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Resource Utilization of Agricultural Waste: From Biomass Energy to Organic Fertilizer

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Abstract This study is to explore the potential of utilizing agricultural waste for the production of biomass energy and organic fertilizers, and evaluate various types of agricultural waste, such as animal manure, crop residues, and food waste, and their effectiveness in generating renewable energy and enhancing soil fertility through organic fertilizers. The study reveals that agricultural waste can be effectively transformed into valuable products. For instance, the total biomass nitrogen reservoir in China is found to be significantly large, with livestock and poultry manure being the largest contributors. Additionally, the valorization of agro-industrial wastes through biorefinery processes can generate substantial amounts of renewable energy and valuable by-products. The incorporation of agricultural waste-to-energy pathways into biomass product and process networks shows promising returns on investment, particularly in the case of converting orange peel wastes into pectin. The findings suggest that the utilization of agricultural waste for biomass energy and organic fertilizer production is not only feasible but also beneficial for sustainable agricultural development. By converting waste into valuable resources, it is possible to reduce reliance on chemical fertilizers and fossil fuels, thereby promoting environmental sustainability and economic growth.

Keywords Agricultural waste; Biomass energy; Organic fertilizers; Waste valorization; Sustainable agriculture

1 Introduction

Agricultural activities generate substantial amounts of organic waste, including crop residues, animal manure, and post-harvest waste. Improper disposal of these materials can lead to significant environmental issues such as soil and water pollution, greenhouse gas emissions, and health hazards due to the proliferation of pests and pathogens (Medina et al., 2015; Mieldažys et al., 2016). The accumulation of agricultural waste not only poses a threat to environmental sustainability but also represents a lost opportunity for resource recovery and utilization (Sharma et al., 2019).

The effective management and utilization of agricultural waste are crucial for promoting sustainable agricultural practices. Transforming agricultural waste into valuable resources such as biomass energy and organic fertilizers can mitigate environmental impacts and enhance soil fertility and crop productivity (Odlare et al., 2011; Chew et al., 2019; Srivastava et al., 2020). Utilizing organic waste for energy production and soil amendments can reduce reliance on chemical fertilizers, lower greenhouse gas emissions, and contribute to a circular economy (Sharma et al., 2019; Rajagopal and Liu, 2020). This approach not only addresses waste management challenges but also supports the sustainable development goals by improving resource efficiency and environmental health (Chojnacka et al., 2019).

This study will examine various types of agricultural waste, their environmental impacts, and the technologies available for their transformation and utilization. The study will also assess the benefits and challenges associated with using agricultural waste for energy and soil enhancement, providing insights into sustainable waste management practices and their implications for agricultural sustainability. By synthesizing current research and developments in this field, the study hopes to highlight the importance of integrating waste management into sustainable agricultural practices and to propose strategies for optimizing the use of agricultural waste resources.

2 Types and Sources of Agricultural Waste

2.1 Classification of agricultural waste

Agricultural waste can be broadly classified into three main categories: crop residues, animal manure, and agro-industrial byproducts. Crop residues include materials such as straw, unmarketable or culled fruits and vegetables, post-harvest or post-processing wastes, clippings, and residuals from forestry or pruning operations (Medina et al., 2015). Animal manure, another significant category, is produced in large quantities from livestock farming and can be utilized for biogas production and as a soil amendment (Schievano et al., 2009; Ardebili, 2020). Agro-industrial byproducts encompass a variety of materials such as sugar beet pulp, starch and confectionary industry by-products, oil cereal industry by-products, and grain and legume by-products (Seidavi et al., 2021).

2.2 Quantitative data on agricultural waste generation

The generation of agricultural waste is substantial. For instance, in Iran, the total amount of agricultural waste is assessed to be 24.3 million tonnes, which can be used to produce significant quantities of biogas, bio-butanol, and bio-hydrogen (Ardebili, 2020). In the United States, the utilization of all available agricultural and forestry residues, animal manure, and municipal solid waste can generate between 3.1 to 3.8 exajoules (EJ) of renewable energy annually (Liu and Rajagopal, 2019). This highlights the vast potential of agricultural waste as a resource for energy production.

2.3 Regional variations in agricultural waste types and quantities

The types and quantities of agricultural waste vary significantly by region. For example, in Italy, swine manure is a common substrate used in biogas plants due to the prevalence of pig farming (Schievano et al., 2009). In contrast, in Iran, the primary agricultural wastes include residues from crops such as wheat, rice, barley, maize, and industrial crops like sugar cane and sugar beet (Ardebili, 2020). These regional differences are influenced by the types of crops grown, the scale of livestock farming, and the specific agro-industrial activities prevalent in each area. Understanding these variations is crucial for developing region-specific strategies for the effective utilization of agricultural waste.

3 Biomass Energy Production from Agricultural Waste

3.1 Technologies for biomass energy production

3.1.1 Anaerobic digestion

Anaerobic digestion (AD) is a well-established technology for converting organic waste into biogas, which primarily consists of methane and carbon dioxide. This process not only reduces greenhouse gas emissions but also produces a valuable digestate that can be used as a fertilizer. Recent advancements in AD technology have focused on optimizing parameters, pretreatments, and co-digestion strategies to enhance biogas yield and process efficiency (Zhang et al., 2019; Atelge et al., 2020). For instance, the integration of AD with gasification has shown promise in improving the economic viability and energy recovery from agricultural waste (Antoniou et al., 2019).

3.1.2 Combustion

Direct combustion is one of the simplest methods for converting biomass into energy. This process involves burning biomass in the presence of oxygen to produce heat, which can be used for power generation or industrial processes. In Colombia, the potential for using agricultural and livestock waste for direct combustion has been explored, showing significant potential to replace traditional fossil fuels and reduce environmental impacts (Gutiérrez et al., 2020). However, the efficiency of combustion systems can be improved by optimizing the design of combustors to enhance oxidative characteristics and increase the yield of high-quality steam (Sarkar and Praveen, 2017).

3.1.3 Gasification

Gasification involves the partial oxidation of biomass to produce syngas, a mixture of carbon monoxide, hydrogen, and methane. This syngas can be used for electricity generation, as a fuel for internal combustion engines, or as a feedstock for chemical synthesis. Studies have shown that gasification of agricultural waste can achieve high purity syngas, making it a viable alternative to coal gasification (Sarkar and Praveen, 2017). Additionally, gasification of digestate from AD processes has been demonstrated to enhance energy recovery and produce valuable byproducts like biochar (Antoniou et al., 2019; Arora et al., 2021).

3.1.4 Pyrolysis

Pyrolysis is the thermal decomposition of biomass in the absence of oxygen, producing bio-oil, syngas, and char. This process is highly versatile, allowing for the production of various energy carriers and valuable byproducts. Research has shown that optimizing pyrolysis conditions, such as temperature and heating rate, can significantly improve the yield and quality of pyrolytic products (Sarkar and Praveen, 2017; Mlonka-Mędrala et al., 2021). For example, pyrolysis of agricultural waste at higher temperatures increases the concentration of hydrogen and methane in the pyrolytic gas, making it a more efficient energy source (Mlonka-Mędrala et al., 2021).

3.2 Case studies of successful biomass energy projects

Several successful biomass energy projects have demonstrated the feasibility and benefits of converting agricultural waste into energy. In Colombia, the combined use of direct combustion and anaerobic digestion has shown the potential to replace a significant portion of fossil fuel use, contributing to a more sustainable energy mix (Gutiérrez et al., 2020). Another notable project in Singapore's Gardens by the Bay utilized gasification to convert horticultural waste into biochar, which was then used as a soil conditioner and in concrete applications, showcasing a circular economy model (Arora et al., 2021). These case studies highlight the diverse applications and benefits of biomass energy projects in different contexts.

3.3 Economic feasibility and energy efficiency of biomass energy systems

The economic feasibility and energy efficiency of biomass energy systems depend on several factors, including feedstock availability, technology choice, and system integration. Anaerobic digestion, for example, can be economically viable when coupled with gasification to enhance energy recovery and produce valuable byproducts (Antoniou et al., 2019). Direct combustion systems, while simpler, may require optimization to improve efficiency and reduce emissions (Sarkar and Praveen, 2017; Gutiérrez et al., 2020). Gasification and pyrolysis offer high energy efficiency and the potential for multiple revenue streams from syngas, bio-oil, and biochar, but they also require significant capital investment and technical expertise (Sarkar and Praveen, 2017; Arora et al., 2021; Mlonka-Mędrala et al., 2021) (Figure 1). Overall, the integration of multiple biomass conversion technologies and the adoption of circular economy principles can enhance the economic and environmental sustainability of biomass energy systems.

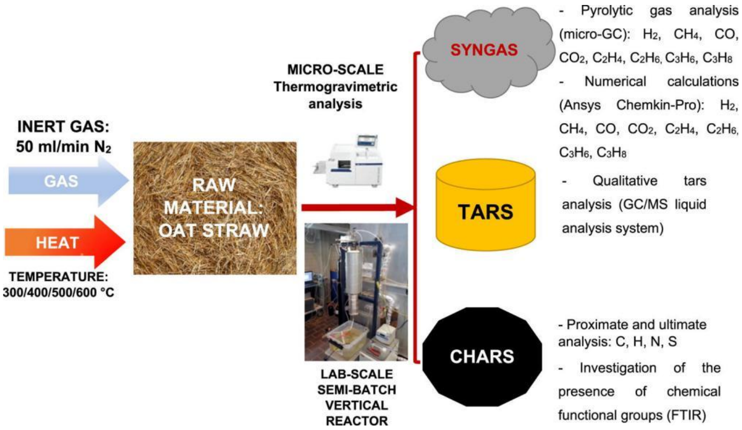

Figure 1 Analysis of agricultural biomass pyrolysis process and its products (Adapted from Mlonka-Mędrala et al., 2021)

4 Conversion Processes for Organic Fertilizer Production

4.1 Composting techniques and methodologies

4.1.1 Windrow composting

Windrow composting is a traditional method where organic waste is piled into long rows (windrows) and periodically turned to maintain aerobic conditions. This technique is widely used due to its simplicity and cost-effectiveness. The process involves the decomposition of organic matter by microorganisms, which is enhanced by regular aeration and moisture control. Windrow composting is suitable for large-scale operations and can handle a variety of organic wastes, including agricultural residues and municipal solid waste (Lim et al., 2016).

4.1.2 Vermicomposting

Vermicomposting utilizes earthworms, particularly species like *Eisenia fetida* and *Perionyx excavatus*, to decompose organic waste into nutrient-rich compost. This method is highly efficient in converting organic waste into high-quality organic fertilizer. Earthworms consume the organic matter, and their excreta, known as vermicast, is rich in nutrients and beneficial microorganisms. Vermicomposting not only enhances nutrient content but also improves the physical properties of the compost, making it an excellent soil amendment (Soobhany, 2019; Kaur, 2020; Chatterjee et al., 2021; Huntley and Ansari, 2021).

4.1.3 In-vessel composting

In-vessel composting involves the decomposition of organic waste in a controlled, enclosed environment. This method allows for better control of temperature, moisture, and aeration, leading to faster and more efficient composting. In-vessel systems can vary from simple bins to sophisticated automated systems. This technique is particularly useful for processing food waste and other organic materials in urban settings, where space and odor control are significant concerns (Schröder et al., 2021).

4.2 Factors influencing compost quality

Several factors influence the quality of compost, including the carbon-to-nitrogen (C/N) ratio, moisture content, aeration, and the presence of microorganisms. The C/N ratio is crucial for microbial activity; an optimal ratio of around 25-30:1 is recommended for efficient composting. Moisture content should be maintained between 40%-60% to support microbial activity without causing anaerobic conditions. Aeration is essential to maintain aerobic conditions and prevent the production of harmful gases like methane and ammonia. The addition of bulking agents and microbial inoculants can enhance the composting process and improve the final compost quality (Lim et al., 2016; Mupambwa and Mnkeni, 2018; Raza et al., 2020).

4.3 Benefits of using compost as an organic fertilizer

Using compost as an organic fertilizer offers numerous benefits for soil health and crop production. Compost improves soil structure, increases water retention, and enhances soil fertility by providing essential nutrients such as nitrogen, phosphorus, and potassium. It also introduces beneficial microorganisms that promote plant growth and suppress soil-borne diseases. Additionally, composting organic waste reduces the volume of waste sent to landfills, thereby mitigating greenhouse gas emissions and contributing to a more sustainable waste management system (Kaur, 2020; Chatterjee et al., 2021; Niedzialkoski et al., 2021; Schröder et al., 2021).

In conclusion, the conversion of agricultural waste into organic fertilizer through various composting techniques not only addresses waste management issues but also provides a sustainable solution for enhancing soil fertility and crop productivity. The integration of windrow composting, vermicomposting, and in-vessel composting, along with the optimization of composting parameters, can lead to the production of high-quality organic fertilizers that support sustainable agricultural practices.

5 Integration of Biomass Energy and Organic Fertilizer Production

5.1 Synergistic approaches for combined energy and fertilizer production

The integration of biomass energy and organic fertilizer production leverages the synergistic potential of various waste management processes. Anaerobic digestion (AD) is a key technology in this integration, where organic waste is converted into biogas and nutrient-rich digestate. The biogas can be used as a renewable energy source, while the digestate serves as an organic fertilizer. For instance, the integration of anaerobic digestion and composting has been shown to effectively recover energy and plant nutrients from pharmaceutical organic waste, producing biogas and compost rich in macro-nutrients (Cucina et al., 2017). Similarly, the co-pyrolysis of agricultural and plastic wastes can produce high-quality bio-oil and reduce solid waste volumes, demonstrating another synergistic approach (Salvilla et al., 2020).

5.2 Case studies highlighting integrated systems

Several case studies illustrate the successful implementation of integrated systems for biomass energy and organic fertilizer production. One notable example is the biorefinery approach at the Federal University of Pernambuco, which processes municipal solid waste to produce biodiesel, biogas, organic compost, and other value-added chemicals. This system not only meets energy and fertilizer needs but also promotes circular economy initiatives (Sousa et al., 2021). Another case study from Poland highlights the production of liquid fertilizers from waste materials, demonstrating the feasibility and environmental benefits of such integrated systems (Pajura et al., 2023) (Figure 2). Additionally, the use of biochar as an additive in anaerobic digestion processes has been shown to enhance methane production and produce nutrient-rich digestate, further exemplifying the benefits of integrated waste management (Shen et al., 2016).

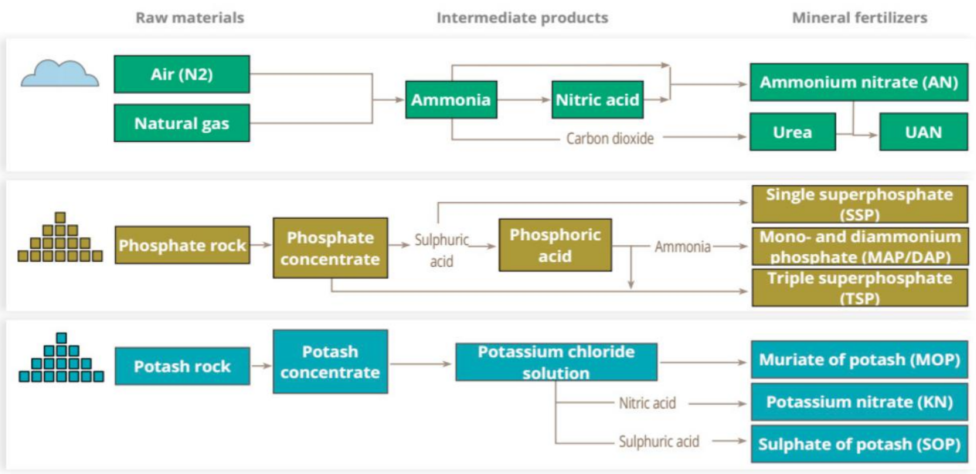

Figure 2 Production of main fertilizer (Adopted from Pajura et al., 2023)

5.3 Environmental and economic benefits of integrated waste management

The environmental and economic benefits of integrating biomass energy and organic fertilizer production are substantial. Environmentally, these integrated systems reduce greenhouse gas emissions, minimize landfill waste, and promote the recycling of valuable nutrients back into the soil. For example, the use of organic waste in agriculture can improve soil fertility and crop yield while reducing the need for chemical fertilizers (Sharma et al., 2019). Economically, these systems lower waste management costs, reduce the dependency on fossil fuels, and create new revenue streams from the sale of biofuels and organic fertilizers. The integrated biorefinery approach in Brazil, for instance, demonstrated significant cost savings in waste management and generated incentives for local economies (Sousa et al., 2021). Furthermore, the production of liquid fertilizers from waste materials in Poland highlights the potential for energy-efficient and environmentally friendly fertilizer production methods (Pajura et al., 2023).

In summary, the integration of biomass energy and organic fertilizer production offers a promising pathway for sustainable waste management, providing both environmental and economic benefits. By leveraging synergistic approaches and implementing integrated systems, it is possible to maximize resource utilization and contribute to a circular economy.

6 Technological Advances and Innovations

6.1 Recent developments in conversion technologies

Recent advancements in conversion technologies have significantly enhanced the efficiency and sustainability of agricultural waste management. One notable development is the improvement of Anaerobic Digestion (AD) processes, which are now more capable of handling the geographical and seasonal variations in waste feedstock (Gontard et al., 2018). Additionally, thermocatalytic reforming (TCR) has emerged as a novel process for converting agricultural waste into energy and valuable materials, such as syngas, bio-oil, and bio-char, with high environmental and economic sustainability (Moreno et al., 2019). Furthermore, the integration of various conversion pathways into a biomass product and process network has been optimized for economic feasibility, demonstrating high returns on investment for certain waste-to-product pathways (Nicoletti et al., 2019).

6.2 Use of biotechnological approaches to enhance waste conversion

Biotechnological approaches have played a crucial role in enhancing the conversion of agricultural waste. Modern biotechnologies now allow for the use of farm animal waste not only as raw materials for organic fertilizers but also for the production of alternative fuels and feed (Gishkaeva and Polonkoeva, 2022). The application of nanomaterials, such as nano zero valent irons (nZVIs) and metal oxide nanoparticles, has been shown to improve the efficiency of biological processes like anaerobic digestion and microbial fuel cells, thereby increasing the quality of the products and minimizing the negative impacts of hazardous materials in the waste (Salehi and Wang, 2022). Additionally, the biorefinery approach, which integrates biomass conversion processes to produce fuels, power, and chemicals, has been proposed to increase the profitability and environmental sustainability of the agricultural sector (Fermoso et al., 2018).

6.3 Advances in process optimization and efficiency improvements

Significant strides have been made in optimizing processes and improving the efficiency of agricultural waste conversion. Data-driven nonlinear adaptive robust optimization has been employed to create a biomass product and process network, optimizing the return on investment for various conversion pathways (Nicoletti et al., 2019). This approach has demonstrated the potential for maximizing the utilization of profitable processing pathways. Moreover, the development of multi-criteria decision support tools applicable at early stages of research has been discussed to address the complexity, seasonality, and regionality of agricultural residue management chains (Gontard et al., 2018) (Figure 3). The use of advanced thermochemical liquefaction techniques, including direct and indirect liquefaction, has also been highlighted for their ability to produce biofuels and valuable chemicals from agricultural and forestry wastes, contributing to the circular economy (Song et al., 2020).

By leveraging these technological advances and innovations, the conversion of agricultural waste into biomass energy and organic fertilizers can be significantly optimized, promoting sustainability and economic viability in the agricultural sector.

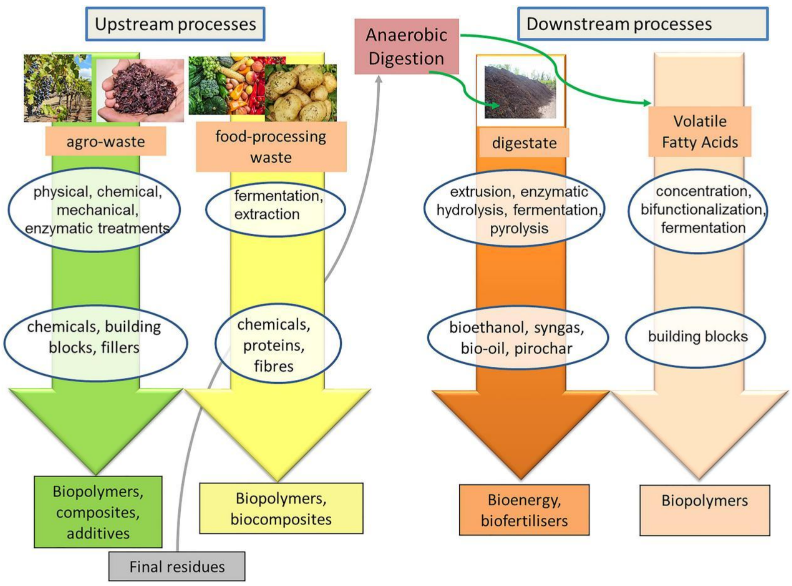

Figure 3 Cascading activities around anaerobic digestion (upstream and downstream processes) to valorise agro and food processing waste (Adopted from Gontard et al., 2018)

7 Environmental and Economic Impacts

7.1 Assessment of greenhouse gas emissions reduction

The utilization of agricultural waste for biomass energy and organic fertilizer production has significant potential to reduce greenhouse gas (GHG) emissions. Various studies have demonstrated that recycling agricultural waste into biofertilizers and energy can mitigate GHG emissions effectively. For instance, the application of anaerobic digestate and olive pomace compost in organic farming systems has shown a reduction in total carbon emissions, with values of 63.9 and 67.0 kg of CO_2 eq Mg^{-1}, respectively (Diacono et al., 2019). Additionally, the use of industrial by-products such as fly ash, steel slag, and phosphogypsum in paddy fields has been found to mitigate methane and nitrous oxide emissions, contributing to lower overall GHG emissions (Kumar et al., 2020). Furthermore, the transformation of biomass waste into organic fertilizers has been shown to reduce life-cycle energy consumption and GHG emissions compared to traditional mineral fertilizers (Kyttä et al., 2020).

7.2 Improvement in soil health and crop productivity

The application of organic waste-derived fertilizers has been shown to improve soil health and enhance crop productivity. Long-term field experiments have indicated that biogas residues and compost can significantly improve soil microbiological properties, such as substrate-induced respiration, potential ammonium oxidation, and nitrogen mineralization, leading to increased crop yields (Odlare et al., 2011). The use of compost and compost-based teas in horticultural systems has also been reported to enhance soil quality and plant health, providing essential nutrients and improving soil structure (Corato, 2020). Moreover, the application of biochar and raw agricultural waste as mulch has been observed to increase soil organic carbon, moisture, and nutrient content, resulting in a 36%-64% improvement in agricultural production (Dey et al., 2020).

7.3 Economic analysis of waste-to-energy and fertilizer systems

Economically, the recycling of agricultural waste into energy and fertilizers presents several benefits. The production of bioenergy from organic waste in Chile, for example, has been estimated to meet 3.3% of the annual energy demand, highlighting the significant potential for energy security and resource efficiency (Ludlow et al., 2021). The use of recycled fertilizers also reduces the costs associated with landfilling, transportation, and the production of chemical fertilizers, while opening avenues for rural employment (Sharma et al., 2019). However, financial, technical, and institutional barriers, such as high investment costs and reliance on landfilling practices, need to be addressed to fully exploit these resources (Ludlow et al., 2021). Additionally, the economic value of recycled fertilizers can be influenced by the allocation methods used in life-cycle assessments, with economic allocation resulting in significantly lower impacts compared to mass allocation (Kyttä et al., 2020).

In summary, the utilization of agricultural waste for biomass energy and organic fertilizer production offers substantial environmental and economic benefits, including GHG emissions reduction, improved soil health and crop productivity, and cost savings. However, overcoming existing barriers is crucial to realizing the full potential of these waste-to-energy and fertilizer systems.

8 Policy and Regulatory Framework

8.1 Overview of relevant policies and regulations

The management and utilization of agricultural waste for biomass energy and organic fertilizer production are governed by various policies and regulations aimed at promoting sustainability and reducing environmental impact. In the European Union, for instance, there are stringent regulations that encourage the use of organic waste to produce fertilizers, aligning with the principles of a circular economy (Pajura et al., 2023). These regulations are designed to reduce the exploitation of natural resources and minimize the energy intensity of the fertilizer industry. Similarly, Spain and the Czech Republic have implemented policies that prioritize the reduction and valorization of agricultural waste biomass (AWB), driven by the circular economy and circular bioeconomy strategies (Duque-Acevedo et al., 2022). These policies are crucial in guiding the sustainable transformation of biomass waste into valuable products like organic fertilizers (Chew et al., 2019).

8.2 Impact of government incentives and subsidies

Government incentives and subsidies play a significant role in the adoption and implementation of technologies for converting agricultural waste into biomass energy and organic fertilizers. The European Commission, for example, has set ambitious goals to reduce the use of non-renewable resources in fertilizer production by 30%, which can only be achieved through incentives for waste valorization and penalties for using non-renewable raw materials (Chojnacka et al., 2019). These incentives not only promote the use of biological waste but also help in mitigating environmental issues such as eutrophication caused by nitrogen and phosphorus runoff from agricultural fields. Additionally, government mandates and policy frameworks have been instrumental in driving the growth of biomass-derived energy products, with a projected increase of 56% in the use of densified solid biofuels from 2010 to 2040 (Bajwa et al., 2018).

8.3 Challenges and opportunities in policy implementation

Despite the positive impact of policies and incentives, there are several challenges in the implementation of these frameworks. One major challenge is the regional availability and proper management of biomass residues, which can hinder the efficient production of biochar and other biomass energy products (Lee et al., 2020). Furthermore, the lack of understanding among farmers regarding the benefits and barriers of using organic waste-based fertilizers poses a significant obstacle (Case et al., 2017). However, these challenges also present opportunities for improvement. For instance, enhancing farmer education and awareness about the advantages of organic fertilizers can lead to better adoption rates. Additionally, developing small-scale waste solubilization or fertilizer installations at the site of waste generation can address issues related to waste transport and sanitary hazards (Chojnacka et al., 2019). Overall, a comprehensive analysis of the trade-offs between energy yields, carbon abatement, and other environmental impacts is essential for optimizing policy implementation and achieving sustainable outcomes (Lee et al., 2020).

By addressing these challenges and leveraging the opportunities, policymakers can create a more robust framework that supports the sustainable utilization of agricultural waste, thereby contributing to environmental conservation and economic growth.

9 Challenges and Future Directions

9.1 Technical and logistical challenges in waste collection and processing

The transformation of agricultural waste into biomass energy and organic fertilizers faces several technical and logistical challenges. One significant issue is the efficient collection and processing of diverse waste streams, such as animal manure, sewage sludge, municipal solid waste, and food waste. The variability in the chemical composition of these wastes necessitates tailored processing techniques to ensure the production of high-quality organic fertilizers (Chew et al., 2019). Additionally, the need for selective waste collection and the enhancement of nutrient recovery efficiency are critical steps that require further technological advancements (Chojnacka et al., 2019). In developing countries, the lack of efficient waste management practices often leads to the open burning or decomposition of biomass residues, contributing to environmental pollution (Tripathi et al., 2019). Moreover, the high investment costs and reliance on landfilling practices pose substantial barriers to the adoption of waste-to-energy technologies (Ludlow et al., 2021).

9.2 Market and adoption barriers for biomass energy and organic fertilizers

The market and adoption of biomass energy and organic fertilizers are hindered by several factors. Financial barriers, such as elevated investment costs, limit the widespread implementation of waste-to-energy projects (Ludlow et al., 2021). Additionally, there is a lack of understanding among farmers regarding the benefits and potential of organic fertilizers derived from waste, which affects their decision-making processes (Case et al., 2017). The complex regulations and national laws governing the use of organic waste in agriculture further complicate the adoption of these sustainable practices (Corato, 2020). In the context of the fertilizer industry, the production of liquid fertilizers from waste materials is seen as a viable alternative to traditional mineral fertilizers, but the market dynamics and business models need to be stabilized to ensure consistent demand and supply (Pajura et al., 2023).

9.3 Research gaps and future research directions

Several research gaps need to be addressed to advance the utilization of agricultural waste for biomass energy and organic fertilizers. There is an urgent need for new technologies that can efficiently exploit the high potential of waste materials, particularly in terms of nutrient recovery and bioavailability (Chojnacka et al., 2019). Further research is required to develop innovative composting techniques and compost-based products that can improve soil quality and plant health while minimizing environmental impacts (Corato, 2020). Additionally, studies focusing on the integration of agri-waste management, biogas production, and policy support are essential to establish a sustainable circular bio-economy (Kapoor et al., 2020). Future research should also explore the potential of low-carbon routes for biomass waste valorization, which can contribute to carbon emission reductions and the development of sustainable construction materials (Tripathi et al., 2019). Finally, enhancing stakeholder cooperation across value chains and promoting awareness about the benefits of biomass in a circular economy are crucial for the successful implementation of these technologies (Sherwood, 2020).

10 Concluding Remarks

The research on the utilization of agricultural waste has demonstrated significant potential in transforming biomass into valuable products such as organic fertilizers and bioenergy. Various studies have highlighted the effectiveness of converting different types of biomass waste, including animal manure, sewage sludge, municipal solid waste, and food waste, into organic fertilizers that enhance soil structure and reduce the need for chemical fertilizers. Additionally, the conversion of agricultural waste into bioenergy through processes like thermocatalytic reforming and anaerobic digestion has shown promising results in terms of economic and environmental sustainability. The integration of agricultural waste-to-energy pathways into biomass product and process networks further optimizes the return on investment and maximizes the utilization of available resources.

Farmers should adopt sustainable waste management practices by utilizing agricultural residues and animal manure to produce organic fertilizers. This not only improves soil health but also reduces dependency on chemical fertilizers, leading to cost savings and environmental benefits. Policymakers should promote and support the development of technologies for biomass waste conversion. This includes providing incentives for the establishment of biorefineries and centralized biogas plants, which can efficiently process agricultural waste and produce bioenergy and other valuable products. Continued research is essential to develop and optimize technologies for biomass waste conversion. Researchers should focus on improving the efficiency of nutrient recovery, exploring new conversion pathways, and assessing the long-term impacts of using organic fertilizers derived from biomass waste on soil health and crop productivity.

The future of agricultural waste utilization lies in the integration of advanced technologies and sustainable practices. By harnessing the potential of biomass waste, we can create a circular economy that not only addresses waste management challenges but also contributes to energy production and soil enhancement. The collaboration between farmers, policymakers, and researchers is crucial to achieving these goals and ensuring the sustainable development of agricultural systems. With continued innovation and support, the transformation of agricultural waste into valuable resources will play a pivotal role in promoting environmental sustainability and economic growth.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Antoniou N., Monlau F., Sambusiti C., Ficara E., Barakat A., and Zabaniotou A., 2019, Contribution to circular economy options of mixed agricultural wastes management: coupling anaerobic digestion with gasification for enhanced energy and material recovery, Journal of Cleaner Production, 209: 505-514. https://doi.org/10.1016/J.JCLEPRO.2018.10.055

Ardebili S., 2020, Green electricity generation potential from biogas produced by anaerobic digestion of farm animal waste and agriculture residues in Iran, Renewable Energy, 154: 29-37.
https://doi.org/10.1016/j.renene.2020.02.102

Arora S., Jung J., Liu M., Li X., Goel A., Chen J., Song S., Anderson C., Chen D., Leong K., Lim S., Fong S., Ghosh S., Lin A., Kua H., Tan H., Dai Y., and Wang C., 2021, Gasification biochar from horticultural waste: an exemplar of the circular economy in Singapore, The Science of the Total Environment, 781: 146573.
https://doi.org/10.1016/j.scitotenv.2021.146573

Atelge M., Atelge M., Krisa D., Kumar G., Eskicioglu C., Nguyen D., Chang S., Atabani A., Al-Muhtaseb A., and Ünalan S., 2020, Biogas production from organic waste: recent progress and perspectives, Waste and Biomass Valorization, 11: 1019-1040.
https://doi.org/10.1007/S12649-018-00546-0

Bajwa D., Peterson T., Sharma N., Shojaeiarani J., and Bajwa S., 2018, A review of densified solid biomass for energy production, Renewable and Sustainable Energy Reviews, 96: 296-305.
https://doi.org/10.1016/J.RSER.2018.07.040

Case S., Oelofse M., Hou Y., Oenema O., and Jensen L., 2017, Farmer perceptions and use of organic waste products as fertilisers – A survey study of potential benefits and barriers, Agricultural Systems, 151: 84-95.
https://doi.org/10.1016/J.AGSY.2016.11.012

Chatterjee D., Dutta S., Kikon Z., Kuotsu R., Sarkar D., Satapathy B., and Deka B., 2021, Recycling of agricultural wastes to vermicomposts: characterization and application for clean and quality production of green bell pepper (*Capsicum annuum* L.), Journal of Cleaner Production, 315: 128115.
https://doi.org/10.1016/J.JCLEPRO.2021.128115

Chew K., Chia S., Yen H., Nomanbhay S., Ho Y., and Show P., 2019, Transformation of biomass waste into sustainable organic fertilizers, Sustainability, 11(8): 2266.
https://doi.org/10.3390/SU11082266

Chojnacka K., Gorazda K., Witek-Krowiak A., and Moustakas K., 2019, Recovery of fertilizer nutrients from materials - Contradictions, mistakes and future trends, Renewable and Sustainable Energy Reviews, 110: 485-498.
https://doi.org/10.1016/J.RSER.2019.04.063

Chojnacka K., Moustakas K., and Witek-Krowiak A., 2019, Bio-based fertilizers: a practical approach towards circular economy, Bioresource Technology, 295: 122223.
https://doi.org/10.1016/j.biortech.2019.122223

Corato U., 2020, Agricultural waste recycling in horticultural intensive farming systems by on-farm composting and compost-based tea application improves soil quality and plant health: a review under the perspective of a circular economy, The Science of the Total Environment, 738: 139840.
https://doi.org/10.1016/j.scitotenv.2020.139840

Cucina M., Zadra C., Marcotullio M., Maria F., Sordi S., Curini M., and Gigliotti G., 2017, Recovery of energy and plant nutrients from a pharmaceutical organic waste derived from a fermentative biomass: integration of anaerobic digestion and composting, Journal of Environmental Chemical Engineering, 5: 3051-3057.
https://doi.org/10.1016/J.JECE.2017.06.003

Dey D., Gyeltshen T., Aich A., Naskar M., and Roy A., 2020, Climate adaptive crop-residue management for soil-function improvement; recommendations from field interventions at two agro-ecological zones in South Asia, Environmental Research, 183: 109164.
https://doi.org/10.1016/j.envres.2020.109164

Diacono M., Persiani A., Testani E., Montemurro F., and Ciaccia C., 2019, Recycling agricultural wastes and by-products in organic farming: biofertilizer production, yield performance and carbon footprint analysis, Sustainability, 11(14): 3824.
https://doi.org/10.3390/SU11143824

Duque-Acevedo M., Ulloa-Murillo L., Belmonte-Ureña L., Camacho-Ferre F., Mercl F., and Tlustoš P., 2022, Sustainable and circular agro-environmental practices: A review of the management of agricultural waste biomass in Spain and the Czech Republic, Waste Management & Research, 41: 955-969.
https://doi.org/10.1177/0734242X221139122

Fermoso F., Serrano A., Alonso-Fariñas B., Fernández-Bolaños J., Borja R., and Rodríguez-Gutiérrez G., 2018, Valuable compound extraction, anaerobic digestion, and composting: a leading biorefinery approach for agricultural wastes, Journal of Agricultural and Food Chemistry, 66(32): 8451-8468.
https://doi.org/10.1021/acs.jafc.8b02667

Gishkaeva L., and Polonkoeva F., 2022, New technologies in the processing of agricultural waste, In Proceedings of the 1st International Conference on Methods, Models, Technologies for Sustainable Development - MMTGE, SciTePress, pp.193-197..
https://doi.org/10.5220/0011568400003524

Gontard N., Sonesson U., Birkved M., Majone M., Bolzonella D., Celli A., Angellier-Coussy H., Jang G., Verniquet A., Broeze J., Schaer B., Batista A., and Sebok A., 2018, A research challenge vision regarding management of agricultural waste in a circular bio-based economy, Critical Reviews in Environmental Science and Technology, 48: 614-654.
https://doi.org/10.1080/10643389.2018.1471957

Gutiérrez A., Eras J., Hens L., and Vandecasteele C., 2020, The energy potential of agriculture, agroindustrial, livestock, and slaughterhouse biomass wastes through direct combustion and anaerobic digestion, The case of Colombia, Journal of Cleaner Production, 269: 122317.
https://doi.org/10.1016/j.jclepro.2020.122317

Huntley S., and Ansari A., 2021, Vermicomposting evaluation of different combinations of organic waste using Perionyx excavates, International Journal of Recycling of Organic Waste in Agriculture, 10(3): 287-295.
https://doi.org/10.30486/IJROWA.2021.1910968.1146

Kapoor R., Ghosh P., Kumar M., Sengupta S., Gupta A., Kumar S., Vijay V., Kumar V., Vijay V., and Pant D., 2020, Valorization of agricultural waste for biogas based circular economy in India: A research outlook, Bioresource technology, 304: 123036.
https://doi.org/10.1016/j.biortech.2020.123036

Kaur T., 2020, Vermicomposting: an effective option for recycling organic wastes, Organic Agriculture, 2020: 1-17.
https://doi.org/10.5772/intechopen.91892

Kumar S., Kumar A., Singh S., Malyan S., Baram S., Sharma J., Singh R., and Pugazhendhi A., 2020, Industrial wastes: fly ash, steel slag and phosphogypsum-potential candidates to mitigate greenhouse gas emissions from paddy fields, Chemosphere, 241: 124824.
https://doi.org/10.1016/j.chemosphere.2019.124824

Kyttä V., Helenius J., and Tuomisto H., 2020, Carbon footprint and energy use of recycled fertilizers in arable farming, Journal of Cleaner Production, 287: 125063.
https://doi.org/10.1016/j.jclepro.2020.125063

Lee M., Lin Y., Chiueh P., and Den W., 2020, Environmental and energy assessment of biomass residues to biochar as fuel: a brief review with recommendations for future bioenergy systems, Journal of Cleaner Production, 251: 119714.
https://doi.org/10.1016/j.jclepro.2019.119714

Lim S., Lee L., and Wu T., 2016, Sustainability of using composting and vermicomposting technologies for organic solid waste biotransformation: recent overview, greenhouse gases emissions and economic analysis, Journal of Cleaner Production, 111: 262-278.
https://doi.org/10.1016/J.JCLEPRO.2015.08.083

Liu B., and Rajagopal D., 2019, Life-cycle energy and climate benefits of energy recovery from wastes and biomass residues in the United States, Nature Energy, 4: 700-708.
https://doi.org/10.1038/s41560-019-0430-2

Ludlow J., Jalil-Vega F., Rivera X., Garrido R., Hawkes A., Staffell I., and Balcombe P., 2021, Organic waste to energy: resource potential and barriers to uptake in Chile, Sustainable Production and Consumption, 28: 1522-1537.
https://doi.org/10.1016/j.spc.2021.08.017

Medina J., Monreal C., Barea J., Arriagada C., Borie F., and Cornejo P., 2015, Crop residue stabilization and application to agricultural and degraded soils: A review, Waste management, 42: 41-54.
https://doi.org/10.1016/j.wasman.2015.04.002

Mieldažys R., Jotautienė E., Pocius A., and Jasinskas A., 2016, Analysis of organic agricultural waste usage for fertilizer production, Agronomy research, 14: 143-149.

Mlonka-Mędrala A., Evangelopoulos P., Sieradzka M., Zajemska M., and Magdziarz A., 2021, Pyrolysis of agricultural waste biomass towards production of gas fuel and high-quality char: Experimental and numerical investigations, Fuel, 296: 120611.
https://doi.org/10.1016/J.FUEL.2021.120611

Moreno V., Iervolino G., Tugnoli A., and Cozzani V., 2019, Techno-economic and environmental sustainability of biomass waste conversion based on thermocatalytic reforming, Waste Management, 101: 106-115.
https://doi.org/10.1016/j.wasman.2019.10.002

Mupambwa H., and Mnkeni P., 2018, Optimizing the vermicomposting of organic wastes amended with inorganic materials for production of nutrient-rich organic fertilizers: a review, Environmental Science and Pollution Research, 25: 10577-10595.
https://doi.org/10.1007/s11356-018-1328-4

Nicoletti J., Ning C., and You F., 2019, Incorporating agricultural waste-to-energy pathways into biomass product and process network through data-driven nonlinear adaptive robust optimization, Energy, 180: 556-571.
https://doi.org/10.1016/J.ENERGY.2019.05.096

Niedzialkoski R., Marostica R., Damaceno F., Costa L., and Costa M., 2021, Combination of biological processes for agro-industrial poultry waste management: Effects on vermicomposting and anaerobic digestion, Journal of Environmental Management, 297: 113127.
https://doi.org/10.1016/j.jenvman.2021.113127

Odlare M., Arthurson V., Pell M., Svensson K., Nehrenheim E., and Abubaker J., 2011, Land application of organic waste – Effects on the soil ecosystem, Applied Energy, 88: 2210-2218.
https://doi.org/10.1016/J.APENERGY.2010.12.043

Pajura R., Masłoń A., and Czarnota J., 2023, The use of waste to produce liquid fertilizers in terms of sustainable development and energy consumption in the fertilizer industry—a case study from Poland, Energies, 16(4): 1747.
https://doi.org/10.3390/en16041747

Rajagopal D., and Liu B., 2020, The United States can generate up to 3.2 EJ of energy annually from waste, Nature Energy, 5: 18-19.
https://doi.org/10.1038/s41560-019-0532-x

Raza S., Tang J., Ali Z., Yao Z., Bah H., Iqbal H., and Ren X., 2020, Ammonia volatilization and greenhouse gases emissions during vermicomposting with animal manures and biochar to enhance sustainability, International Journal of Environmental Research and Public Health, 18(1): 178.
https://doi.org/10.3390/ijerph18010178

Salehi B., and Wang L., 2022, Critical review on nanomaterials for enhancing bioconversion and bioremediation of agricultural wastes and wastewater, Energies, 15(15): 5387.
https://doi.org/10.3390/en15155387

Salvilla J., Ofrasio B., Rollon A., Manegdeg F., Abarca R., and Luna M., 2020, Synergistic co-pyrolysıs of polyolefin plastics with wood and agricultural wastes for biofuel production, Applied Energy, 279: 115668.
https://doi.org/10.1016/J.APENERGY.2020.115668

Sarkar A., and Praveen G., 2017, Utilization of waste biomass into useful forms of energy, Biofuels and Bioenergy (BICE2016) International Conference, Bhopal, India, 23-25 February 2016, Springer International Publishing, pp.117-132.
https://doi.org/10.1007/978-3-319-47257-7_12

Schievano A., D'Imporzano G., and Adani F., 2009, Substituting energy crops with organic wastes and agro-industrial residues for biogas production, Journal of Environmental Management, 90(8): 2537-2541.
https://doi.org/10.1016/j.jenvman.2009.01.013

Schröder C., Häfner F., Larsen O., and Krause A., 2021, Urban organic waste for urban farming: growing lettuce using vermicompost and thermophilic compost, Agronomy, 11: 1175.
https://doi.org/10.3390/AGRONOMY11061175

Seidavi A., Azizi M., Swelum A., El-Hack M., and Naiel M., 2021, Practical application of some common agro-processing wastes in poultry diets, World's Poultry Science Journal, 77: 913-927.
https://doi.org/10.1080/00439339.2021.1960461

Sharma B., Vaish B., Monika, Singh U., Singh P., and Singh R., 2019, Recycling of organic wastes in agriculture: an environmental perspective, International Journal of Environmental Research, 13: 409-429.
https://doi.org/10.1007/s41742-019-00175-y

Shen Y., Linville J., Leon P., Schoene R., and Urgun-Demirtas M., 2016, Towards a sustainable paradigm of waste-to-energy process: enhanced anaerobic digestion of sludge with woody biochar, Journal of Cleaner Production, 135: 1054-1064.
https://doi.org/10.1016/J.JCLEPRO.2016.06.144

Sherwood J., 2020, The significance of biomass in a circular economy, Bioresource technology, 300: 122755.
https://doi.org/10.1016/j.biortech.2020.122755

Song C., Zhang C., Zhang S., Lin H., Kim Y., Ramakrishnan M., Du Y., Zhang Y., Zheng H., and Barceló D., 2020, Thermochemical liquefaction of agricultural and forestry wastes into biofuels and chemicals from circular economy perspectives, The Science of the Total Environment, 749: 141972.
https://doi.org/10.1016/j.scitotenv.2020.141972

Soobhany N., 2019, Insight into the recovery of nutrients from organic solid waste through biochemical conversion processes for fertilizer production: a review, Journal of Cleaner Production, 241: 118413.
https://doi.org/10.1016/j.jclepro.2019.118413.

Sousa M., Silva A., Correia R., Leite N., Bueno C., Pinheiro R., Santana J., Silva J., Sales A., Souza C., Aquino K., Souza R., Pinheiro I., Henríquez J., Schuler A., Sampaio E., Dutra E., and Menezes R., 2021, Valorizing municipal organic waste to produce biodiesel, biogas, organic fertilizer, and value-added chemicals: an integrated biorefinery approach, Biomass Conversion and Biorefinery, 12: 827-841.
https://doi.org/10.1007/S13399-020-01252-5

Srivastava R., Shetti N., Reddy K., and Aminabhavi T., 2020, Sustainable energy from waste organic matters via efficient microbial processes, The Science of the Total Environment, 722: 137927.
https://doi.org/10.1016/j.scitotenv.2020.137927

Tripathi N., Hills C., Singh R., and Atkinson C., 2019, Biomass waste utilisation in low-carbon products: harnessing a major potential resource, npj Climate and Atmospheric Science, 2: 1-10.
https://doi.org/10.1038/s41612-019-0093-5

Zhang L., Loh K., and Zhang J., 2019, Enhanced biogas production from anaerobic digestion of solid organic wastes: current status and prospects, Bioresource Technology Reports, 5: 280-296.
https://doi.org/10.1016/J.BITEB.2018.07.005