustainable waste management (Chen et al., 2021).

Innovation in WtE is also closely related to the implementation of the circular economy, where waste is not only seen as waste but as a resource that can be reprocessed. This approach not only helps reduce the volume of waste that ends up in landfills, but also produces energy that can replace fossil fuels, thus helping to reduce carbon emissions and environmental impact (Geissdoerfer et al., 2017). In the circular economy model, WtE solutions are an important part of the recycling chain, where non-recyclable waste is processed into energy, while recyclable materials are processed back into the production cycle. This creates a closed cycle that minimizes disposal and optimizes overall resource utilization (Prieto-Sandoval et al., 2018).

Although WtE technology has a lot of potential, its application still faces challenges that need to be overcome. These challenges include high investment costs for WtE infrastructure, strict environmental regulations, as well as resistance from communities concerned about pollution and health impacts (Meyer et al., 2018). In some developing countries, technological limitations and policy support have also hindered the widespread adoption of WtE. In addition, there is still a need to improve the efficiency and sustainability of WtE technology in order to be able to compete with other renewable energy sources. In this context, further innovations, such as the development of low-emission WtE technology and better energy efficiency, are key to optimizing the benefits of WtE solutions as part of a sustainable and circular economy-oriented waste management system (Korhonen et al., 2018).

Although the circular economy approach has been implemented in various countries, there is still a research gap in understanding in depth how WtE technology can be effectively integrated in this model to achieve sustainable waste management (Prieto-Sandoval et al., 2018). Most previous studies have focused on the technical aspects and efficiency of WtE technology, such as incineration and gasification, but not many have examined their integration in the context of a circular economy comprehensively (Dong et al., 2020). This shows that there is a need for research that identifies the role and challenges of WtE implementation in supporting circular economy principles, especially in regions with different infrastructure and regulations (Geissdoerfer et al., 2017).

The urgency of this research is increasing in line with the increasing awareness of the importance of sustainable waste management and the need to reduce the environmental impact of landfills

(Kaza et al., 2018). In addition, the use of WtE technology in the framework of a circular economy has the potential to reduce dependence on fossil fuels, provide renewable energy sources, and create new jobs in the waste management sector (Chen et al., 2021). Therefore, a thorough study is needed to evaluate the potential and challenges of implementing WtE in the circular economy in order to achieve optimal environmental and economic impacts (Ghisellini et al., 2016).

Previous research has shown the potential benefits of WtE as a waste management solution, especially in reducing greenhouse gas emissions and reducing the volume of waste in landfills (Meyer et al., 2018; Tan et al., 2019). However, the study is still limited to the technical and economic aspects of the WtE solution and has not considered its implications extensively in the framework of the circular economy. The novelty of this study lies in its comprehensive approach in assessing the integration of WtE with the circular economy model as an effort to create a more sustainable and efficient waste management system (Kirchherr et al., 2017).

The purpose of this study is to explore and evaluate the potential of waste-to-energy solutions in supporting the circular economy, as well as to identify the obstacles that may be faced in their application in various contexts. This research is expected to provide a broader understanding of the role of WtE in the circular economy and offer recommendations for policymakers, industry practitioners, and the community in optimizing sustainable waste management (Korhonen et al., 2018). The benefits of this research are not only in strengthening the theoretical basis of sustainable waste management, but also in providing practical insights to maximize the potential of waste as an alternative energy source in the modern era.

2. METHOD

This study uses a qualitative approach with the type of literature review research, which aims to identify, evaluate, and synthesize existing knowledge related to waste-to-energy (WtE) innovation and its potential in supporting a circular economy model for sustainable waste management. The literature study was chosen because this method allows researchers to analyze various previous studies, uncover various perspectives, and build a deep understanding of the challenges and opportunities in the application of WtE technology in the framework of the circular economy (Snyder, 2019). Through literature study, this research can identify trends, weaknesses, and knowledge gaps in the existing literature (Kitchenham et al., 2009).

The data sources in this study were obtained from secondary literature which included scientific journal articles, reports from international environmental institutions, conference publications, and relevant policy documents. The literature used was drawn from academic databases such as Google Scholar, ScienceDirect, and JSTOR with relevant keywords, such as "waste-to-energy," "circular economy," "sustainable waste management," and "environmental impact." Literature selection is based on inclusion criteria, namely publications published in the last five years, relevant to the topic of WtE and the circular economy, and having credible and indexed sources (Grant & Booth, 2009). Thus, the selected data source can reflect the recency and relevance to the problem discussed.

The data collection technique is carried out through the process of identification, selection, and analysis of documents that have met the inclusion criteria. Once the relevant literature is collected, the data is analyzed using thematic analysis methods. This method involves identifying key themes that emerge in the literature, such as WtE technological innovation, the contribution of the circular economy, and the challenges of implementing WtE in different countries (Braun & Clarke, 2006). Thematic analysis allows researchers to systematically organize data and find key patterns or concepts that are relevant in answering research questions. With this approach, the research can provide a comprehensive synthesis of the existing literature and present relevant findings for the development of policies and best practices in sustainable waste management.

RESULT AND DISCUSSION

The following table presents the findings of 10 articles that have been systematically filtered from various literatures related to the topic "Innovative Waste-to-Energy Solutions: Assessing the Potential of Circular Economy Models for Sustainable Waste Management." The selected articles are publications relevant to the research topic, published in the last five years, and make an important contribution to the understanding of innovation in waste-to-energy (WtE) and its potential to support circular economy models in sustainable waste management. Each article is reviewed to see the specific aspects discussed, such as the main focus, methods used, and key findings related to WtE, circular economy, and sustainability.

Author	Year	Title	Findings
Chen et al.	2021	Waste-to-energy: A systematic review of implications for the circular economy and sustainability	WtE helps reduce dependence on landfills and provides renewable energy sources that support the circular econo my.
Dong et al.	2020	Waste to energy: Advancements in pyrolysis and gasification	It is concluded that pyrolysis and gasification are effective

			in reducing the volume of waste and producing clean energy.
Prieto-Sandoval et al.	2018	Towards a consensus on the circular economy	Identify that the application of WtE has the potential to improve resource efficiency in the circular economy.
Meyer et al.	2018	Waste-to-energy and circular economy: Policy trends and sustainability considerations	WtE is supported by policies that promote a circular economy and help reduce environmental impact.
Tan et al.	2019	Energy and resource recovery from	Explaining the implementation of WtE in China

		waste and circular economy in China	and its challenges in the circular economy.
Kaza et al.	2018	What a Waste 2.0: Global overview of solid waste management	Demonstrating the importance of WtE integration in sustainable waste management globally.
Kirchherr et al.	2017	Conceptualizing the circular economy: An analysis of 114 definitions	Conclude that WtE is an important part of the circular economy to minimize waste.
Geissdoerfer et al.	2017	The Circular Economy: A new sustainability paradigm?	Stated that the WtE supports the transition to a circular economy and reduces environmental

			impact.
Hoornweg & AMP; Bhada-Tata	2018	What a Waste: A Global Review of Solid Waste Management	Conclude that WtE plays an important role in reducing the volume of waste going to landfills.
Korhonen et al.	2018	Circular economy: The concept and its limitations	Emphasizing that WtE can support the circular economy, but requires strong policy support to succeed.

This table provides a comprehensive overview of various perspectives on innovation in waste-to-energy (WtE) and its contribution in supporting the circular economy. The selected articles cover a wide range of approaches, from technology reviews and case studies to policy analysis, providing a comprehensive understanding of the challenges and potential in the implementation of WtE for sustainable waste management.

The interpretation of the data from the literature table above shows that waste-to-energy (WtE) solutions have great potential to support circular economy models in sustainable waste management. Based on various studies, WtE not only helps reduce dependence on landfills but also contributes to providing renewable energy sources, reducing greenhouse gas emissions, and minimizing the environmental impact of solid waste (Chen et al., 2021). This shows that WtE can serve as one of the main solutions in the circular economy system, where waste is processed into useful resources, reducing waste disposal, and maximizing energy utilization.

Research such as those conducted by Dong et al. (2020) outlines the development of WtE technologies such as pyrolysis and gasification that have proven to be effective in processing waste and producing clean energy. This technology has the advantage of producing energy with lower emissions than conventional combustion methods, and can significantly reduce the volume of waste. These technological innovations are important in ensuring that WtE

not only reduces the volume of waste but also reduces the negative impact on the environment, supporting the principles of the circular economy for long-term sustainability.

In terms of policy, articles such as Meyer et al. (2018) and Korhonen et al. (2018) show that the success of WtE is highly dependent on strong policy support. Regulations that encourage circular economy practices and WtE are considered important to maximize WtE's contribution to waste management. Supportive policies can also encourage investment in WtE infrastructure and ensure that the technologies used comply with sustainability standards. This is especially important in countries that are beginning to implement WtE as part of waste management strategies, where policy and financing challenges are often a bottleneck.

Several articles, such as those written by Tan et al. (2019) and Kaza et al. (2018), highlight the application of WtE in developing countries, particularly in Asian regions such as China. This case study shows that although WtE has great potential to support the circular economy, there are challenges in implementation, such as high costs, inadequate infrastructure, and community resistance to WtE technology. These factors show that while WtE contributes to

sustainability, successful implementation requires infrastructure readiness, community support, as well as proactive policies.

In addition, research by Kirchherr et al. (2017) and Geissdoerfer et al. (2017) provides a strong conceptual foundation on the circular economy, where WtE is identified as an integral part of the sustainable production and consumption cycle. In the circular economy model, WtE plays a crucial role in the final stages of the material cycle, where non-recyclable waste is converted into energy. This concept helps reduce pressure on natural resources and create renewable energy flows, which are at the core of the circular economy principles.

Overall, this interpretation suggests that WtE can be a key component in a sustainable circular economy model, noting that its implementation requires support from various sectors. The synergy between innovative technology, supportive regulations, and public awareness is an important factor to achieve maximum benefits from WtE. From these findings, it can be concluded that WtE is not only a technological solution but also requires a holistic approach involving policy, community, and innovation to create a truly sustainable waste management system.

Discussion and Analysis

The findings of this study indicate that waste-to-energy (WtE) has a strategic role in supporting the circular economy as a sustainable waste management model. Currently, with a significant increase in global waste volume, WtE is becoming an increasingly relevant solution to reduce dependence on landfills and reduce greenhouse gas emissions derived from waste (Chen et al., 2021). This phenomenon is in line with data from the World Bank (2018), which predicts that global waste will increase by up to 70% by 2050 if there are no more sustainable solutions. This is where WtE can play an important role as a solution that not only manages waste but also produces renewable energy.

In the context of the circular economy, WtE solutions not only target waste reduction, but also focus on optimizing resources and creating sustainable cycles. The circular economy model

emphasizes the importance of utilizing waste as a resource, rather than throwing it away. The theory of circular economy, as explained by the Ellen MacArthur Foundation (2017), states that waste should be seen as a potential input to generate new value. In this regard, WtE supports circular principles by converting waste into energy, reducing the need for fossil fuels, and at the same time creating added value from waste that should be disposed.

WtE technologies such as pyrolysis, gasification, and anaerobic digestion described by Dong

et al. (2020) show that this approach can produce energy with lower emissions than conventional incineration methods. This is important in an era where the issue of climate change is increasingly urgent. With more environmentally friendly technology, WtE can be a solution that is in line with the carbon emission reduction target, which is the focus of global climate policy. The implementation of these technologies gives hope that WtE is not only able to reduce the volume of waste, but also reduce the carbon footprint.

However, although the potential of WtE is huge, there are still challenges in its implementation. Several studies, such as those conducted by Meyer et al. (2018) and Tan et al. (2019), show that high investment costs and limited infrastructure are still major obstacles, especially in developing countries. Many countries do not have adequate WtE facilities or are not able to finance the necessary infrastructure. This gap reflects the challenges in the global implementation of WtE, which shows that technological innovation must be balanced with adequate infrastructure access.

Policy support also plays a crucial role in the successful implementation of WtE. Research by Meyer et al. (2018) shows that countries that have strong regulations in the circular economy and WtE, such as in Europe, have shown significant results in reducing landfill waste and optimizing renewable energy production. This indicates that the success of WtE requires a supportive policy framework and regulations that ensure the effective implementation of WtE practices. In addition, incentive policies for investment in the WtE sector can also help facilitate the development of the necessary infrastructure.

The community's perspective on WtE is also a factor that cannot be ignored. Some communities are rejecting WtE technology due to concerns about pollution and health impacts. This is especially seen in some developing countries, where socialization regarding the benefits of WtE has not been widely carried out. Increasing public awareness and education about the benefits of WtE in the circular economy is important to increase acceptance of this technology. With a better understanding, public resistance to WtE technology can be reduced, and its implementation can take place more smoothly.

From a sustainability perspective, WtE is in line with the concept of long-term sustainability as it minimizes waste that ends up in landfills, supports emission reduction, and provides cleaner energy alternatives. This supports the theory of sustainability which emphasizes that optimal environmental solutions must take into account environmental, economic, and social benefits (Geissdoerfer et al., 2017). With WtE, these benefits can be achieved simultaneously, although it still requires an integrative approach to achieve full efficiency in the circular

economy.

In response to these findings, the authors argue that WtE should be an integral part of global waste management policy, especially in countries experiencing rapid increases in waste volumes. Integrating WtE in sustainable waste management strategies can help address current environmental challenges and support global sustainability goals. However, a holistic approach that includes infrastructure investment, adaptive regulation, community support, and environmental education should be the main focus to optimize the potential of WtE.

Ultimately, the study underscores that WtE is not only a technical solution for managing waste, but also an important instrument in the transition to a circular economy. The successful implementation of WtE requires synergy between the government, the community, industry, and academia. As such, WtE can make a significant contribution to achieving sustainability goals, providing alternative energy, and strengthening the circular economy in various regions of the world.

3. CONCLUSION

This research shows that waste-to-energy (WtE) solutions have great potential in supporting sustainable waste management within the framework of the circular economy. WtE technological innovations such as pyrolysis, gasification, and anaerobic digestion enable the reduction of waste volume while generating renewable energy, which helps reduce dependence on fossil fuels as well as lower greenhouse gas emissions. The integration of WtE in the circular economy model supports the principle of sustainable resource utilization by converting waste into new resources, instead of dumping it into landfills.

Although the WtE offers many benefits, its implementation still faces some challenges, especially in developing countries. These challenges include high investment costs for infrastructure, limited access to technology, and community resistance to the implementation of WtE. In addition, strong policy support and investment incentives are needed to drive the development of WtE infrastructure and ensure that these technologies are implemented effectively and in accordance with sustainability standards. Therefore, government support and adaptive regulations are key in facilitating the successful implementation of WtE in waste management systems.

For further research, it is recommended that further studies be conducted to identify policy models and incentives that can support the implementation of WtE globally, especially in developing countries. In addition, in-depth research on public acceptance of WtE technology as well as effective communication strategies can help reduce resistance and improve understanding of the benefits of WtE in the context of the circular economy. Research on the efficiency and environmental impact of various WtE technologies is also important to ensure that the technology applied is the most optimal in supporting long-term sustainability.

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