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Exploring the Capacity of Agricultural Residue as a Sustainable Energy Resource to Enhance Madagascar's Energy Security

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Abstract*: *Biomass represents a significant and emerging energy source. This study assessed and compared the potentiality of agricultural waste to be converted into renewable energy sources in Madagascar. A model for estimating biomass energy potential was exploited, and relevant data about crop and animal populations was extracted from the Food and Agriculture Organization's statistics database (FAOSTAT). Five types of crop residue were considered, including rice, sugarcane, corn, beans, and cassava, and four animal species like cattle, pigs, chickens, and sheep. Diverse conversion actors; the Ratio Product (RPR), Surplus Availability Factor (SAF), and Low Heating Value (LHV), were obtained from various literature sources and were used to assess the potential energy from agricultural residue. Subsequently, all collected data were meticulously compiled utilizing Microsoft Excel and subjected to comprehensive descriptive analysis facilitated by the OriginLab software, enabling advanced data manipulation and visualization. Our findings reveal that Madagascar generates approximately 27.78 million tons of agricultural residue annually, with the potential to produce 181.91 petajoules (PJ) of energy, primarily derived from crop residue, estimated at 128.75 PJ annually, which constitutes 70.8% of the total energy potential. With appropriate technology, the estimated energy potential could fulfill 48.7% of total energy consumption in Madagascar. Consequently, future investigations should prioritize research efforts to identify and implement optimal conversion technologies.

Keywords*: *Madagascar, Agricultural Waste, Energy Potential, Crop Residue, Livestock Waste.

I. INTRODUCTION

The agricultural sector is one of the most significant producers of solid waste [1] and is responsible for 21% of greenhouse gas emissions [2, 3], which has negative impacts. According to the FAO, in 2022, the agricultural sector made a significant contribution to the GDP, accounting for 4% of the global GDP. Furthermore, it constitutes 26.81% of the global workforce and 38.14% of the total land area [4]. Notably, in developing countries like Madagascar, agriculture is crucial to political development. The sector plays a significant role in poverty reduction and is a major source of income [5], accounting for around 30% of national GDP and 40% of merchandise export earnings [6]. As actual demographic growth continues to increase, the demand for agricultural production and waste generation rises accordingly [7]. This further contributes to a substantial portion of worldwide solid waste generation. Managing this waste constitutes a global solid waste management challenge. The improper management of agricultural residue can lead to severe environmental consequences, including land degradation, groundwater contamination, and greenhouse gas emissions.

Fig. 1. Dumping Site in Madagascar

Burning and landfilling remain the most common ways to dispose of agricultural residue, which harms the surrounding environment [8]. In Madagascar, where waste management systems are inadequate, the practice of burning agricultural residue is a common practice [9], which leads to air pollution and soil degradation. Over one million tons of crop residue are burned yearly in Madagascar [10], contributing significantly to environmental pollution [11]. The Ministry of Environment estimates 1549 dumping sites, with 1477 being in rural areas. Over 50% of the waste is thrown away, 20% burned, and 10% buried [12], which resulted in the emission of potent pollutants that lead to humanity's health vulnerability and climate change [13]. Globally, 16% of deaths were caused by pollution, while in Madagascar, about 31.3% of annual deaths in 2016 [11]. On the other hand, Madagascar has abundant sustainable energy sources, like hydropower wind, solar, and biomass [14, 15]. Due to the lack of proper technology, biomass derived from forests constitutes the highest part of the energy source in Madagascar, accounting for approximately 80 % of the total energy supply; however, non-renewable sources contribute around 20% [16].

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As Fig.2. shows, that wood biomass from forests constitutes the primary source of biomass [15], which constitutes the primary source of dry forest degradation, climate change [17], and air contamination environment [11].

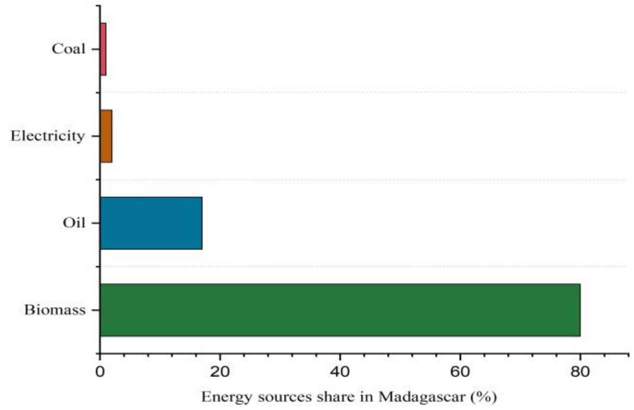

Fig. 2. Share in Energy Source in Madagascar

The country generated 2.09 TWh of electricity in 2021, and per capita consumption was about 67.6kwh/cap [18]. According to World Bank data, electricity access in Madagascar is about 35.1% [19] and 5% in rural areas [16]. Fig 3 shows that over 60% of electricity is generated from non-renewable sources, like oil and coal fossil fuels [20]. Addressing both agricultural waste and energy challenges in Madagascar and promoting alternative methods is crucial for sustainable development. Shifting from non-renewable to renewable sources has been recognized as a viable solution within the energy sector. Several investigations have been carried out to address the challenge of agricultural waste management, particularly between 2000 and 2018 [21], with the United States, China, and India leading in this research area [22]. Various authors affirmed that, with proper management like recycling and energy recovery [23, 24], agricultural residue can be considered a potential renewable resource material. Thus, converting agricultural waste into energy is one of the promising solutions [25]. This approach can positively contribute to the achievement of various Sustainable Development Goals (SDGs) such as access to affordable and clean energy, environmental pollution reduction, and climate change mitigation [26] through the concept of circular economy.

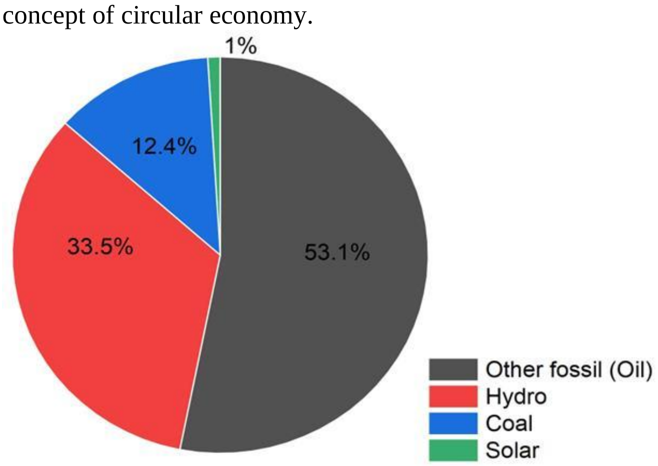

Fig. 3. Electricity Source in Madagascar

In Madagascar, Tolessa, Bélières [27][60] mentioned that the available livestock manure and crop residues could produce substantial volumes of methane and heat energy per agricultural household in Vakinankaratra. This energy could not only substitute domestic fuels but also serve as fertilizer for crops. R., Rajaonahy [28] confirmed that zebu manure and rice straw present the most suitable technology [28]. Those previous investigations advanced the idea that anaerobic digestion is an appropriate technology for agricultural waste conversion [29]. Yet, no scientific paper reflected how much biomass is generated and available for energy conversion in Madagascar. This study aims to fill the Gap and provide a clear understanding of the potentiality of Madagascar to implement the technology for agricultural waste to energy conversion by assessing the potential agricultural waste available for energy conversion. The study will also explore the potential energy from Agricultural waste by each type of residue. Agricultural waste generation depends on several factors, such as farming practices and geographical location. Thus, each assessment step will use a common model and different conversion parameters from various literature. The results of this investigation will serve as a guide for stockholders in decision-making regarding the implementation of agricultural waste valorization technology.

II. METHODOLOGY

A. Study Areas

The study area is Madagascar, an island in the Indian Ocean, geographically separated from Africa by the Mozambique Canal. With an area of 587,040 km2, it ranks as the fourth-largest island on the planet [30]. The island features tropical climates, substantial arable land, and diverse agricultural activities. With 30.3 million inhabitants [31], agriculture plays a vital role in the country's economy and generates abundant waste residues to be recycled.

B. Data source and Collection

All data, including the type and quantities of crop and livestock generation for Madagascar, were obtained from the FAO database. Different parameters obtained from different scientific papers were applied in this study including, Residue Ratio Product (RPR), Surplus Availability Factor (SAF), and Low Heating Value (LHV).

C. Energy Potential Assessment from Crop Residue

Crop residues are the leftovers from crop harvesting. The quantity of crop waste is directly linked to crop yield and production[32]. However, the quantity of crop residue varies depending on factors such as location, plant variety, climate conditions, and agricultural practices [27]. Some studies classified crop waste into gross residue and surplus.

- **Gross Residue Estimation**

The gross residue constitutes the total waste generated from a particular crop. The amount of crop residue generated depends on the crop specificity.

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Three crucial factors, including the crop area, crop yield, and RPR value, are used to determine the potential crop residue for a specific crop. For Madagascar, the gross residue will be assessed by applying the equation below.

$$GR = \sum_{i=1}^{n} Si * Zi * RPRi \quad (1)$$

Where:

- GR: the gross residue or total waste generated by crop.
- Si: is the area of plantation of each type of crop.
- Zi: is the production yield of each type of crop.
- RPRi: is the residue-to-product ratio of each type of crop.

- ***Surplus Availability Assessment***

The surplus residue constitutes the quantity of the waste available for the conversion process. It consists of the total crop waste after typical applications, such as livestock bedding and household cooking fuel. Based on the value obtained from the previous equation, the surplus available is calculated by the following equation:

$$SRA = \sum_{i=1}^{n} GRi * SAFi \quad (2)$$

Where:

- SRA: is the surplus availability
- GRi: the gross residue or total residue the crop generates.
- SAFi: is the surplus availability factor for crop residue.

- ***Energy Potential from Crop Residue***

$$EPc = \sum_{i=1}^{n} SRAi * LHVi \quad (3)$$

Where:

- EPc: is the bio-energy potential from crop residue,
- SRAi: is the surplus residue available for each crop,
- LHVi: is the lower heating value for each type of crop residue.

D. Livestock Residue Energy Potential

Livestock waste is generated from animal husbandry, like manure, urine, bedding materials, feed residues, and other byproducts [33]. This study has assessed four types of animals: cattle, sheep, chicken, and pig.

$$EPl = 365 \sum_{i=1}^{n} Ni * Di * Ci * LHVi \quad (4)$$

Where:

- EPl: the bio-energy potential from livestock manure
- Ni: the population of each animal or species,
- Di: the daily dry manure coefficient of each animal species
- Ci: the collection efficiency of animal excrement
- LHVi is the lower heating value of livestock excrement.

III. RESULTS AND DISCUSSION

A. Significance of the Agricultural sector in Madagascar

Globally, maize, wheat, rice, and sugarcane are significant crops grown [34]. About 47% of crop residue is generated from Asia and 6% from Africa [25]. Like all other developing countries, Madagascar's economy is primarily agricultural, with 83.2% of households engaged in farming [35].

The agricultural sector is crucial both socially and economically since it employs about 80% of the active population and accounted for 27% of the country's national GDP in 2020 [36]. Over 90% of agricultural output is directed towards the domestic market. In Madagascar, the cultivation landscape is remarkably varied, influenced by the country's diverse geographical and climatic conditions. Approximately 75% of the food produced by rural households is designated for local consumption [37].

According to the data in Fig.4., rice, sugarcane, and cassava share a large part in crop production, while chickens and cattle are in livestock farming. Madagascar produces around 4 MT of rice, 3 MT of sugarcane, and 2.8 MT of cassava per year.

Rice is a staple food in Madagascar and is practiced by 68% of households, with cultivation occupying 1.3 ha (FAO, 2022) [35]. This indicated a significant reliance on the crop and potentially favorable conditions for higher yields, resulting in greater residue biomass. According to INSTAT2021, 77.9% of agricultural households actively engaged in farming activities. Due to their high energy value resulting from their significant starch content, the cultivation of cereals such as rice, corn, and wheat, as well as roots and tubers like potatoes and cassava, yams, taro, and sweet potatoes, is widely grown in the country [36].

On the other hand, animal husbandry is practiced by 71.3% of agricultural households; cattle constitute the main important husbandry in Madagascar, with an average amount of 9.7 million head (FAO,2022). Poultry farming is also spread throughout the territory of Madagascar.

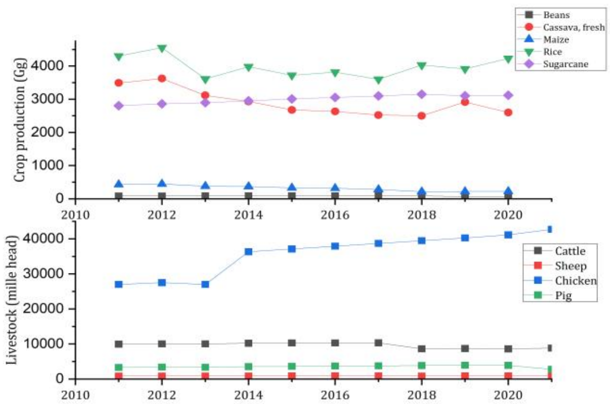

Fig. 4. Agricultural Production in Madagascar

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B. Crop Residue Generation Assessment

Crop residue is the leftover plant material after the harvesting period. Generally, cassava peeling, cassava stalk, rice straw, rice stalk, sugar cane bagasse, sugarcane top, and leaves are the typical composition of crop residue in West Africa [38].

Energy production depends on crop and residue availability, which is the portion that remains after other components are consumed for different purposes [39]. This work has considered five types of crops, including rice, maize, cassava, sugarcane, and beans.

The finding in Fig. 5 estimated that Madagascar generates approximately 19.24 million tons (MT) of gross agricultural residue annually from these crops: 46.13%, 39.23%, 9.52%, 4.17%, and 0.95 for cassava, rice, sugarcane, maize, and beans, respectively. These crops generate approximately 9.554 MT of surplus residue, representing 49.7% of the total residue.

A closer examination of the composition of agricultural waste reveals that rice, sugarcane, and cassava are the predominant contributors, accounting for approximately 94% of total residue in Madagascar.

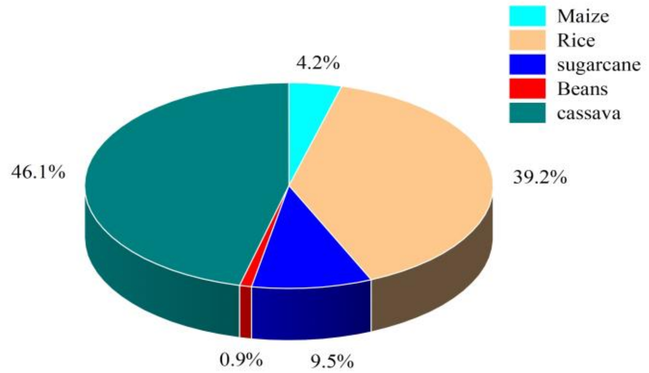

Fig. 5. Crop Residue Share in Madagascar

Crop wastes are commonly used as animal feed, composted, disposed of in landfills, and sometimes burned, constituting a veritable environmental threat [39]; health disease and climate change constitute the world's challenges.

In 2020, according to the Food and Agriculture Organization, Madagascar accounted for approximately 1.1106 MT tons of crop waste burned annually. This practice produced approximately 4.0567 kilotons (kt) of methane (CH_4) and 0.1053 kt of nitrous oxide (NO_2). Additionally, direct emission from manure left in pastures contributed approximately 12.058 kt of nitrous oxide (NO_2) in 2020 and is expected to be 20.50 kt in 2050 [40]. However, biofuel production from biomass is a potential solution to address the energy demands and reduce the use of non-renewable energy sources [25]. This can be done by applying appropriate technology, including thermochemical conversion [41] that combines thermal and chemical reactions to produce a valuable product like syngas, bio-oil, and biochar from the organic residue [42]. Additionally, the biochemical conversion process is another technology that involves the breakdown of organic matter into biofuel by using enzymes from bacteria and other microorganisms [43]. The technology efficiency and the biofuel quality depend on the composition of available residue [32]. Understanding the composition of agricultural waste is crucial for developing efficient management strategies and energy conversion.

C. Manure Generation Assessment

Four animal types have been assessed: cattle, sheep, chicken, and pig. Those animals generate various kinds of waste like urine, bedding materials, feed residues, and other byproducts of animal production [33], but only manure is considered in this study. The availability of livestock waste relies on the size of the livestock operation, the type and number of animals, and management practices. In this case, animal waste was obtained by applying factors including the coefficient of dry excreta and collection.

The result in Fig.6. shows that more than 8.239 MT of dry manure is produced annually. Cattle generate an average of 6,375 MT of manure annually, representing 76.5% of total manure. Pig and chicken manure represent 12.7% and 9.3% of the annual manure production. The finding demonstrated the importance of cattle in manure generation.

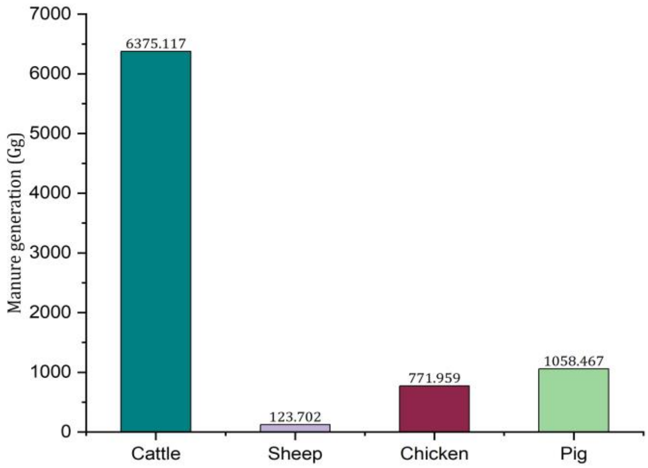

Fig. 6. Livestock Manure Generation in Madagascar

In terms of collection, the dung collection efficiency depends on the farming method. In free-range systems, the collection efficiency is lower than that in advanced farming operations. Logistics, like collection and transportation, is also crucial in waste management and energy valorization [44]. This study employed the typical coefficient of the dung collection ratio to determine the amount of dung collected. It was evaluated that for cattle, sheep, chickens, and pigs, the dry dung collection ratio is about 45%, 35%, 70%, and 80%, respectively [45].

For Madagascar, the collected dung was evaluated at 4.2 MT, representing 51.2% of annual manure generation. Cattle manure was about 66.7% of total dung collected, 19% for pigs, 12% for chicken, and 1% for sheep. Thus, cattle and pigs constituted most of the animal residue available for energy conversion. This collected dung represents a potential residue available for energy generation. Thus, livestock manure is continually generated on farms where animals are raised. Livestock manure consists primarily of 75% water and 25% solid matter (organic or inorganic), as well as various pathogenic microorganisms [46].

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Animal dung provides multiple environmental and economic benefits. Several studies affirm different ways to manage livestock waste, such as biofuel production and composting [33, 47].

Nitrogen, phosphorus, and potassium in animal dung benefit soil properties [33, 48]. It can also be converted into biofuel by various pathways, like pyrolysis, charcoal briquette, and biogas by anaerobic digestion.

Manure presents a significant opportunity for bioenergy conversion due to its abundance, renewable nature, and properties. Thus, the generation and availability of livestock waste play crucial roles in determining the feasibility and efficiency of bioenergy conversion processes. However, the existence of pathogenic organisms, antibiotics, and biosolids in livestock excrement can potentially harm the animal's health. Improper management of that waste may result in carbon emissions in the atmosphere, which may cause environmental contamination and the spread of diseases, and also contribute to greenhouse gas emissions, which leads to climate change [47].

D. Potential Energy from Agricultural Waste

The energy potentiality from agricultural waste refers to its ability to be converted as an energy source through different technologies and processes.

- **Crop Residue Energy Potential Assessment**

Table- I: Crop Residue Energy Conversion Parameters [45, 49, 50]

Crop residue	Residue type	RPR_i	SAF_i	LHV (MJ/kg)	Energy (PJ/y)
Maize	Stalks	2	0.8	15	7.70
	Cobs	0.3	1	15.5	1.49
	Husks	0.2	1	12	0.77
Rice	Straw	1.54	0.72	13.45	59.28
	Husks	0.36	0.62	16	14.19
Sugarcane	Bagasse	0.29	1	13	11.32
	Tops &leaves	0.32	0.8	15.8	12.15
Cassava	Stalk	0.062	0.41	16.99	1.24
	Peelings	3	0.2	10.61	18.46
Beans	Straws	2.23	0.80	14.70	2.14
Total					128.75

PJ: Petajoule, MJ: Megajoule.

The result elucidated in Table -I reveals that the total crop residue energy potential in Madagascar is approximately 128.75PJ, with rice, sugarcane, and cassava demonstrating the most pronounced energy potentials at 73.47 PJ, 23.47 PJ, and 19.70PJ, respectively. However, beans and maize exhibit comparatively lower energy potential values. Specifically, maize presents a moderate energy output at 9,97 PJ, while beans yield a residual energy value of approximately 2.14 PJ.

Thus, rice and sugarcane are the most promising bioenergy sources, boasting significant residue outputs. Due to their substantial residual biomass, these crops warrant prioritization in bioenergy development initiatives.

This comprehensive analysis illuminates these crops' significant role in the country's energy landscape, highlighting avenues for further exploration and utilization of agricultural residues to meet energy demands sustainably.

- **Livestock Manure Energy Potential Assessment**

The study concentrates on four key animal species. Thus, the finding in Table -II indicates that Madagascar can produce 53 PJ of energy from livestock waste. These findings highlight the substantial contribution that livestock-based energy generation could offer to Madagascar's energy landscape, emphasizing the importance of further exploration and strategic utilization of this renewable resource.

Table- II: Animal Manure to Energy Conversion Parameter[45]

Livestock	Dry dung(kg/d)	Collection eff%	LHV (GJ/t)	Energy (PJ/y)
Cattle	1.8	45	13	37.29
Sheep	0.4	35	14	0.61
Chicken	0.06	70	11	5.94
Pig	0.8	80	11	9.31
Total				**53.16**

Cattle generate the most energy, followed by pigs and chickens. Together, cattle, pigs, and chickens contribute 70%, 17%, and 11% of the energy potential.

Moreover, the study of livestock manure as a viable source of bioenergy potential highlights the significance of cattle, pigs, and chickens. These distinct livestock categories emerge as pivotal elements within Madagascar's agricultural sector, indicating their crucial contribution to the broader framework of bioenergy production from agricultural waste. Such insights underscore the need for targeted initiatives to harness the bioenergy potential inherent in these livestock categories, thereby fostering sustainable energy production practices in Madagascar.

E. Madagascar Energy Supply and Agricultural Waste Energy Potential

As presented in Fig. 2., biomass, oil, coal, and electricity are the primary sources of energy in Madagascar, and biomass constitutes the primary source of energy supply. However, the country is characterized by a lack of electricity access. The country's principal energy uses are household cooking, electricity, lighting, and industrial sectors. Cooking represents 93% of energy consumption, wood fuel represents 82% of the energy source for cooking, and 17% of charcoal is from wood forests [51]. In 2021, 1.4% of the population has access to clean fuel for cooking [20].

According to the International Renewable Energy Agency (IRENA), Madagascar's total energy supply is about 373,529 terajoules (TJ), of which 85% is from biomass sources [52]. Wood represents approximately 85% of all biomass, followed by charcoal at 12% and another source at 3% [16]. This leads to environmental pollution.

According to the findings in Tables I and II, crop residue and livestock waste can generate a considerable bioenergy potential of 181.91 PJ, predominantly sourced from crop residues (128.75 PJ), followed by livestock waste (53.16 PJ).

Thus, the estimated potential energy from agricultural waste is to fulfill 48.7% of total energy consumption in Madagascar.

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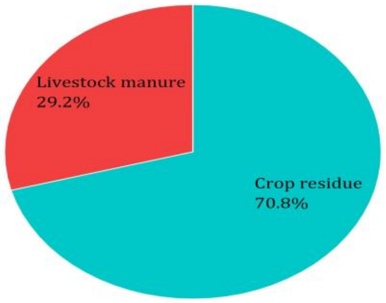

Fig. 7. Share of Potential Energy

The finding in Fig. 7 shows that crop residue generates 70.8% of energy, and livestock manure generates 29.3% of energy potential from agricultural waste. This presents a promising solution to diversify the energy source and reduce reliance on non-sustainable sources in Madagascar.

F. Agricultural Waste Management and Policy in Madagascar

Agricultural waste constitutes a large part of global waste and presents a global challenge. In Madagascar, waste management strategies include waste reduction, source separation, reuse, recycling, composting [12], and eventual landfilling. However, these methods are still in the experimental in the country. Also, there is a lack of waste treatment facilities in Madagascar [53]. Various regulations have been established regarding waste management [9]:

- Decree n° 2012-753 issued on 07 August 2012, related to the Ban on waste under the Basel Convention in Madagascar until a suitable treatment center is installed.
- Decree n° 2012-754, issued 07 August 2012, related to the End-of-Life Products, Waste Sources, and Hazardous Waste Management Procedures for implementing the Basel Convention.
- Decree n° 2012 -900, issued 23 January 2013, prohibits the importation, distribution, sale, use, and production of pesticide-active ingredients in agriculture and chemicals for industries in the framework of the application of the Rotterdam Convention and the Convention of Stockholm Madagascar.
- Decree n° 2014-1587 issued 2014 October 07 related to Prohibiting the production, importation, marketing, and use of plastic bags on the Malagasy national territory.
- Decree n° 2015-930 Classification and environmentally sound management of waste electrical and electronic equipment in Madagascar.
- Decree n° 2017-010 prohibits the production, importation, marketing, stockpiling, and use of plastic bags and bags made with plastic on the national territory.

Nonetheless, the regulation and structure concerning agricultural waste management are still missing. Traditional burning and landfilling crop residue are common ways to treat waste in Madagascar. An annual 1 MT/year of crop residue is estimated to be burned and contributes significantly to environmental pollution [10].

Madagascar faces a significant challenge in waste management. Additionally, there is still no specific regulation or framework for agricultural waste management.

G. Clean Energy Initiative and Energy Policy in Madagascar

Madagascar is among the low-income countries [54] with low electricity access rates. For instance, in 2021, only 35.1% of the population had access to electricity [55]. In the rural zone, 5% of the population has access to electricity [56]. Moreover, wood is the country's most essential energy source [57].

As part of the Stockholm Convention on persistent organic pollutants ratified by Madagascar in August 2005 [9], and also part of the commitment of the Parish Agreement in 2015 to address the issue of climate change. Madagascar has tried to address environmental problems through various policies and regulations.

The Madagascar government aims to improve the use of clean energy, increase electricity access to 70%, and ensure that 20% of households use biological fuels by 2030 [58]. It also aims to increase clean and sustainable energy use by incorporating 85% of energy generated from renewable sources.

Art 10 Law n°2017- 020, related to the Madagascar Electricity Code, defined Renewable Energy Sources (RES) as natural and continuous energy flows in our surroundings, including renewable sources, solar heat, wind, water, ocean, waste, and biomass.

Furthermore, through recent reforms, the Madagascar government has sought collaborations and encouraged investments in the energy sector [59]. Various international partners actively support Madagascar's energy sector development:

- Since 1972, following the establishment of ambassadorial diplomatic relations between China and Madagascar, a range of initiatives have been put in place to bolster renewable energy development in Madagascar. This commitment is underscored by a substantial investment totaling $71.20 million in 2017.
- In 2018, the World Bank implemented biogas in rural households in Madagascar, which led to 3,642 tons of CO_2e due to the use of biogas instead of wood fuel and also reduced the country's consumption of non-renewable dry wood by 2,084 t per year or 4,168 t of green wood each year[51]. Furthermore, in February 2023, the Digital and Energy Connectivity for Inclusion in Madagascar (DECIM) project was initiated to enhance the country's access to renewable energy and digital services.

IV. CONCLUSIONS AND RECOMMENDATIONS

Madagascar has significant potential for renewable energy sources. Despite the absence of appropriate technology, biomass from wood accounts for the largest portion of energy consumption. Biofuel from biomass presents a promising source of energy that respects the global environmental policy. This study demonstrates that Madagascar has the potential to generate 181.91 PJ of energy via crop residue and livestock manure, Where crop residue shares 70.8% of total energy potential.

The finding estimated that potential energy from agricultural waste could fulfill 48.7% of total energy consumption in Madagascar. This presents a promising opportunity to diversify the energy mix and reduce the dependence on fossil fuels in the country. Energy conversion efficiency and energy output composition depend on technology efficiency. Thus, future investigations should identify the most suitable technology for different residues.

In addition, it is imperative to implement a regulatory framework governing sustainable management practices of agricultural waste within the nation. This study underscores the critical importance of promoting opportunities for renewable energy in Madagascar, addressing the pressing need for sustainable development in the energy sector, and providing valuable visions for policymakers. These visions offer direction for well-informed decision-making procedures, aiding in the creation and execution of efficient policies and strategies aimed at advancing sustainable energy development.

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Availability of data and material	Not relevant.
Authors contributions	All authors have equal contributions in this article.

REFERENCES

1. Babu, S., et al., Exploring agricultural waste biomass for energy, food and feed production and pollution mitigation: A review. Bioresour Technol, 2022. 360: p. 127566. https://doi.org/10.1016/j.biortech.2022.127566
2. Adejumo, I.O. and O.A. Adebiyi, Agricultural Solid Wastes: Causes, Effects, and Effective Management. Solid Waste Management, 2020.
3. Sun, J., et al., An estimation of CO 2 emission via agricultural crop residue open field burning in China from 1996 to 2013. Journal of Cleaner Production, 2016. 112: p. 2625-2631. https://doi.org/10.1016/j.jclepro.2015.09.112
4. Nazimudheen, G., et al., Physiochemical characterization and thermal kinetics of lignin recovered from sustainable agrowaste for bioenergy applications. International Journal of Hydrogen Energy, 2021. 46(6): p. 4798-4807. https://doi.org/10.1016/j.ijhydene.2020.03.172
5. Statistics, M.N.I.o., Global results on RGPH-3 of 2018 of Madagascar, in December 2020. 2020, INSTAT, Madagascar: https://madagascar.unfpa.org/sites/default/files/pub-pdf/resultat_globaux_rgph3_tome_01.pdf.
6. El-Haggar Salah M, G.M., L. Gennaro, Agricultural waste as an energy source in developing countries.pdf. Semantic Scholar, 2004.
7. Alao, M.A., O.M. Popoola, and T.R. Ayodele, Waste-to-energy nexus: An overview of technologies and implementation for sustainable development. Cleaner Energy Systems, 2022. 3. https://doi.org/10.1016/j.cles.2022.100034
8. Ramaroson, V., et al., Tritium as tracer of groundwater pollution extension: case study of Andralanitra landfill site, Antananarivo–Madagascar. Applied Water Science, 2018. 8(2). https://doi.org/10.1007/s13201-018-0695-9
9. Research, U.N.I.f.T.a., National inventories of waste open burning, in Madagascar Inventory report. 2017, ONUDI: https://stopopenburning.unitar.org/site/assets/files/1023/madagascar-_inventory_report_for_open_burning_project-_dec2017.pdf.
10. FAO, S., Food and agriculture data, in Food and Agriculture Organisation. 2022, Food and Agricultural Organization of United Nations: https://www.fao.org/faostat/en/#home.
11. Pollution, G.A.o.H.a., Madagascar health and pollution,Accelerating the Implementation of Actions to Reduce, Pollution-Related Illness, in Global Alliance on Health and Pollution, E. Ministry of Environment, and Forests (MEEF) Editor. 2019, Global Alliance on Health and Pollution.
12. Coalition, C.a.C.a., Solid waste management, city profil, in global-recycling.info. 2015, Global Recycling Magazine: https://global-recycling.info/archives/7576.
13. Raza, M.H., et al., Environmental and Health Impacts of Crop Residue Burning: Scope of Sustainable Crop Residue Management Practices. Int J Environ Res Public Health, 2022. 19(8). https://doi.org/10.3390/ijerph19084753
14. Madagascar, E.D.B.o., Madagascar, the Boundless energy island, in Economic Development Board of Madagascar. 2017, EDBM: https://edbm.mg/wp-content/uploads/2018/01/Guide-Energie-ENG.pdf.
15. Praene, J.P., et al., Electricity generation from renewables in Madagascar: Opportunities and projections. Renewable and Sustainable Energy Reviews, 2017. 76: p. 1066-1079. https://doi.org/10.1016/j.rser.2017.03.125
16. Qin, L., et al., Towards Circular Economy through Waste to Biomass Energy in Madagascar. Complexity, 2021. 2021: p. 1-10. https://doi.org/10.1155/2021/6631837
17. Randriamalala, J.R., et al., Estimating wood charcoal supply to Toliara town in southwestern Madagascar, a comparison of methods. Scientific African, 2021. 14. https://doi.org/10.1016/j.sciaf.2021.e01011
18. countryeconomy.com. Madagascar Electricity consumption. countryeconomy.com 2021; Available from: https://countryeconomy.com/energy-and-environment/electricity-consumption/madagascar.
19. Worldbank, Access to electricity % of population in Madagascar, in World Bank Database. 2022, World Bank: The World Bank.
20. Ritchie, H., M. Roser, and P. Rosado, Madagascar: Energy Country Profile-Access to energy, in Madagascar: Energy Country Profile, M.E.C. Profile, Editor. 2022, Our World in Data.
21. Duque-Acevedo, M., et al., Agricultural waste: Review of the evolution, approaches and perspectives on alternative uses. Global Ecology and Conservation, 2020. 22. https://doi.org/10.1016/j.gecco.2020.e00902
22. Sertolli, A., et al., Biomass Potential and Utilization in Worldwide Research Trends—A Bibliometric Analysis. Sustainability, 2022. 14(9). https://doi.org/10.3390/su14095515
23. Khan, A.H., et al., Current solid waste management strategies and energy recovery in developing countries - State of art review. Chemosphere, 2022. 291(Pt 3): p. 133088. https://doi.org/10.1016/j.chemosphere.2021.133088
24. Hsu, E., Cost-benefit analysis for recycling of agricultural wastes in Taiwan. Waste Manag, 2021. 120: p. 424-432. https://doi.org/10.1016/j.wasman.2020.09.051
25. Kamusoko, R., et al., Strategies for valorization of crop residues into biofuels and other value-added products. Biofuels, Bioproducts and Biorefining, 2021. 15(6): p. 1950-1964. https://doi.org/10.1002/bbb.2282
26. Gatto, A., The energy futures we want: A research and policy agenda for energy transitions. Energy Research & Social Science, 2022. 89. https://doi.org/10.1016/j.erss.2022.102639
27. Tolessa, A., et al., Assessment of Agricultural Biomass Residues for Anaerobic Digestion in Rural Vakinankaratra Region of Madagascar. BioEnergy Research, 2021. 15(2): p. 1251-1264. https://doi.org/10.1007/s12155-021-10336-7
28. R., M., et al., Experimental Investigation of Anaerobic CoDigestion of Organic Waste Madagascar. Journal of Multidisciplinary Engineering Science and Technology, 2016. Vol. 3 Issue 1, January - 2016(2016).
29. Balmer, L., Feasibility study for valorization of organic waste through anaerobic digestion in a rural municipality of Madagascar, in Ecole Polytechnique Federale de Lausanne Section de Chimie et Genie Chimique. 2016, Ecole Polytechnique Federale de Lausanne Section de Chimie et Genie Chimique. p. 73.
30. Jian, G., et al., A novel GRACE reconstructive filter to extract the mass changes in Madagascar. Geophysical Journal International, 2023. 235(2): p. 1493-1503. https://doi.org/10.1093/gji/ggad316
31. Prospect, U.N.-W.P. Madagascar Population 1950-2024. Madagascar - Historical Population Data 2024 [cited 2024; Available from: https://www.macrotrends.net/global-metrics/countries/MDG/madagascar/population.

32. Anand, A., et al., Assessment of crop residues-based electricity generation potential for energy security in Bangladesh. Bioresource Technology Reports, 2021. 15: p. 100812. https://doi.org/10.1016/j.biteb.2021.100812
33. Parihar, S., et al., Livestock waste management a review. Journal of Entomology and Zoology Studies, 2019.
34. Bhuvaneshwari, S., H. Hettiarachchi, and J.N. Meegoda, Crop Residue Burning in India: Policy Challenges and Potential Solutions. Int J Environ Res Public Health, 2019. 16(5). https://doi.org/10.3390/ijerph16050832
35. Statistics, M.N.I.o., Menages Agricole Madagascar, in Recesement General de la Pepulation et Habitation-3. 2021, INSTAT, Madagascar.
36. Garruchet, V., Agriculture in Madagascar, evolution, key figures and challenges, in AgriTrop. 2023, PreRad Indian Ocean.
37. Vincent Garruchet, P.-M.B., Isabelle Mialet-Serra, L'Agriculture à Madagascar, evolution et defis, in PreRad Ocean Indian. 2023.
38. Thomsen, S.T., Z. Kádár, and J.E. Schmidt, Compositional analysis and projected biofuel potentials from common West African agricultural residues. Biomass and Bioenergy, 2014. 63: p. 210-217. https://doi.org/10.1016/j.biombioe.2014.01.045
39. Alengebawy, A., et al., Rice straw for energy and value-added products in China: a review. Environmental Chemistry Letters, 2023: p. 1-32.
40. Worldbank, Agriculture and Food, in Agriculture and Food. 2023, World Bank: Agriculture and Food.
41. Khan, A., et al., Thermochemical conversion of agricultural waste to hydrogen, methane, and biofuels: A review. Fuel, 2023. 351. https://doi.org/10.1016/j.fuel.2023.128947
42. Lee, S.Y., et al., Waste to bioenergy: a review on the recent conversion technologies. BMC Energy, 2019. 1(1). https://doi.org/10.1186/s42500-019-0004-7
43. Saravanan, A., et al., Techno-economic and environmental sustainability prospects on biochemical conversion of agricultural and algal biomass to biofuels. Journal of Cleaner Production, 2023. 414: p. 137749. https://doi.org/10.1016/j.jclepro.2023.137749
44. Vlyssides, A., S. Mai, and E.M. Barampouti, Energy Generation Potential in Greece From Agricultural Residues and Livestock Manure by Anaerobic Digestion Technology. Waste and Biomass Valorization, 2015. 6(5): p. 747-757. https://doi.org/10.1007/s12649-015-9400-5
45. Gabisa, E.W. and S.H. Gheewala, Potential of bio-energy production in Ethiopia based on available biomass residues. Biomass and Bioenergy, 2018. 111: p. 77-87. https://doi.org/10.1016/j.biombioe.2018.02.009
46. Mawdsley, J.L., Pathogens in livestock waste, their potential for movement through. Applied Soil Ecology, 1994.
47. Yue, D., A. Sarkar, and C. Guang, Impacts of Incentive and Disincentive Mechanisms for Ensuring Environmentally Friendly Livestock Waste Management. Animals (Basel), 2022. 12(16). https://doi.org/10.3390/ani12162121
48. Shakya, S.K., et al., Livestock waste management practices to strengthen the farm profitability. Journal of Entomology and Zoology Studies 2022. https://doi.org/10.22271/j.ento.2022.v10.i5d.9075
49. Okello, C., et al., Bioenergy potential of agricultural and forest residues in Uganda. Biomass and Bioenergy, 2013. 56: p. 515-525. https://doi.org/10.1016/j.biombioe.2013.06.003
50. Tanyi, R.J. and M.S. Adaramola, Bioenergy potential of agricultural crop residues and municipal solid waste in Cameroon. AIMS Energy, 2023. 11(1): p. 31-46. https://doi.org/10.3934/energy.2023002
51. Ferrer, M., Capitalization of biogas sector and improved stoves in Madagascar, in Etc Terra Rongead. 2018, Etc Terra Rongead.
52. Agency, I.R.E., Energy profile Madagascar_Africa_RE_SP, in International Renewable Energy Agency. 2023, International Renewable Energy Agency.
53. Rajaona, A.R., et al., Feasibility Study of the Implementation of a Wastewater Treatment Plant in the City of Tulear Madagascar 2018. European Journal of Environment and Earth Sciences, 2023. 4(4): p. 1-8. https://doi.org/10.24018/ejgeo.2023.4.4.410
54. Bank, W., Least Cost Electricity Access Development project in Energy and Extractives Global Practice Africa Region, E.a.E.G.P.-A. Region, Editor. 2019, The World Bank.
55. info, W.d., Energy consumption in Madagascar, in World data.info. 2023, World data.info: World data.info.
56. Garcia, F.P.K. and A.K. Raji, Access to Efficient and Sustainable Energy Case of Madagascar. PowerAfrica, 2020. https://doi.org/10.1109/PowerAfrica49420.2020.9219881
57. Andrianajaina, T., Lateral electrification,for a new way of rural electrification in Madagascar. International Journal Of Advance Research And Innovative Ideas In Education, 2022.
58. Madagascar, M.o.E.a.H.M., A next Decade Action Agenda to advance SDG7 on sustainable energy for all, in line with the goals of the Paris Agreement on Climate Change, in SDG7 Energy Compact of the Ministry of Energy and Hydrocarbons (MEH) – Madagascar. 2022, United Nation.
59. BEGUERIE, V. and K. BLANCHARD, The potential for renewable energies in rural areas of Madagascar, in ONUDI. 2009, UNIDO SCRIBD. p. 31-87.
60. Hung, D. P. (2019). Impact of Information Technology on Agriculture Development. In International Journal of Engineering and Advanced Technology (Vol. 8, Issue 6s3, pp. 1–3). https://doi.org/10.35940/ijeat.f1001.0986s319

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