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Regional Biogas Potential from Agricultural and Livestock Residues: A Sustainable Renewable Energy Strategy for Madagascar

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Abstract

Madagascar faces major energy challenges while producing large quantities of agricultural and livestock residues that currently are poorly managed or openly burned. This study assesses the potential of recoverable agricultural residues for biogas production for domestic energy generation in agricultural areas of Madagascar through decentralized farm-level anaerobic digestion (AD) and identifies regions with the highest biogas production potential. Organic substrate production data for 24 regions were combined with residue-to-product ratio (RPR), total solids (TS) and volatile solids (VS) contents, and livestock manure characteristics. The results estimated 2389 $Mm^3 \cdot y^{-1}$ of theoretical biogas potential and 129,319 $TJ \cdot y^{-1}$ of available energy throughout Madagascar. Sofia region showed the highest biogas potential, followed by the Atsimo-Andrefana and Atsinanana regions. The study also evaluates the sustainability of decentralized AD at a farm-scale level by treating cattle manure in a 2.5 m^3 digester, estimating that it is possible to save around 5.65 kg wood·day $^{-1}$ $inhabitant^{-1}$ through biogas combustion, with significant ancillary benefits in terms of improved energy security and reduced deforestation. A 10% TS slurry concentration and a 30-day hydraulic retention time (HRT) are considered for preliminary reactor sizing. While providing important advantages such as clean renewable energy generation, reduced deforestation, and efficient waste management, critical aspects for diffused decentralized AD deployment are connected to costs and reactor maintenance, which require skilled personnel, as well as the need for knowledge sharing with local stakeholders (farmers and inhabitants) to highlight the advantages of biogas generation at a farm-scale level. Dedicated financial incentives, in addition, might be provided by the government to boost diffused decentralized AD implementation in Madagascar. These preliminary findings demonstrate the significant theoretical potential of agricultural and livestock residues for renewable energy production in Madagascar through decentralized AD, while highlighting the need to carefully address feedstock collection, logistics, water availability, infrastructure, and institutional constraints for practical AD development.

Keywords: crop residues; livestock manure; anaerobic digestion; biogas; anaerobic co-digestion; renewable energy

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Academic Editor: Jacopo Bacenetti

Received: 2 September 2026
Revised: 11 October 2026
Accepted: 15 October 2026
Published: 17 October 2026

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1. Introduction

Energy is a key driver of modern socioeconomic development. It supports a wide range of sectors, including healthcare, agriculture, education, industry, and other essential services [1]. Global energy demand is continuously increasing due to population growth, urbanization, and industrial development. According to the U.S. Energy Information Administration, global energy consumption is expected to be 34% higher in 2050 than it was in 2022 [2]. This growing energy demand has increased dependence on fossil fuels, creating major concerns about energy security, environmental impacts, and climate change. Therefore, many countries are accelerating the transition toward renewable and cleaner energy sources, with dedicated investments and supportive policies [3]. This effort is also well aligned with the United Nations 2030 Agenda for Sustainable Development, particularly Sustainable Development Goal 7, which promotes access to affordable, reliable, sustainable, and modern energy for everybody [4].

Among renewable energy sources, biomass represents a promising resource due to its diffused availability and wide potential for energy production. The valorization of agricultural and livestock organic residues can contribute to renewable energy generation while reducing waste and associated environmental impacts [5]. In recent years, numerous scientific studies have focused on assessing biomass potential and developing sustainable pathways for its efficient utilization [6–11]. One of these pathways is anaerobic digestion (AD), a mature biological process that converts biodegradable organic materials, such as agricultural residues, food waste, sewage sludge and livestock manure, into biogas and digestate. Under oxygen-free conditions, microorganisms break down organic matter through four main stages, producing biogas composed mainly of methane (CH_4) and carbon dioxide (CO_2), as well as digestate, a nutrient-rich by-product that can be used as an organic fertilizer in agriculture [12,13]. AD is a flexible technology that can be applied at different scales, from small household systems to large-scale centralized plants, making it suitable for various organic waste management and local supply chain needs [14]. These environmental and agricultural benefits have increased interest in AD for decentralized energy production, particularly in developing countries [8,15,16].

In Madagascar, agriculture is a major sector of the economy, contributing approximately 25% of the gross domestic product (GDP) and employing around 70% of the active population [17,18]. However, the expansion of agricultural activities has increased the generation of agricultural residues, which remain inadequately managed. Each year, more than one million tons of crop residues are left along roadsides or near rice fields and are subsequently burned, partly due to their volumetric constraints [7,19]. These practices pose severe risks to public health and contribute to environmental degradation and greenhouse gas emissions [20]. At the same time, electricity access remains limited in Madagascar. According to World Bank data [21], in fact, only 42.5% of the population had access to electricity in 2024, with a marked disparity between urban and rural areas: the electrification rate is approximately 75.9% in urban areas compared with only 26.5% in rural areas, where around 67% of the population lives. Despite this limited access, Madagascar has substantial renewable energy resources for clean energy production, particularly biomass, which accounts for about 80% of the country's primary energy supply [6]. However, biomass is still mainly managed through traditional and inefficient practices, raising concerns about its sustainability and negative environmental impacts.

AD offers an outstanding opportunity to address both organic waste management and energy challenges in Madagascar. Previous studies have investigated the energy potential of these organic resources. Tolessa et al., e.g., assessed the availability of manure from four types of livestock and agricultural residues from 17 crops in smallholder farming systems in the rural Vakinankaratra region during 2017–2018. Their results showed that the

available livestock manure and crop residues could generate approximately 291 ± 92 and 745 ± 122 Nm^3 of methane per agricultural household per year, respectively, corresponding to 10.5 ± 3.34 and 26.8 ± 4.28 GJ of heat [15]. Rajaonahy et al., instead, investigated the co-digestion of various organic wastes using different mixing ratios to determine the highest biogas yield. Their results showed that the zebu manure and rice straw mixture (ratio 1:1) was the most suitable substrate for biogas production [8]. Vita et al. estimated that agricultural residues could satisfy up to 48.7% of Madagascar's total energy demand when appropriate conversion technologies are applied [19]. Finally, Rakotoarivelo et al. developed a regional biomass database for Madagascar, estimating the availability of recoverable crop residues as energy resources [7]. However, a comprehensive regional assessment of recoverable crop and livestock residues and their biogas and energy potential is still not available for Madagascar, with practical insight into effective application at a decentralized scale. In addition, the potential contribution of biogas to reducing domestic firewood use and the sustainability of household-scale anaerobic digesters have received limited attention.

Therefore, this study aims to quantify the recoverable residues from four livestock categories (cattle, poultry, pigs, and goats/sheep) and five major agricultural crops (rice, maize, sweet potato, sugarcane, and cassava) widely available across the regions of Madagascar for decentralized AD at a farm-scale level. It evaluates their potential for biogas production and the corresponding energy content. A household-scale digester scenario is later studied to estimate the digester size that could potentially be installed at a small farm level using cattle manure as a reference substrate. The study further estimates the potential amount of firewood that could be replaced by biogas in a typical small-scale farm, highlighting the related environmental benefits. The Atsimo-Andrefana region was selected for this scenario because of its high cattle manure generation. The results are expected to provide a regional overview of biogas potential in Madagascar and support the identification of suitable opportunities for decentralized biogas production at a farm-scale level.

2. Materials and Methods

2.1. Study Area

The present study covers all 24 administrative regions of Madagascar [22]. As previously mentioned, the country has a predominantly agricultural economy, with 65.7% of agricultural households recorded in 2022 [23]. For crop production, 68.6% of households are engaged in rice cultivation, the staple food of the Malagasy population. Regarding livestock production, instead, cattle and poultry farming are the prevalent activities, involving 61.2% and 36.1% of households, respectively [24]. This strong reliance on agriculture makes Madagascar particularly relevant for assessing the availability and regional distribution of crop and livestock residues for biogas production. The adopted approach for this study is summarized in Figure 1 and could be potentially replicated in other areas of developing countries to ascertain the organic substrate availability for AD and prioritize areas with a higher biogas production potential.

2.2. Data Source

All crop and livestock production data for this study were obtained from the FAOSTAT database for the 2015–2024 period [24]. The estimation of residue amount and energy potential requires several input parameters, including the residue-to-product ratio (RPR), total solid (TS) and volatile solid (VS) content of the crop, daily VS production per livestock, lower heating value (LHV), and biogas yield per unit of VS (Tables 1 and 2). These parameters vary considerably from country to country and region to region due to differences in crop characteristics, animal weight, feed intake, and local environmental conditions.

Using region-specific data is therefore preferable for accurate residue and energy potential assessment. However, such data remain limited for Madagascar. So, values reported in relevant studies from Madagascar and other African countries were selected and applied to estimate the energy potential of crop residues and livestock manure.

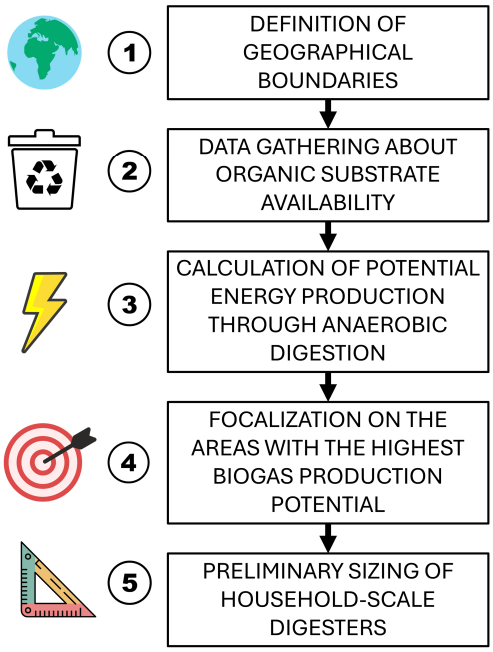


Figure 1. Conceptual approach applied in this study.

Table 1. Crop residues input parameters used for biogas potential estimation [7,19,25–33].

Crop Residues	Residue-to-Product Ratio (-)	Surplus Availability Factor ($kg \cdot kg^{-1}$)	Total Solids ($kg\ TS \cdot kg^{-1}$)	Volatile Solids ($kg\ VS \cdot kg\ TS^{-1}$)	Biogas Yield ($m^3 \cdot kg\ VS^{-1}$)	LHV ($GJ \cdot t^{-1}$)
Rice straw	1.5	72	0.91	0.841	0.35	13.45
Cassava peelings	3	20	0.295	0.852	0.66	10.61
Sweet potato vines	0.4	80	0.918	0.857	0.22	14
Maize stalks	1.8	80	0.85	0.891	0.56	15
Sugarcane tops & leaves	0.1	80	1.00	0.941	0.52	15.8

Table 2. Livestock manure input parameters for biogas potential estimation [19,34,35].

Types of livestock	Total Solids ($kg\ TS \cdot head^{-1} d^{-1}$)	Collection Efficiency (%)	Volatile Solids ($kg\ VS \cdot kg\ TS^{-1}$)	Biogas Yield ($m^3 \cdot kg\ VS^{-1}$)	LHV ($GJ \cdot t^{-1}$)
Cattle	1.86	43	0.93	0.21	13
Swine/pig	0.33	80	0.71	0.4	11
Goat/sheep	0.37	32	0.91	0.28	14
Poultry	0.05	68	0.47	0.5	11

2.3. Assessment of Energy Potential from Crop Residues

Crop residues refer to plant materials left in the field after harvesting, including leaves, roots, straw, stalks, bagasse, and peels. In this study, rice, cassava, sugarcane, sweet potato, and maize were selected based on their high production volumes in Madagascar and the availability of biogas yield data for their residues.

According to Bundhoo and Surroop [25], the theoretical calculation of crop residues can be determined by Equation (1), where Q is the gross amount of crop residues ($kt \cdot y^{-1}$), M is the yearly crop production ($kt \cdot y^{-1}$) [24] and RPR is the residue-to-product ratio for that particular crop.

$$Q = M \cdot RPR \quad (1)$$

Equation (2) is used to quantify the available crop residues for biogas production [19,36]:

$$A_{CR} = Q \cdot RF \quad (2)$$

where A_{CR} is the amount of yearly available crop residues ($kt \cdot y^{-1}$), Q is the gross amount of crop residues ($kt \cdot y^{-1}$), and RF is the recoverable mass fraction (%).

The theoretical biogas potential, BP ($m^3 \cdot y^{-1}$) of the available crop residue is calculated by Equation (3) [19,36]:

$$BP = A_{CR} \cdot TS \cdot VS \cdot BY \cdot 10^6 \quad (3)$$

where BP is the yearly biogas potential of the selected crop residue ($m^3 \cdot y^{-1}$), A_{CR} is the yearly available crop residues ($kt \cdot y^{-1}$), VS is the volatile solids fraction of total solids (kg VS·kg TS^{-1}), TS is the total solids content (kg TS·kg^{-1}) and BY is the biogas yield per unit of volatile solids ($m^3 \cdot kg\ VS^{-1}$).

The energy potential of the crop residue is finally estimated using Equation (4) [19]:

$$EP = A_{CR} \cdot LHV \cdot 10^3 \quad (4)$$

where EP is the energy potential from crop residue ($GJ \cdot y^{-1}$), A_{CR} is the yearly available crop residues ($kt \cdot y^{-1}$), and LHV is the lower heating value for the crop residue ($GJ \cdot t^{-1}$).

2.4. Energy Potential of Livestock Manure

Livestock waste is generated from animal husbandry and includes manure, urine, bedding materials, and feed residues. In this study, cattle, chickens, swine/pigs and sheep/goats were considered, according to their local availability, with only manure assessed as a potential feedstock for bioenergy production.

The quantity of available livestock effluent biomass can be estimated using Equation (5) [34].

$$LW = 365 \cdot N \cdot TS \cdot RF \quad (5)$$

where LW is the annual amount of recoverable livestock manure (kg TS·y^{-1}), N is the number of livestock (heads), TS is the daily total solids per head (kg TS·$head^{-1} \cdot d^{-1}$), and RF is the recoverable mass fraction.

Equation (6) can be employed to determine the annual biogas potential of a particular livestock in a selected African region [15,34].

$$BP = LW \cdot VS \cdot BY \quad (6)$$

where BP is the annual biogas potential generated from recoverable livestock manure ($m^3 \cdot y^{-1}$), LW is the annual recoverable manure (kg TS·y^{-1}), VS is the volatile solids fraction of total solids (kg VS·kg TS^{-1}), and BY is the biogas yield per unit of volatile solids ($m^3 \cdot kg\ VS^{-1}$).

The energy potential of the livestock manure was estimated using Equation (7) [19]:

$$EP = LW \cdot LHV \cdot 10^{-3} \quad (7)$$

where EP is the energy potential of livestock manure crop residue ($GJ \cdot y^{-1}$), LW is the annual amount of recoverable livestock manure ($kg \cdot y^{-1}$), and LHV is the lower heating value for the crop residue ($GJ \cdot t^{-1}$).

For each region of Madagascar, the amount of residues produced (reported in FAO data 2015/2024) was considered to calculate the total biogas production potential and the amount of theoretical energy embedded in these organic substrates. As previously reported, rice, cassava, sugarcane, maize and sweet potatoes were considered as the main crops, while cattle, swine/pigs, poultry and goat/sheep manure were included as the main livestock residues. Subsequently, the amount of biogas and recoverable energy from the single substrates were summed up to calculate the overall theoretical energy available for each Madagascar's region.

2.5. Preliminary Sizing of the Digesters

For Madagascar, the implementation of large-scale centralized digesters may be constrained by the collection and transportation of feedstock, water requirements for slurry preparation, infrastructure and investment costs, and limited technical capacity for operation and maintenance [19,25]. Therefore, this study focuses on small-scale digesters suitable for individual households or small farms rather than large centralized systems. A fixed-dome digester constructed underground was considered, as this configuration is commonly used for household-scale AD reactors in developing countries [37].

The required digester size directly depends on daily feedstock availability, household size, slurry feeding rate, and hydraulic retention time (HRT). In this study, cattle manure was selected as the reference feedstock for the household-scale assessment because of its widespread availability across Madagascar. However, other livestock manure and crop residues considered in this study might also be used for biogas production, either separately or through co-digestion with cattle manure, further increasing the amount of generated biogas and produced energy. Atsimo-Andrefana region was selected for the preliminary sizing of the household digester scenario due to its wide availability of cattle manure. The household scenario assumes a household size of 4–5 people, which is considered representative of Madagascar [38].

The daily household biogas requirement for cooking was calculated using Equation (8) [39]:

$$V_{biogas} = C_b \cdot t \quad (8)$$

where V_{biogas} is the daily biogas requirement for cooking ($m^3 \cdot d^{-1}$), C_b is the average biogas consumption rate of the cooking stove ($m^3 \cdot h^{-1}$), and t is the daily cooking time using biogas ($h \cdot d^{-1}$).

The Sustainable Energy for All (SEforALL) assessment for Madagascar reports approximately one hour of cooking per day for households using electricity and liquefied petroleum gas (LPG), compared with three hours or more for households using wood and charcoal [40]. A cooking time of 4 h/day was adopted in this study to provide a conservative estimate of household biogas demand. The average biogas consumption rate of the cooking stove was assumed to be 0.4 $m^3 \cdot h^{-1}$ [39], which is within the range reported for commonly used biogas burners in developing countries [37]. Therefore, the daily biogas requirement was estimated at 1.6 $m^3 \cdot d^{-1}$.

The amount of VS required per day to produce the 1.6 m^3 of daily biogas demand was calculated from the specific biogas yield using Equation (9):

$$M_{VS} = \frac{V_{biogas}}{BY} \quad (9)$$

where M_{VS} is the daily VS requirement (kg VS·d^{-1}), V_{biogas} is the daily biogas requirement, and BY is the biogas yield per unit of volatile solids (m^3·kg VS^{-1}).

The corresponding total solids requirement was estimated using Equation (10):

$$M_{TS} = \frac{M_{VS}}{VS} \quad (10)$$

where M_{TS} is the daily mass of total solids (kg TS·d^{-1}), M_{VS} is the daily VS requirement (kg VS·d^{-1}), and VS is the volatile solid fraction of total solids (kg VS·kg TS^{-1}).

The amount of fresh feedstock required per day can then be calculated using Equation (11) [41]:

$$M_{fresh} = \frac{M_{TS}}{TS} \quad (11)$$

where M_{fresh} is the daily fresh feedstock requirement (kg·d^{-1}), M_{TS} is the daily mass of total solids (kg TS·d^{-1}) and TS is the total solid fraction of the fresh feedstock (kg TS·kg^{-1}).

The required slurry mass was calculated from the target TS concentration of the digestion slurry using Equation (12) [42]:

$$M_{slurry} = \frac{M_{TS}}{TS_{slurry}} \quad (12)$$

where M_{slurry} is the daily mass of slurry (kg·d^{-1}), M_{TS} is the daily mass of total solids (kg TS·d^{-1}) and TS_{slurry} is the total solid fraction of the digestion slurry. A target concentration of 10% TS was adopted based on the selected AD design criterion [10,43].

The amount of water required for slurry preparation was calculated using Equation (13) [41]:

$$M_{water} = M_{slurry} - M_{fresh} \quad (13)$$

where M_{water} is the daily water requirement (kg·d^{-1}), M_{slurry} is the daily slurry (kg·d^{-1}), and M_{fresh} is the daily fresh feedstock (kg·d^{-1}).

The daily slurry flow rate was then estimated by Equation (14) [12,44]:

$$Q_{slurry} = \frac{M_{slurry}}{\rho_{slurry}} \quad (14)$$

where Q_{slurry} is the slurry flow rate (m^3·d^{-1}), M_{slurry} is the daily amount of slurry (kg·d^{-1}) and ρ_{slurry} is the slurry density, assumed to be 1000 kg·m^{-3}, consistent with values commonly used in AD preliminary design studies [45–47].

The AD digester volume requirement for the household digester scenario was calculated by Equation (15) [12,44:

$$V_{digester} = Q_{slurry} \cdot HRT \quad (15)$$

where $V_{digester}$ is the required digester volume (m^3), Q_{slurry} represents the substrate daily feed rate (m^3·d^{-1}), and HRT is the average hydraulic retention time for the substrate in the digester (days). An HRT of 30 days was adopted for the present assessment, corresponding to the range commonly used for mesophilic AD systems [43,44].

3. Results and Discussion

3.1. Significance of the Agricultural and Livestock Sector in Madagascar

The results reported in Figure 2, based on FAO data 2015/2024, indicate that Madagascar's annual agricultural production was dominated by rice (4284 kt·y^{-1}), sugarcane (3127 kt·y^{-1}) and cassava (2601 kt·y^{-1}), followed by sweet potatoes (1184 kt·y^{-1}), and

maize (262 kt·y^{-1}) [24]. Regarding livestock farming, cattle presented an average population of approximately 8.4 million heads per year, while poultry accounted for approximately 40 million heads annually. Pig and small ruminant populations (goats and sheep) were comparatively lower, at approximately 1.8 million and 2.5 million heads per year, respectively [24]. The predominance of rice and cattle production is consistent with their importance in Malagasy agricultural systems, particularly given the widespread involvement of rural households in crop and livestock farming and the central role of rice in the national food system. These substantial amounts of organic substrates consequently highlight a significant potential for agricultural residue recovery and subsequent bioenergy valorization through AD.

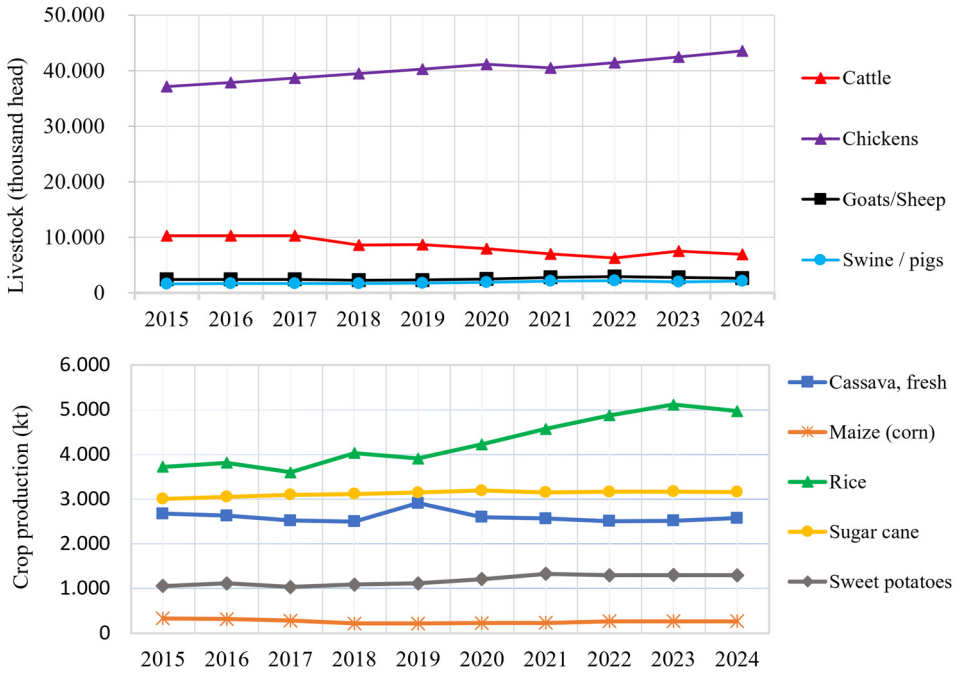


Figure 2. Production of agricultural residues in Madagascar in the period 2015–2024.

3.2. Availability of Recoverable Agricultural Residues for Anaerobic Digestion

The results show that Madagascar generates approximately 6814 kt of recoverable crop residues and 3245 kt of livestock manure annually [24], with crop residues accounting for 67.74% and livestock residues for 32.26% of the total recoverable agricultural biomass, respectively. This important resource base highlights the considerable potential for diverting agricultural and livestock residues to AD for efficient biogas production.

The estimated crop-residue resource is primarily associated with rice, cassava, sugarcane, sweet potato, and maize production. In this study, the principal residues considered were cassava peelings, rice straw, sugarcane tops and leaves, sweet potato vines, and maize stalks, with their quantities estimated using the corresponding RPRs summarized in Table 1. As shown in Figure 3, cassava peelings and rice straw constitute the largest shares of crop residues, accounting for 50.38% and 41.5%, respectively, whereas sweet potato vines, maize stalks, and sugarcane residues contributed only 3.06%, 3.04%, and 2.02%, respectively, showing a limited biogas generation potential.

The livestock residue assessment further demonstrates a strong predominance of cattle manure. The estimated manure quantities depend on livestock population, animal-specific manure production, TS content, and assumed collection efficiency (Table 2). Consistently, cattle manure accounted for 75.58% of the total recoverable livestock residues, followed by poultry manure (15.40%), pig manure (5.62%), and goat and sheep manure (3.40%).

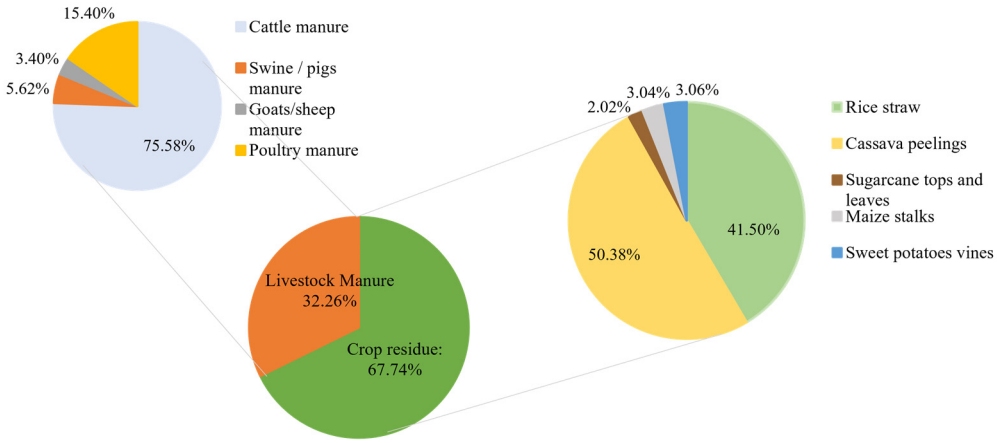


Figure 3. Percentage of recoverable agricultural and livestock residues in Madagascar.

These distributions have important implications for the future development of small-scale decentralized AD systems for domestic biogas generation in Madagascar. However, it should be considered that some residues are already valorized for other uses, such as rice straw and other crop residues, which are currently used as livestock feed, and livestock manure, which is typically recovered as organic fertilizer. These competing uses may reduce the quantity of residues that can be sustainably diverted to biogas production and should be evaluated case by case, highlighting the benefits of sustainable biogas generation to local stakeholders. In addition, it should be mentioned to local stakeholders that AD could contribute to closing the agricultural nutrient cycle by producing stabilized digestate that can be safely used as an organic and nutrient-rich fertilizer [44]. Furthermore, anaerobic co-digestion of crop residues with cattle manure, such as rice straw–cattle manure and cassava residues–cattle manure mixtures, may further improve feedstock management while allowing part of the crop residues to be valorized for biogas production. Rajaonahy et al., e.g., found that a 1:1 mixture of rice straw and cattle manure provided the most suitable substrate combination for biogas production among the mixtures evaluated in their study [8].

3.3. Availability of Recoverable Biomass Residues Across the Regions

Figure 4 presents the map of the total biomass substrates available for biogas production across the 24 regions of Madagascar. Remarkably, the Atsimo-Andrefana region showed the highest quantity of available biomass substrates, at approximately 881 kt·y^{-1}, followed by Sofia (749 kt·y^{-1}) and Atsinanana (539 kt·y^{-1}) regions, whereas Ambatosoa, Ihorombe and Betsiboka regions showed the lowest quantities, at approximately 131 kt·y^{-1}, 202 kt·y^{-1} and 260 kt·y^{-1}, respectively. The large residue potential in the Atsimo-Andrefana region can be associated with its substantial cassava production, with the high RPR of cassava peelings and the important contribution of cattle farming.

The results of the conducted assessment show that the available crop residues and the recoverable livestock manure represented similar shares of the total recoverable biomass across the regions of Madagascar. In Atsimo-Andrefana region, e.g., crop residues accounted for approximately 455 kt·y^{-1}, compared with 425 kt·y^{-1} of livestock manure, while Atsinanana and Vatovavy regions presented approximately 448 kt·y^{-1} and kt·y^{-1} of crop residues, respectively, and 91 kt·y^{-1} and 24 kt·y^{-1} of livestock manure, respectively. The lower total biomass availability in some regions does not necessarily mean that their biogas generation potential is limited. For example, Boeny and Sofia regions have substantial quantities of cattle manure, estimated at approximately 199 kt·y^{-1} and 252 kt·y^{-1} respectively, which could be directly valorized through AD or co-digested with locally

available crop residues. Therefore, AD deployment should consider not only the total biomass quantity but also the type and composition of available biomass in each region. This regional potential could support local renewable energy production, reduce fossil fuel dependence, and improve electricity and heat access in areas with limited supply. However, to effectively assess the amount of organic substrates that could be valorized through AD, additional factors must be considered, such as spatial distribution of resources, local farm size, transport and energy infrastructure; future studies are needed to deepen and prioritize these aspects for an effective implementation of biogas production systems in Madagascar.

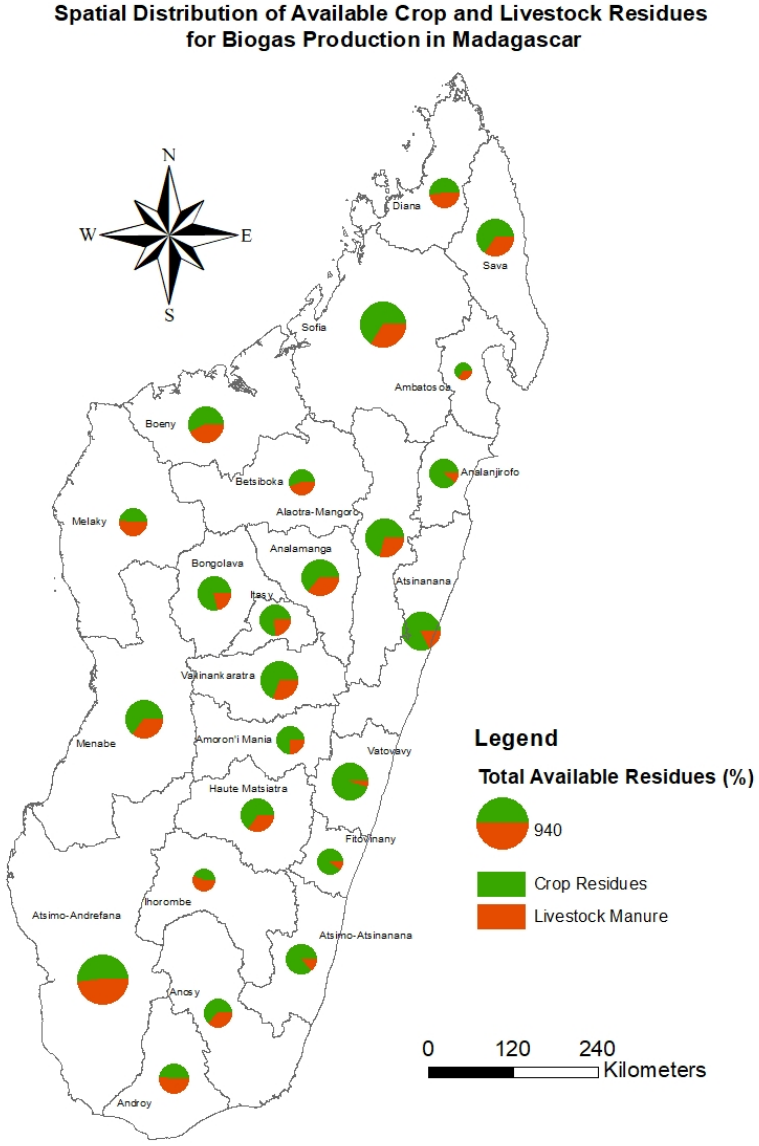


Figure 4. Map of theoretical available agricultural and livestock residues of Madagascar (kt/year).

3.4. Theoretical Values of Biogas and Energy of Agricultural and Livestock Residues

Table 3 summarizes the theoretical biogas and energy estimated from the recoverable residues across the 24 regions of Madagascar. The total theoretical biogas and energy potentials were estimated at 2388 $hm^3 \cdot y^{-1}$ and 129,318 $TJ \cdot y^{-1}$. The estimated values indicate that agricultural and livestock residues can provide a substantial source of renewable energy if they are effectively collected and converted through AD systems. This potential is particularly relevant for Madagascar, where the existing energy system remains highly dependent on biomass. According to IRENA's Renewable Energy Statistics 2025, in fact, Madagascar's total primary energy supply was approximately 185,446 TJ in 2023. The

129,319 TJ·y^{-1} of theoretical energy potential estimated in this study from biogas generation corresponds to approximately 69.7% of Madagascar's total primary energy supply in 2023 [48]. This preliminary result highlights the potential contribution of agricultural and livestock residues to diversifying Madagascar's energy supply and reducing dependence on conventional biomass sources. However, this comparison represents a theoretical potential and does not account for feedstock collection losses and seasonal availability, which need to be considered in future research.

Table 3. Biogas and energy potential of agricultural residues across the region.

Regions	Biogas Potential ($m^3 \cdot y^{-1}$)	Energy Potential ($GJ \cdot y^{-1}$)
Alaotra Mangoro	129,941,198	6,853,903
Ambatosoa	31,387,572	1,670,497
Amoron'i Mania	73,637,493	3,864,253
Analamanga	117,913,406	6,311,145
Analanjirofo	79,872,754	4,215,293
Androy	72,105,290	4,228,290
Anosy	71,960,265	4,062,670
Atsimo Andrefana	196,125,019	11,154,054
Atsimo Atsinanana	80,361,836	4,384,497
Atsinanana	130,724,406	6,966,614
Betsiboka	62,764,998	3,405,627
Boeni	113,692,006	6,098,475
Bongolava	100,779,686	5,379,755
Diana	83,147,512	4,437,913
Fitovinany	63,515,595	3,470,513
Haute Matsiatra	98,903,562	5,323,575
Ihorombe	44,508,051	2,591,932
Itasy	87,293,271	4,582,669
Melaky	68,653,271	3,982,392
Menabe	125,730,310	6,733,785
Sava	122,343,016	6,470,815
Sofia	181,514,229	9,950,550
Vakinankaratra	129,406,357	6,697,841
Vatovavy	122,619,103	6,481,605
MADAGASCAR-TOTAL	2,388,900,205	129,318,662

The current results also reveal that the regional distribution of biogas generation potential does not linearly follow the distribution of total biomass availability. Sofia region presented the highest theoretical biogas potential, at approximately 150 $hm^3 \cdot y^{-1}$, followed closely by Atsimo-Andrefana (149 $hm^3 \cdot y^{-1}$) and Atsinanana (115 $hm^3 \cdot y^{-1}$) regions, whereas Ambatosoa, Ihorombe, and Betsiboka regions recorded the lowest biogas generation potentials. Overall, Atsimo-Andrefana region shows the highest total amount of agricultural and livestock residues, demonstrating that biomass quantity alone does not directly determine energy production. This difference comes from variations in residue type, TS and VS contents of the selected organic residues, and specific methane yields; therefore, regions with low biomass quantities may nevertheless achieve higher biogas production when their available substrates show better biodegradability and greater energy-conversion potential. Consistently, Alvaro et al. identified priority areas for biogas production through anaerobic co-digestion of rice straw, pig manure, and palm-oil mill effluent in Colombia by Geographic Information System (GIS) and substrate localization, showing that it is not sufficient to consider substrate availability, but territorial distribution and availability of complementary co-substrates must be included in the assessment [49].

Atsimo-Andrefana region was therefore selected for the subsequent digester assessment because of its highest theoretical biogas potential and the wide availability of cattle

manure. However, the proposed preliminary assessment can be applied to any of the regions of Madagascar, and even exported to other African countries. A Brazilian case study reported that cattle manure represents 73–84% of biogas potential in an assessment including other substrates such as sugarcane processing residues, food waste and sewage sludge, further highlighting the importance of this organic residue [50]. Another important case study from Bangladesh consistently reported that cattle manure roughly represents 70% of the total biogas production potential, by considering in the assessment other substrates such as poultry residues and rice straw, potentially leading to 2 million small-scale household digesters diffused on the territory [51].

3.5. Size and Related Operating Parameters of Household-Scale Digester

The preliminary digester sizing has been developed to identify the energy generated from the available organic feedstock in the Atsimo Andrefana region for a small-scale AD at a household or farm level, substituting conventional wood burning. Cattle manure was considered as the substrate to be treated, according to its wide availability in the region and the fact that it is normally available in domestic farms. The digestion process is assumed to operate under near-neutral pH conditions (6.8–7.5) and at mesophilic temperature, which is generally suitable for agricultural/livestock AD and compatible with Madagascar's climate conditions [8].

The input characteristics of the digester to be installed at a farm-scale level are summarized in Table 4, considering 5 cattle per household. With a target slurry concentration of 10% TS content and an HRT of 30 days, the resulting slurry flow is approximately 0.08 $m^3 \cdot d^{-1}$, corresponding to a theoretical total digester volume of approximately 2.5 m^3. The corresponding OLR has been calculated at approximately 3.05 kg $VS \cdot m^3 \cdot d^{-1}$ (Table 4), which provides relatively moderate loading conditions for safe digester design.

The HRT of 30 days represents the average residence time of the digestion slurry in the reactor. The selected value is consistent with literature studies reporting typical HRT values of approximately 30–60 days for agricultural/livestock AD, with shorter HRTs possible for highly biodegradable substrates and optimized reactor configurations [43]. The calculated OLR of 3.05 kg $VS \cdot m^3 \cdot d^{-1}$ is also within a technically plausible operating range. Literature on cattle manure digestion commonly identifies approximately 3–5 kg $VS \cdot m^3 \cdot d^{-1}$ as a general OLR range for AD systems [52]. Therefore, the value of 3.05 kg $VS \cdot m^3 \cdot d^{-1}$ adopted in the present design is conservative and may provide a reasonable starting point for a preliminary feasibility assessment.

Table 4. Theoretical input parameters of the household-scale digester for the Madagascar case [39,40,43,47,53].

Parameters	Region of Atsimo Andrefana
Daily cooking time	4 $h \cdot day^{-1}$
Daily biogas requirement for cooking	1.6 $m^3 \cdot day^{-1}$
Daily mass of VS	7.62 kg $VS \cdot day^{-1}$
Daily mass of TS	8.19 kg $TS \cdot day^{-1}$
Daily mass of fresh feedstock	51.20 $kg \cdot day^{-1}$
Daily mass of slurry	81.93 $kg \cdot day^{-1}$
Daily water requirement	30.72 $L \cdot day^{-1}$
Daily slurry flow rate	0.08 $m^{-3} \cdot day^{-1}$
Retention time of digester	30 days
Digester volume	2.5 m^3
Number of cattle required per household	5

The 2.5 m^3 reactor size is a modular reference whose applicability depends on the amount of organic feedstock that can actually be collected and supplied continuously; therefore, multiple modules could be operated in parallel in high-resource availability areas, such as larger farms. This modular approach is particularly relevant to Madagascar's situation because agricultural and livestock residues are spatially dispersed and often generated by small-scale farms, making collection distance and continuous feedstock supply important constraints.

A significant environmental benefit can be obtained by using biogas in AD in substitution of wood by domestic AD, as recapped in Table 5: according to the significantly higher efficiency of biogas combustion (60% versus 17% of wood), it is possible to save around 5.65 kg wood·day^{-1}·$household^{-1}$, increasing in addition energy security and self-sufficiency of small households. Substituting wood with biogas can lead to important ancillary benefits such as reduced deforestation, restoration of natural areas and preservation of ecosystems, which cannot be directly monetized but are deeply connected with environmental sustainability.

Table 5. Theoretical amount of wood saved in Atsimo Andrefana by using biogas [54,55].

Parameters	Region of Atsimo Andrefana
Biogas lower heating value (LHV)	20 MJ·m^{-3}
Biogas burning efficiency	60%
Useful energy from biogas	12 MJ·m^{-3}
Wood LHV	20 MJ·kg^{-1}
Wood burning efficiency	17%
Useful energy from wood	3.4 MJ·kg^{-1}
Wood saved	3.53 kg·m^{-3}
Wood saved per day	5.65 kg·day^{-1}·$household^{-1}$

The adopted simplified approach for digester sizing could be extended to other regions in Madagascar and other African countries, prioritizing areas with high substrate availability and/or substantial biogas generation potential, boosting the full-scale application of diffused small-scale AD systems and subsequently the generated renewable energy from biogas.

3.6. Limitations and Recommendations for Development of Decentralized Anaerobic Digestion in Madagascar

Despite the substantial agricultural and livestock residue potential for biogas generation identified in this study, several constraints limit the full-scale development of AD and AcoD in Madagascar. Agricultural residues, in fact, are still commonly managed through open burning or other conventional disposal practices [7], while dedicated systems for their collection, treatment, and valorization remain limited. In addition, a clear regulatory and institutional framework specifically addressing the collection and energy valorization of agricultural and livestock residues remains insufficient, even if waste-management regulations exist [19], hindering the development of full-scale AD projects.

Another major constraint is represented by the economic aspects connected to AD infrastructure. These costs can be particularly difficult to sustain in rural areas typical of Madagascar, where agricultural and livestock residues are often dispersed among small-scale farms and transportation infrastructure is limited. Dedicated incentives may be needed to boost the applicability of small-scale decentralized digesters throughout Madagascar, improving renewable energy generation and security at a local level; however, specific training and technical information must be given to local inhabitants and farmers to guarantee that digesters are operated smoothly and that the biogas is efficiently col-

lected and valorized for energy generation. Another ancillary benefit of distributed biogas generation includes reduced deforestation as biogas substitutes wood, providing indirect environmental benefits that cannot be directly translated into economic advantages.

Feedstock logistics and technical capacity may represent additional limitations. Crop residues generally require collection, storage, size reduction, and appropriate mixing before digestion, while their seasonal availability can make continuous reactor feeding difficult, especially at a small-scale household level. Limited infrastructure for biomass collection and transportation may therefore substantially reduce the practically available feedstock compared with the theoretical quantities estimated in this study. Water availability is another relevant constraint, as water is required for preparing the digestion slurry, while water scarcity remains a significant challenge in several regions of Madagascar, particularly in the southern part of the country, where even access to safe drinking water is limited.

To support the full-scale development of distributed household AD systems in Madagascar, a clear renewable energy strategy is needed at a national level; biomass energy should be recognized as an important component of the national energy system. The establishment of an appropriate legal and institutional framework is also essential to support AD projects from the planning stage through construction and operation, while ensuring adequate environmental control. In parallel, improved knowledge of AD technologies and their potential benefits should be developed among government authorities, private-sector actors, investors, farmers, local inhabitants, and technical professionals involved in Malagasy energy projects [25]. Capacity-building and training programs could therefore help strengthen local expertise in the design, construction, commissioning, and operation of biogas plants. At the local level, awareness among farmers is an important aspect to encourage the collection, management, and sustainable use of agricultural residues as AD feedstocks [19,25], highlighting the benefits of diverting them from alternative uses and valorizing them through AD.

For regions facing water scarcity, alternative water sources, such as treated wastewater, could be used for slurry preparation to reduce the freshwater requirement of AD. Wastewater reuse can help reduce pressure on freshwater resources and improve resource efficiency as part of a circular water-management approach [56]. However, its direct use in AD requires appropriate treatment to ensure that contaminants do not affect the digestion process or create environmental and health risks. Finally, stronger cooperation between government institutions, universities, private investors, and local communities could help create the conditions needed for long-term investment and wider adoption of diffused small-scale AD reactors in Madagascar.

The benefits and risks of the implementation of small-scale diffused digesters in Madagascar are further summarized in Figure 5, according to the study conducted.

3.7. Limitations of This Study

Some limitations should be considered when interpreting the results of this study. First, the conducted technical assessment focuses on the major agricultural and livestock resources available in Madagascar, including rice, maize, cassava, sugarcane, sweet potato, cattle, pigs, poultry, and goats and sheep; therefore, residues from other agricultural and livestock activities are not included. The estimated national residue potential should consequently be interpreted as the potential associated with the selected major agricultural and livestock resources, rather than the total organic residue potential of Madagascar. In addition, the production data cover the period 2019–2024, which provides a relatively limited timeframe for assessing long-term variations in biomass production and organic residue generation.

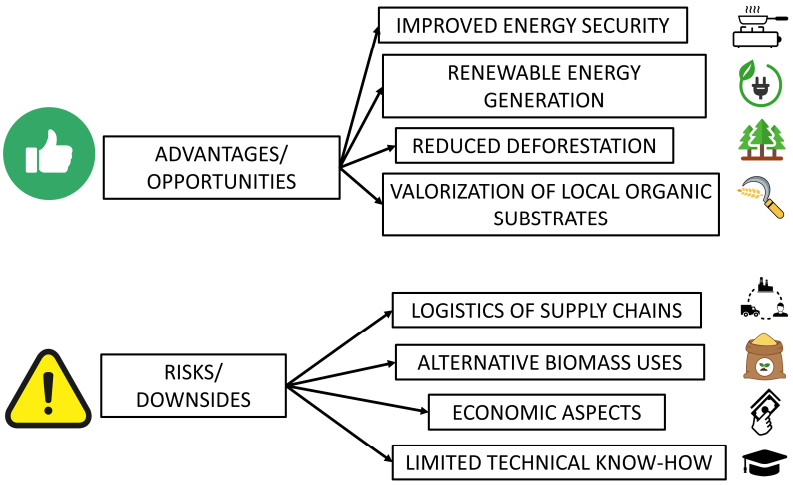


Figure 5. Advantages and risks connected to diffused small-scale anaerobic digestion implementation in Madagascar.

A further limitation concerns the RPRs, which were obtained from international literature due to the limited availability of Madagascar-specific data. Since RPRs vary with crop varieties and agricultural practices, applying fixed values across regions may therefore introduce uncertainty into the estimated residue quantities. Dedicated studies at a local level, such as detailed physicochemical characterization of the produced substrates and bio-methanization tests, could be performed in the future to gather more information about the effective characteristics and anaerobic biodegradability of the organic substrates specifically available in Madagascar.

The assumption that all produced feedstocks are continuously available for biogas production is also another key limitation of the current study. In practice, competing uses, seasonal availability, and the collection and transportation of dispersed residues can significantly reduce the practically recoverable feedstock. In this sense, knowledge sharing with local stakeholders is critical to enhance the perception that biogas can be a useful resource for energy security at a household level, substituting wood and rendering the houses and farms more independent of external energy sources.

Moreover, the estimated biogas potential remains theoretical, as the calculations are based on methane yields reported mainly in literature studies. Actual yields at a full-scale level may substantially differ because of substrate variability, pretreatment, co-digestion conditions, HRT, OLR, process stability, and operational efficiency. Consequently, the practical biogas and energy potentials might be lower than the theoretical values reported in the current study. Once selected areas are defined, pilot-scale studies must be conducted to ascertain AD reactor stability as well as the effective energy yields, improving the knowledge about continuous process operations before moving to full-scale AD application. Finally, proper digestate valorization must be ensured, with safe agricultural application for organic matter and nutrient recovery.

4. Conclusions

This study assessed the theoretical energy potential of agricultural and livestock residues for biogas production through AD across Madagascar's 24 regions. The selected residues represent a significant renewable energy resource for biogas production, with crop residues providing the largest share and livestock manure serving as a complementary feedstock. The total theoretical biogas potential was estimated at approximately 2389 $Mm^3 \cdot y^{-1}$, corresponding to 129,319 $TJ \cdot y^{-1}$ of theoretical energy. The regional results also show that biomass quantity alone is not sufficient to identify the most suitable areas

for biogas production. Atsimo-Andrefana region showed the highest quantity of available biomass, whereas Sofia region presented the highest theoretical biogas potential, followed by Atsimo-Andrefana and Atsinanana regions. This difference reflects the influence of residue type, TS and VS contents, and specific biogas yields on the total energy generation potential. A small-scale household digester of 2.5 m^3 was preliminarily sized to assess the practical applicability of AD in Madagascar, referring to cattle manure as treated substrate and the Atsimo-Andrefana region as the region with the highest biomass availability. It was shown that biogas may substitute around 5.65 kg wood·day^{-1}·$household^{-1}$ for energy production for cooking, providing additional benefits such as improved energy security, renewable energy generation and reduced deforestation, with evident environmental advantages. However, these values remain theoretical and may be reduced in practice by seasonal availability, competing residue uses, collection and transport constraints, water requirements, infrastructure costs, and limited technical capacity. Future studies should therefore gather more specific feedstock data by conducting local experimental campaigns at laboratory and pilot-scale levels, and assess in a more detailed way the techno-economic feasibility of selected small-scale decentralized AD projects. Overall, the current findings provide a basis for identifying priority regions and supporting agricultural and livestock-residue-based AD in Madagascar for renewable energy transition and safe energy supply in agricultural and decentralized areas.

Author Contributions: Conceptualization, N.O.M. and N.R.-R.; methodology, N.O.M. and N.R.-R.; software, N.O.M.; validation, N.O.M., N.R.-R. and M.M.; formal analysis, N.O.M., N.R.-R. and M.M.; investigation, N.O.M.; resources, N.O.M., N.R.-R. and M.M.; data curation, N.O.M.; writing—original draft preparation, N.O.M.; writing—review and editing, N.O.M. and M.M.; visualization, N.O.M.; supervision, M.M. and N.R.-R.; project aTSinistration, M.M.; funding acquisition, N.R.-R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by TWAS UNESCO through the TWAS-SISSA-Lincei Research Visits Programme Agreement, grant number 3240327503.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used during the study are reported in the Zenodo repository at the following link: https://doi.org/10.5281/zenodo.23179358.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript

AD	Anaerobic Digestion
AcoD	Anaerobic co-Digestion
CHP	Combined Heat and Power
GDP	Gross Domestic Product
GIS	Geographic Information System
HHV	Higher Heating Value
HRT	Hydraulic Retention Time
LPG	Liquefied Petroleum Gas
OLR	Organic Loading Rate
RPR	Residue-to-Product Ratio
TS	Total Solids
VSs	Volatile Solids

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