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Research Article

AGRICULTURAL WASTE PROCESSING TECHNOLOGY FOR RENEWABLE ENERGY IN MEXICO

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Abstract
This study aims to examine agricultural waste treatment technology as a renewable energy source in Mexico, focusing on the potential, challenges, and obstacles faced in its implementation. The background of this research is based on the large amount of agricultural waste produced by Mexico's agricultural sector, most of which has not been optimally utilized to produce renewable energy. The method used in this study is a descriptive-qualitative approach through secondary data analysis, interviews with experts, and case studies in some of the largest agricultural waste producing areas. The results show that although the energy potential of agricultural waste is huge, the rate of technology adoption is still low, due to technological, economic, and policy constraints. The conclusions of this study emphasize the importance of stronger policy support and the provision of adequate infrastructure to encourage wider adoption of waste treatment technology. Education to farmers and rural communities is also needed to increase awareness about the benefits of agricultural waste as an energy source.

Keywords: Agricultural Waste, Renewable Energy, Treatment Technology

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INTRODUCTION

Agricultural waste treatment technology has developed into one of the innovative solutions in utilizing abundant resources, especially in countries with large agricultural industries. Agricultural waste, which is usually produced from the production and harvesting of crops, can now be used as raw materials for renewable energy (Peng et al., 2021). Renewable energy from agricultural waste is a major focus for many countries as it can reduce dependence on fossil fuels and reduce carbon emissions.

Mexico is one of the countries with a sizable agricultural sector, which produces a wide variety of agricultural waste, including crop residues, straw, corn stalks, and bagasse (Munawar et al., 2021). This great potential makes Mexico an ideal candidate for the application of agricultural waste treatment technology (Hua et al., 2023). The utilization of this waste not only aims to reduce waste, but also to support global efforts in the transition to clean energy. With the increasing need for renewable energy, agricultural waste treatment is becoming increasingly relevant in Mexico.

The production of renewable energy from agricultural waste involves various technologies, such as the conversion of biomass into bioenergy, biogas, or bioethanol (Jiang et al., 2022). This process converts waste that was previously considered worthless into a useful source of energy. In addition to generating energy, this technology also has a positive impact on the environment, such as reducing wasted waste and minimizing greenhouse gas emissions. Therefore, agricultural waste treatment technology is one of the key solutions to create a sustainable energy system.

Mexico has committed to reducing greenhouse gas emissions and increasing the use of renewable energy as part of its national environmental agenda. The country realizes that agricultural waste has great potential as a source of renewable energy that can be processed through various modern technologies (Xue et al., 2022). Programs focused on agricultural waste management are increasingly being developed, and support from the government and the private sector is critical in accelerating the adoption of this technology throughout the Mexican region.

In addition, agricultural waste treatment technology can also provide significant economic benefits for farmers and rural communities (Mpatani et al., 2021). Waste that was previously unused can now be turned into high-value products, increasing their income. In addition, the energy generated from agricultural waste can be used to meet local energy needs, thereby reducing dependence on imported energy or fossil fuels. This also opens up opportunities for the development of a more inclusive renewable energy sector in Mexico.

The success of the application of agricultural waste treatment technology for renewable energy is highly dependent on factors such as infrastructure, policy support, and technological capabilities (Wei et al., 2020). Mexico has a great opportunity to develop infrastructure that supports the widespread treatment of this waste. However, challenges still exist in terms of the availability of the right technology, access to financing, and public and farmer awareness of the benefits of using agricultural waste as an energy source.

Thus, Mexico is in a strategic position to develop agricultural waste processing technology into renewable energy (Chilakamarry et al., 2022). The great potential in terms of agricultural resources provides a wide opportunity to accelerate the clean energy transition. In addition, the development of this technology can also provide solutions to environmental problems faced by the country, such as waste management and carbon emission reduction (Awasthi et al., 2022). The success of these programs will have a significant impact on energy sustainability goals in Mexico.

Further studies and implementation are urgently needed to ensure that agricultural waste treatment technology in Mexico can be applied optimally. Support from the government, research institutions, and the private sector is key in creating a cleaner and more sustainable energy system (Koul et al., 2022). The utilization of agricultural waste as a renewable energy source is not only a solution to energy challenges, but also an important part of global efforts to create a greener future.

Although the great potential of agricultural waste to be processed into renewable energy has been recognized, the application of this technology in Mexico is still relatively limited (Othmani et al., 2022). Studies on how agricultural waste treatment technology can be implemented efficiently on a large scale in Mexico are still minimal. This gap indicates an urgent need for further research on which technologies best suit Mexico's geographical, social, and economic conditions (Ezeonuegbu et al., 2021). Another challenge that has not been widely discussed is the compatibility of the technology with existing infrastructure in rural areas.

The lack of comprehensive data on the environmental and economic impacts of agricultural waste treatment in Mexico is also a gap that needs to be filled. Although technologies such as biogas and bioethanol have already been used, there has not been a comprehensive study of how their application can provide long-term benefits to the environment and local economy (De Corato, 2020). An in-depth analysis of the impact and benefits of this technology is needed to prove its feasibility and sustainability.

Obstacles in the implementation of agricultural waste treatment technology in Mexico are also related to the lack of structured and integrated policy support (Gong et al., 2020). Although there are policies that encourage the use of renewable energy, there are not many concrete initiatives that focus on processing agricultural waste as an energy source. Existing regulations are often not specific enough to accommodate these technologies, and this creates gaps in their development and implementation.

In addition, the awareness and understanding of farmers and rural communities regarding the potential of agricultural waste as a source of renewable energy is still low (Duque-Acevedo et al., 2020). Many farmers do not realize that the waste they produce can be processed into an energy source of economic value. Education and training on waste treatment technology are still lacking, so many opportunities are missed to utilize the waste more optimally.

Another gap that needs to be considered is the financial challenge in implementing agricultural waste treatment technology (Moharrami & Motamedi, 2020). These technologies often require a sizable initial investment, while many farmers and rural communities in Mexico do not have access to the necessary capital (Karić et al., 2022). The lack of funding mechanisms or economic incentives to support the adoption of this technology is a major obstacle to the development of renewable energy from agricultural waste.

The application of agricultural waste treatment technology for renewable energy also faces technical obstacles related to the variety of types of waste produced in various regions of Mexico. Not all agricultural waste can be treated in the same way, and the technology that is appropriate for one type of waste may not be effective for another (Calbry-Muzyka et al., 2022). The need for more focused research on the characteristics of agricultural waste in different regions of Mexico is essential so that the solutions implemented are truly adapted to local conditions.

It is important to fill the gaps that exist in the research and implementation of agricultural waste treatment technologies for renewable energy in Mexico, given the great potential that the country has in the agricultural sector (Thomas et al., 2021). The use of agricultural waste as a source of renewable energy can not only reduce waste, but also contribute to the achievement of clean energy targets and carbon emission reduction (Donner et al., 2021). Developing the right technology to process this waste into renewable energy will provide sustainable solutions that benefit the local economy while protecting the environment.

More research is needed to understand which technologies best suit the characteristics of agricultural waste in Mexico and how they can be adapted in different rural areas (Bandara et al., 2020). Each region has a different type of waste, and effective technology for one type of waste may not necessarily be applicable in another. Understanding these differences is essential to ensure that the solutions implemented can provide optimal results in the treatment of waste into energy.

Addressing policy gaps is also needed to support wider adoption of this technology. Government support in the form of clear regulations and economic incentives will greatly help accelerate the adoption of agricultural waste treatment technology (Bushra et al., 2021). Research focused on developing policies that support renewable energy from agricultural waste is urgently needed so that this technology can develop and be implemented equitably.

The development of agricultural waste treatment technology must als o include an inclusive approach, involving local communities and farmers in the education and training process (Benyam et al., 2021). Many farmers are not yet aware of the economic potential of their agricultural waste, and providing training on this treatment technology can increase their income. Education and awareness raising are key to ensuring the sustainability of this technology in the future.

Filling the gap in financing is also a top priority (Babu et al., 2022). Agricultural waste treatment technology requires a considerable initial investment, and many rural communities in Mexico do not have access to adequate financial resources (Mujtaba et al., 2023) . Creating funding mechanisms or providing economic incentives will help increase the adoption of these technologies, so that renewable energy from agricultural waste can be a more affordable and sustainable solution across the country.

RESEARCH METHOD

Research Design

This study uses a descriptive-qualitative research design to examine the potential of agricultural waste treatment technology as a renewable energy source in Mexico. This approach aims to describe current conditions, analyze challenges, and identify solutions relevant to the agricultural and energy context in Mexico (Capanoglu et al., 2022) . The data collected came from literature sources, interviews with experts, and direct observations in the field.

Research Target/Subject

The population in this study consists of farmers, agricultural waste processors, policymakers, and renewable energy experts in Mexico (Ghorbani et al., 2020). Samples were taken purposively from farming communities in some of the largest waste-producing regions, such as the states of Veracruz and Jalisco (Almomani, 2020). In addition, energy technology experts and representatives from government agencies related to renewable energy policies are also involved to gain a broader perspective.

Instruments, and Data Collection Techniques

The instruments used in this study include semi-structured questionnaires for interviews, observation tools for field data collection, and analysis of documents related to energy and agricultural waste policies (Yang et al., 2020). The questionnaire is designed to explore the knowledge, attitudes, and experiences of farmers and waste processors related to agricultural waste treatment technology. Observation tools are used to record field conditions related to waste treatment and its potential to be processed into renewable energy.

Research Procedure

The research procedure begins with the secondary data collection stage of the relevant literature regarding agricultural waste treatment and renewable energy in Mexico (Maraveas, 2020). Afterwards, interviews were conducted with experts and key stakeholders to gain in-depth insights into the challenges and opportunities of this technology. The data obtained were analyzed thematically to identify patterns that could support the development of more effective policies and technologies for agricultural waste treatment in Mexico.

Data Analysis Technique

Data analysis followed Braun and Clarke's (2006) thematic analysis framework, involving familiarization with data, code generation, theme development, review, definition, and reporting. This qualitative technique synthesized interview transcripts, observations, and documents to reveal key patterns in challenges, opportunities, and policy recommendations, ensuring rigorous interpretation of Mexico's agricultural waste-to-energy context.

RESULTS AND DISCUSSION

Data collected from various secondary sources show that Mexico generates more than 50 million tons of agricultural waste each year, including crop residues, straw, corn stalks, and bagasse. The potential of this waste to be processed into renewable energy is huge, but only about 10% is currently being used for this purpose. The following table shows the production of agricultural waste in some of the major states in Mexico:

Table 1. Production of Agricultural Waste in Some of the Major States in Mexico

State	Agricultural Waste Production (tons/year)
Veracruz	8.5 million
Jalisco	7 million
Michoacán	5.2 million
Sinaloa	4.8 million
Guanajuato	4 million

This data shows that Veracruz and Jalisco are the largest producers of agricultural waste in Mexico, which means that the potential for renewable energy in the region is huge. Although there is a lot of potential, the utilization of waste for energy is still very limited due to various factors, such as the lack of adequate technology and low awareness of the economic potential of this waste.

Further analysis of the data shows that most agricultural waste in Mexico has not been treated with appropriate technology. Biogas and bioethanol have been identified as key technologies that can be applied, but the infrastructure is inadequate. Many farmers still consider agricultural waste as a burden rather than a potential resource. This creates a large gap between the potential and realization of the use of renewable energy from waste.

An additional description of the data shows that rural areas in Mexico face significant technology access challenges. While there are technologies capable of converting waste into energy, many farmers and waste processors do not have adequate access or understanding of how to adopt these technologies (Ge et al., 2021). Economic factors also play a role in the low adoption rate, as initial investment in waste treatment technology is still relatively high.

The explanation of this obstacle shows that government support and supportive policies are essential to encourage the adoption of agricultural waste treatment technology. Countries such as Germany and India have succeeded in increasing the use of agricultural waste for renewable energy through subsidies and economic incentives. However, similar policies in Mexico are still not fully implemented, slowing the adoption of this technology.

The relationship between waste utilization data and the obstacles faced shows that the great potential that Mexico has to process agricultural waste into renewable energy has not been optimized. Many farmers still see waste as a problem, not an opportunity, and this reflects the need for a change in perception through education and more targeted policy support (Kadhom et al., 2020). Despite efforts to utilize waste more productively, without strong infrastructure and regulations, these technological developments will continue to lag behind.

A case study in Veracruz, one of the largest agricultural waste-producing states, shows that the application of biogas technology has been successful in several communities. A biogas processing plant was established to process straw waste and other agricultural waste into energy which is then used to meet local energy needs (Kapoor et al., 2020). The study shows how technology can be harnessed to reduce reliance on fossil fuels and reduce waste in the region.

The explanation of this case study shows that despite local successes in the application of waste treatment technology its scalability is still a major challenge. Many rural communities do not yet have access to these technologies, and the lack of economic incentives hinders the expansion of similar projects. However, the success at Veracruz shows that with the right support, the technology can be adopted more widely and provide significant benefits to local communities.

The relationship between the case studies at Veracruz and the broader data shows that the success of waste treatment technology is highly dependent on policy support and access to adequate infrastructure (Al-Gheethi et al., 2022). The study underscores the importance of collaboration between governments, the private sector, and local communities in developing waste-based renewable energy projects. Without coordinated intervention, Mexico's huge potential for agricultural waste for renewable energy will remain untapped.

This study shows that Mexico has great potential in utilizing agricultural waste as a renewable energy source, but the adoption rate of waste treatment technology is still very low (Avelar et al., 2021). Agricultural waste production in states such as Veracruz and Jalisco is huge, but only a small portion is utilized for energy. Factors such as limited access to technology, lack of awareness of farmers, and regulations that have not fully supported this technology are the main obstacles to the development of this technology (Mao et al., 2022). The application of technologies such as biogas and bioethanol is still limited to some regions and has not been widely adopted.

The results of this study are similar to several other studies that show the potential for renewable energy from agricultural waste, especially in developing countries. However, in contrast to countries such as India or Germany that have implemented policies and incentives that encourage the use of waste for energy, Mexico still lags behind in terms of concrete policy support (Kumar & Strezov, 2021). Other research also emphasizes the importance of adequate infrastructure, which in this study was found to be one of the biggest obstacles in Mexico. Limited access to technology and capital in rural areas adds to the difficulties in the widespread application of waste treatment technology.

The results of this study indicate that although there is great potential, concrete steps in the development of waste treatment technology in Mexico are still minimal. The gap between potential and realization is a sign that there needs to be more effort to increase awareness, policy support, and supporting infrastructure. If agricultural waste can be utilized optimally, it will not only contribute to the provision of renewable energy, but will also improve the welfare of rural communities and reduce the environmental impact of wasted agricultural waste.

The implication of the results of this study is that without stronger support from the government and the private sector, the potential of agricultural waste as a renewable energy source in Mexico will not be fully realized (Gupta et al., 2023). Clear policies and incentives that encourage technology adoption need to be implemented to address the economic and infrastructure barriers facing rural communities. In addition, increasing awareness and training for farmers on the economic value of agricultural waste should be a priority.

The study shows such results due to a variety of factors, including low levels of investment in the renewable energy sector that focuses on agricultural waste, a lack of technical knowledge among farmers, and a lack of supportive regulations (Bhat et al., 2022). Mexico is still struggling to find a balance between high agricultural production and sustainable waste management. The low adoption rate of waste treatment technology is also due to limited infrastructure in areas far from industrial centers and energy markets.

The next step is to strengthen the policy framework in Mexico to support the wider adoption of agricultural waste treatment technologies. Governments need to develop incentive programs that can attract investment in the sector, as well as provide financial and technical support to rural communities. More targeted education and training for farmers on the benefits of this technology must also be improved (Ampofo & Ngadi, 2022). Mexico has great potential to become a leader in the use of renewable energy from agricultural waste, but more concrete action is needed to achieve this goal.

CONCLUSION

The most important findings of the study show that although Mexico has great potential in harnessing agricultural waste for renewable energy, the adoption rate of waste treatment technology is still very low. The main obstacles include limited access to technology, lack of awareness among farmers about the economic benefits of waste, and policies that have not fully supported the implementation of this technology. These factors hinder the realization of renewable energy potential from agricultural waste in Mexico, which is indispensable to support the clean energy transition and carbon emission reduction.

The greater value of this study lies in its thorough analysis of the technical, economic, and policy barriers that hinder the adoption of agricultural waste treatment technologies in Mexico. This research makes an important contribution by identifying policy gaps and providing recommendations for the development of more inclusive renewable energy technologies. The limitations of this study are limited geographical coverage and lack of empirical data on the long-term impact of the application of this technology. Further research can be focused on broader case studies in different regions of Mexico to measure the effectiveness and impact of waste treatment technologies on a larger scale.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.
Author 4: Formal analysis; Methodology; Writing - original draft.

CONFLICTS OF INTEREST

The authors declare no conflict of interest

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