Assessment of Agricultural Biomass Residues for Anaerobic Digestion in Rural Vakinankaratra Region of Madagascar

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Abstract

This study estimates agricultural residue biomass available for biogas generation in small farming systems in the rural Vakinankaratra region of Madagascar, during 2017–2018. Estimations of biomass were done using a combination of agricultural household surveys, literature models, and publicly available data. Manure from four types of farm animals and 17 residue types from ten crops were assessed. In the studied period, gross biomass produced from animal manure and crop residue was 19.4$\pm$7.41 and 7.3$\pm$1.08 tonnes fresh weight per year per agricultural household, respectively, of which up to 54% and 83% are estimated as recoverable for the production of bioenergy in the studied area, respectively. Estimations indicate that available animal manure and crop residue have the potential to generate 291$\pm$92 and 745$\pm$122 Nm^3 of methane per year per agricultural household respectively, equivalent to 10.5$\pm$3.34 and 26.8$\pm$4.28 GJ of heat energy from manure and residues, respectively. Theoretically, the average estimated energy potential can result in the complete substitution of domestic fuels in agricultural households. Approximately 0.12 tonnes of nitrogen per household per year can be recovered from the estimated digestate (using all residue types) after energy recovery, which can be employed for crop fertilization. The recovered nitrogen corresponds to 0.26 tonnes urea fertilizer per household per year. The investigation shows that anaerobic digestion based on crop residue and manure has the potential to meet a significant portion of energy needs of smallholder farmers in the Vakinankaratra region of Madagascar and can make an important contribution to providing fertilizer for on-farm use.

Keywords: animal manure, crop residue, digestate, energy potential, methane, smallholder farm

Introduction

Biomass plays a significant role globally as a renewable energy source, providing approximately 10% of the world primary energy supply [1]. To meet increasing demands on modern energy access, biomass must be utilized more efficiently by, for example, biogas production as opposed to combustion of raw biomass [2]. The lack of energy access is one of the most serious challenges in Madagascar [3]. Cooking by electricity and gas (including biogas) remains luxury energy source for most of the population in the rural area of the country [4]. Electricity access remains low at about 15% of the population, and only 4% in rural areas have access to electricity as of 2015 [5]. Around 80% of the population works in the agricultural sector [3], and the majority of households rely on traditional sources of energy for cooking and heating, and kerosene and candles for lighting. Firewood and charcoal have been used by the majority of the population (95% of households) as their basic energy source leading to increasing concerns regarding local deforestation [4]. Poor indoor air quality is associated with premature deaths and contribute to a broad range of child and adult diseases [6], which in turn negatively impacts the production capacity of agricultural households.

Biomass can replace traditional fuels and reduce energy poverty, greenhouses gas (GHG) emissions and contribute to rural development [7], if properly utilized with appropriate technology. Agricultural residues from crops (carbon-rich) and animal production (nitrogen-rich) are good sources of bioenergy and can contribute significantly to bioenergy generation, particularly through anaerobic digestion (AD) [8]. Biogas generation through AD is one of the most promising technologies for decentralized rural energy production as it not only generates clean energy (biogas) but can also generate organic fertilizer (digestate) for farming applications [9]. Compared to direct burning and composting, AD offers both clean fuel and organic fertilizer, rather than simply one or the other. However, its implementation and usage is still in the early stages in most developing African countries, especially in a small farming system where it was anticipated to have an impact. This is partly linked to a poor understanding of the biomass resources potential and/or inefficient utilization thereof for other purposes in smallholder farming systems. Data on agricultural residue yields remains limited, while data on crop yields are readily available, as the main objective of agricultural production was always to maximise yields, whereas the total biomass yield was not considered important [10]. Furthermore, there is poor understanding to what degree other uses would possibly compete for the available biomass, for example, the demand for use as animal feed, and as use for recycling nutrients via composting or direct combination as fertilizer [11].

Anaerobic digestion technology implementation not only produces biogas but also produces a stabilized digested slurry (digestate) that can serve as a source of plant nutrients [12]. The digested matter can be utilized as a biofertilizer to improve soil fertility and biological quality, and thereby improve crop productivity or to grow fodder for animal feed [12–14]. Anaerobic digestion transforms nitrogen into an immediately available form, offering a quick fertiliser response that can be applied when crops display signs of deficiency [15]. Small-scale farmers represent most of the rural population in developing African countries, and the use of mineral fertilizers is very low; consequently, there is a chance for high-quality bio-fertilizers to help farmers in improving productivity. Its implementation also provides a good opportunity for mitigation of GHG and reducing global warming via (i) substituting fuelwood for cooking, (ii) substituting kerosene for lighting and cooking, (iii) substituting mineral fertilizers, and (iv) reducing deforestation [16].

So far, the potential availability of agricultural residues for bioenergy in Madagascan smallholder farming systems has not been reported. Thus, this study aims to determine whether the agricultural residue biomass resources in the farming systems in the rural Vakinankaratra highlands of Madagascar is adequate to make AD viable and sustainable. The study objectives are a) to estimate the potential availability of gross agricultural residue biomass feedstock resource through surveys; b) to quantify a portion of gross agricultural residue biomass resources that is recoverable and available for the production of bioenergy; c) to estimate the available biomethane energy potential of the available residue biomass resources, and d) to estimate the digestate potential of the residue biomass available.

Methodology

Sampling and data collection

A survey of a sample of agricultural households in the Highlands area of the Vakinankaratra region was carried out by The National Center for Applied Research on Rural Development (FOFIFA) and The French Agricultural Research Centre for International Development (CIRAD) as part of the Project "Ecological intensification pathways for the future of crop-livestock integration in African agriculture" (EcoAfrica). The survey was carried out with two teams of specifically trained investigators/pollsters from a sample of 405 agricultural households drawn at random from 15 fokontany (smallest administrative division) belonging to five municipalities chosen to represent the diversity of production systems of this agroecological zone (see, **Fig. 1** and **Table 1**). The questionnaires made it possible to identify the productive resources, the allocation of these resources according to agricultural activities, practices and performances obtained for the entire agricultural year 2017/18 (October 2017 - September 2018). The farm surveys were conducted with paper questionnaires, and the information collected was entered into a database with using Microsoft Access. The verification and the auditing were done with using Microsoft Access, and the data were exported to Statistical Packages for Social Sciences (SPSS) to carry out the statistical analysis.

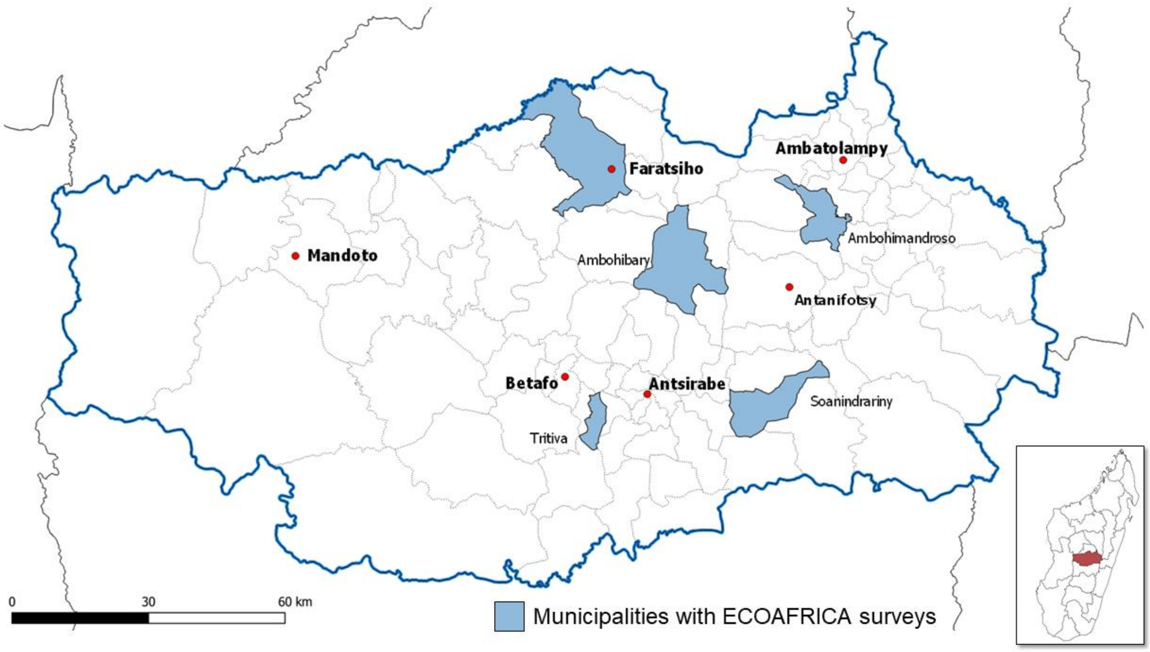

Fig. 1 Map of the surveyed region (Vakinankaratra) in Madagascar. Note: number of populations, farms and animals are provided in (**Table 1**) and supplementary material (**Table S1**).

Table 1 Population in the study region [17].

	Population in 2018
Vakinankaratra region	2 079 659
of which rural population	85%
Urban areas	
District of Antsirabe I	246 354
Municipality of Ambatolampy	32 291
Municipality of Betafo	34 336
The five rural municipalities surveyed	
Farathsio	46 569
Ambohibary	48 603
Ambohimandroso	36 166
Tritriva	9 536
Soanindrariny	25 646

Availability of agricultural residue biomass resources for AD

Agricultural residue biomass availability analysis comprises the estimation of biomass potentially available from either crop residue or animal manure categories. From agricultural production in smallholder farming systems, the energy potential of the available residue resources was estimated according to the steps illustrated in (**Fig. 2**) [18].

Crop residue biomass availability estimation

Crop residues are generated from agricultural activities as by-products of crop production systems, and usually, its quantity depends on the crop yields. Biomass from crop residues is generally classified into two different categories: process residues and field residues. Field residues are defined as the residues which remain in the fields as a by-product of post-harvesting activities of the crop, whereas process crop residues are those generated during the processing of crops [9]. Field residues availability for energy uses is normally low, due to practical challenges associated with the collection of residues and the fact that all residues cannot be removed without influencing soil fertility adversely. On the other hand, process residues are usually obtainable in greater amounts as a result of the processing of the crop and may be utilized as an energy source [19]. The technical limitations (methods of harvesting, processing and transporting), and possibility of destruction by uncontrolled fires are also a factor for residue availability.

The biomass residue availability potentials can be classified into gross residue potential, which includes the total quantity of biomass residue generated, and the recoverable residue potential which only constitutes the technically recoverable residues, or that proportion of the residues that remain once residues have been employed for other competing uses, e.g. employed for heating and cooking fuel, soil fertility, animal feeding and bedding, surface mulching, etc. [10,20,21]. The potential of gross and recoverable crop residue can be estimated using equations 1-2 [20–23]. The potential of both the gross residue and the recoverable residue are assessed in this study.

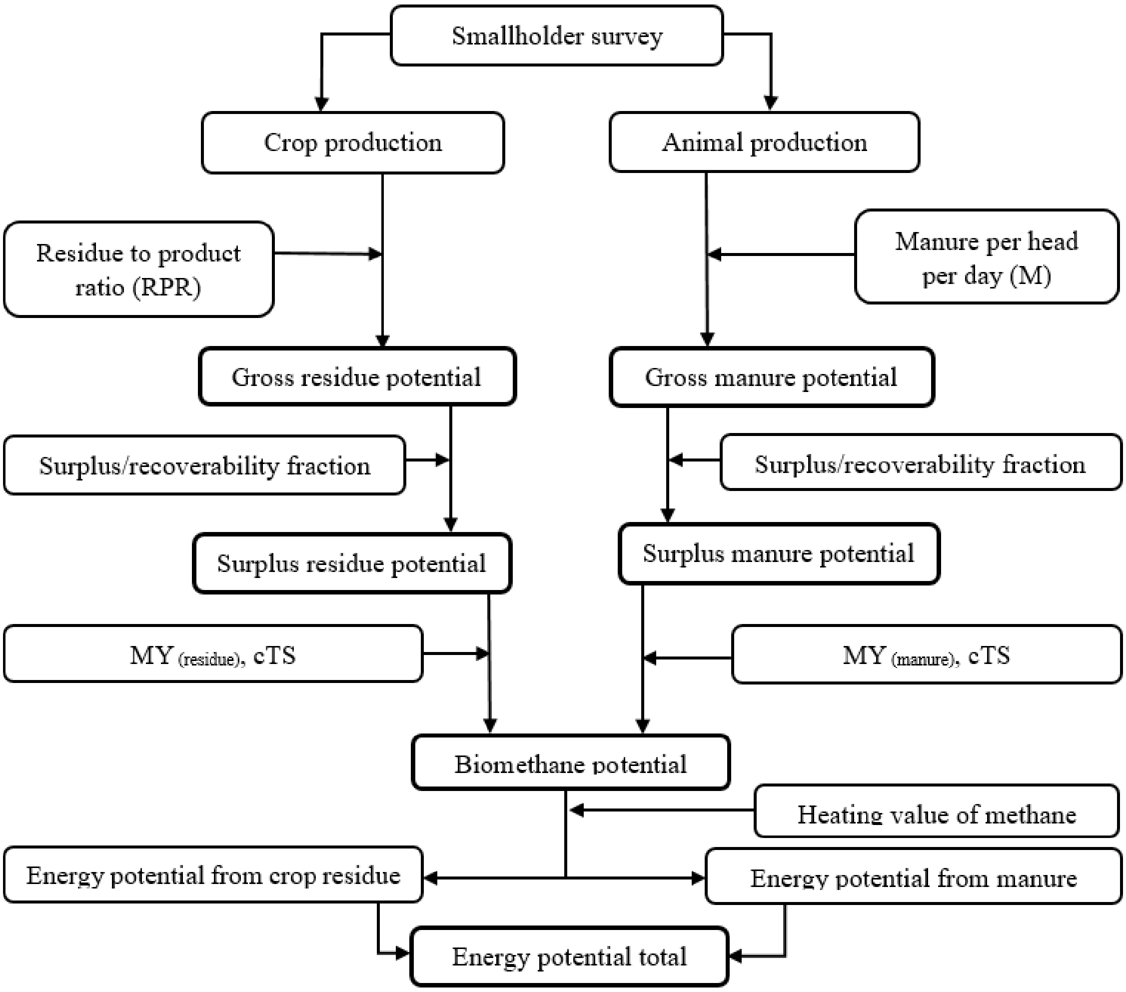

Fig. 2 Flow chart for determining the recoverable energy potential from agricultural residue biomass resources. Where MY is methane yield and cTS is total solid concentration.

Gross residue biomass resource potential

The gross residue potential estimation of a particular agricultural crop relies on the area cultivated, the crop yield and the residue-to-product ratio (RPR). The yields of crop residue vary even more than the yields of the crop and are thus difficult to take into consideration, as it relies on location, plant variety, climate conditions, agricultural practices and other factors [10]. Due to this reason, the residue-to-product ratio (RPR) values determined in the relevant literature at crop level were compiled for different crops and the average value for each crop residue type was used as given in (**Table 2**). The potential of gross crop residue is estimated using eq. (1):

$$GRP = \sum_{i=1}^{n} A(i)CY(i)RPR(i) \tag{1}$$

where *GRP* is the gross residue potential generated from "*n*" numbers of crops in tonnes (t); $A_{(i)}$ is the area under the i^{th} crop in hectare (ha); $CY_{(i)}$ is the average crop yield of the i^{th} crop in $t.ha^{-1}$, and $RPR_{(i)}$ is the residue-to-product ratio of the i^{th} crop.

Table 2 Crop residue type, residue to product ratio (RPR), recoverability factor (RF), concentration of total solid (cTS) and methane yield (MY).

Crop	Residue type	RPR* ($g.g^{-1}$)	RF* ($g.g^{-1}$)	cTS* (%)	MY† ($Nm^3CH_4.kgTS^{-1}$)	Reference*
Rice	Straw	1.54	0.72	84	0.264	[2,9,28,19–22,24–27]
	Husks	0.36	0.62	92	0.232	[2,19,20,22,24,26–30]
Maize	Stalks	2.00	0.80	85	0.268	[20–24,26,27]
	Cobs	0.30	1.00	92	0.348	[2,20–24,26,27,30]
	Husks	0.20	1.00	89	0.238	[2,21,23,24,27]
Potato	Stems & leaves	0.54	0.80	60	0.144	[21,25,30]
	Peelings	0.75	0.80	35	0.329[31,32]	[2,27]
Cassava	Stalk	0.12	0.80	85	0.192	[2,21,27–30]
	Peelings	0.25	0.20	40	0.323	[2,21,28,30]
Soybean	Straw & pods	2.23	0.80	85	0.225	[2,21,22,25,27–31,35]
Beans	Straws	2.23	0.80	90	0.189[34]	[27,31,33]
Sweet potato	Peelings & leaves	0.45	0.80	35	0.297[35]	[2,21,27,28,30]
	Straw	0.50	0.80	80	0.144	[2]
Taro	Peelings	0.20	0.80	29	0.275[36]	[27,30,36]
	Straws	0.50	0.80	60	0.167	[2,30]
Tobacco	Stem/stalks	1.47	1.00	85	0.226[37]	[21,25,28,30,33]
Cabbage	Foliage & stem	2.50	0.95	15	0.265[32]	[25,33]

* Calculated average. † Unless stated otherwise all values based on [2].

Recoverable residue biomass potential

As described above, it is assumed that not all crop residue biomass will be available for the production of bioenergy attributable to their variation in nature and competitive uses. The field-based biomass residue amounts that can be collected realistically is estimated via the recoverability fraction (also called surplus availability factor) of the crop residue biomass [21,27]. The recoverability factor (RF) is the fraction of residues that are available realistically for the production of bioenergy after part of it is utilized elsewhere [2,21,38]. The RF values for residue biomass were compiled from similar previous studies in different developing countries and the average value for each crop residue type was used due to lack of data specific to Madagascar, in order to estimate the recoverable residue potential as presented in (**Table 2**). The recoverable residue potential is estimated using eq. (2):

$$RRP = \sum_{i=1}^{n} GRP_{(i)}\ RF_{(i)} \tag{2}$$

where, RRP is the recoverable residue potential from "n" number of crops in (t); $GRP_{(i)}$ is the gross residue potential generated from the i^{th} crop in (t); and $RF_{(i)}$ is recoverability factor of i^{th} crop.

Methane and energy potential estimation from crop residue

The potential of the biomethane of the crop residues was estimated using eq. (3). The values of the specific methane yield and the mean total solids concentration for the crop residues were obtained from literature as given in (**Table 2**) [18].

$$MP = RRP \cdot MY \cdot cTS \tag{3}$$

where, MP is the potential methane production of crop residue ($Nm^3CH_4.y^{-1}$); MY is the methane yield from literature ($Nm^3\ CH_4.kgTS^{-1}$), and cTS is the concentration of total solid (%).

The potential amount of energy available from the recoverable methane have been transformed from Nm^3 methane to gigajoule (GJ) of heat energy, applying the factor 0.036 $GJ.m^{-3}$ methane [2].

Animal manure availability estimation

Animal manure is an important input in the production of biogas. The quantity of animal manure (AM) potentially generated and recovered are estimated using the number of animals (P_{live}, head), mean annual manure production per animal (M, $kg.y^{-1}.head^{-1}$), and recoverable fraction (RF). The animal manure biomass quantity which can be collected for energy application is calculated using eq. (4) [27].

$$AM = P_{live} \cdot M \cdot RF \tag{4}$$

Methane potential estimation from animal manure

To estimate the potential methane production from animal manure the main parameters needed comprise estimated manure per head per day, the concentration of total solids in the manure as well as the methane yield per unit of total solids. To estimate the quantity of biomethane that can be generated by each animal category, parameter values are derived from similar studies carried out in Ghana and Tanzania [2,39], as described in (**Table 3**). Equation (5) can be used to estimate the potential of biomethane from animal manure that can be generated from recoverable manures [18]:

$$MP = AM \cdot cTS \cdot MY \tag{5}$$

where MP is the potential methane production from recoverable manure ($Nm^3CH_4.y^{-1}$), cTS is total solid concentration (%), and MY is the methane yield from literature ($Nm^3CH_4.kgTS^{-1}$).

Table 3 Quantity of estimated manure (M), RF, cTS and MY.

Type of livestock	*M** ($kg.h^{-1}d^{-1}$)	*RF* ($kg.kg^{-1}$)	*cTS** (%)	*MY* ($Nm^3CH_4.kgTS^{-1}$)	References for *RF* and *MY*
Cattle	12.00	0.50	12	0.207	[19,24,27,29,32,40]
Pigs	3.60	0.80	11	0.247	[21,41]
Goats & sheep	2.00	0.33	25	0.220	[2,19,24,27,31]
Poultry	0.02	0.50	25	0.220	[2,19,41]

*All values based on [2,39].

Energy potential estimation from animal manure

To estimate the potential amount of energy available from animal effluents, manure generated by cattle, pigs, poultry, goats and sheep are considered.

Fuel equivalents estimation

In developing countries, the generated biogas can be used for the replacement of most commonly used traditional fuels such as firewood and kerosene. Biogas equivalent fuels were estimated based on the assumption that 80% of the produced biogas would be utilized for substituting firewood and the remaining 20% for substituting kerosene used in the households [16]. Firewood and kerosene equivalents of the generated biogas were then computed applying the calorific values of these fuels. All values of the coefficients were derived from literature and utilized in the estimation, as summarized in the supplementary material in (**Table S2**).

Digestate potential estimation

Digestate is a high-quality organic fertilizer for crops with significant contents of nitrogen (N), phosphorus (P) and potassium (K), micronutrients, and organic matter. It is usually utilized as fertiliser to crops without any further processing. In this study, the total quantity of digestate potential and its fertilizer equivalent was estimated. For the estimation, the mass of the digestate generated was calculated by subtracting the biogas mass (the quantity of substrate transformed into biogas) from the substrate/feedstock mass, as presented in the supplementary material (**Table S2-4**). The mass of the biogas was derived based on the specific biogas yield and biogas density, by assuming the composition of biogas (average 60% CH_4 and 40% CO_2), and component densities (CH_4 0.72 $kg.m^{-3}$ and CO_2 1.96 $kg.m^{-3}$) [40]. The nutrient contents (N, P, and K) in the digestate were calculated by assuming that the digestate comprises a mean value of 52 g N, 42 g P_2O_5, and 43 g K_2O per kg digestate on a dry weight basis [42].

Results

The biomass resources availability analysis of agricultural residue was conducted based on the number of agricultural households that practice mixed farming (crop and livestock production). **Fig. 3** shows that rice, maize, and potatoes were the most common crops, cultivated by 96% (irrigated 91% and rain-fed 36%), 87%, and 82% of all farmers, respectively, but additional crops were also cultivated by smallholder farmers, including beans, sweet potatoes, soybean, taro, cassava, tobacco, and others. Furthermore, several farmers had small numbers of animals mainly poultry, cattle, pigs, and very few small ruminants (sheep and goats).

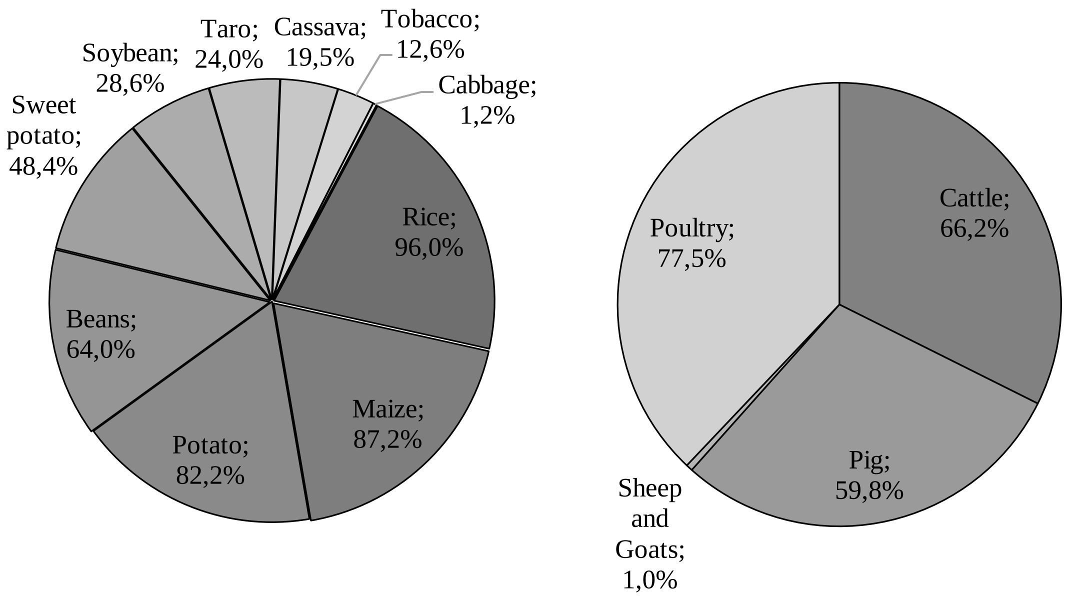

Fig. 3 Distribution of agricultural households by type of activity (percentage) (left) crop production, and (right) livestock production.

The gross and recoverable biomass potential, available biomethane and its energy potential, and digestate potential of agricultural residues biomass (including crop residues and animal manure) were estimated for farming households in rural Vakinankaratra highlands in 2017/18 in Madagascar. Biomass estimations are conducted based on the percentage of the household that farmed with a particular crop or animal species.

Crop residue biomass resource and energy potential

In the agricultural system of rural Vakinankaratra highlands, the main crop residues during the 2017/18 production year are from rice, maize, potato, cabbage, soybean, sweet potato, cassava, beans, taro, and tobacco. Residual biomass from these crops that are relevant to the production of biogas consists of the straw, husks, stalk, cobs, leaves, stems, peels and shells/pods following harvesting and/or processing. The annual estimates of the gross residues in the agricultural system are based on the production of crop and residue-to-product ratio. **Table 4** presents the mean crop production data and the generated residue potential from these crops during the 2017/2018 production year. The potential methane production and its equivalent total amount of energy from the residues are also displayed in the table. From 17 crop residue types generated by ten crops, the estimated gross crop residue is approximately 7.3 t per year on a fresh weight basis per smallholder farming household. At an individual crop level, the generated crop residue per household (HH) is dominated by residues from potato (average 1.66 t generated by 82% HH), rice (average 1.38 t generated by 96% HH), and maize (average 0.62 t generated by 87% HH) per year.

Table 4 Residue estimates from agricultural crops and their total energy potential per smallholder farming household.

Crop	HH (%)	Average P_{crop} (t.yr^{-1})	Residue type	Gross residue generated FM* (t.yr^{-1})	Recoverable residue generated FM* (t.yr^{-1})	Methane potential (Nm^{3}CH$_4$.yr^{-1})	Energy potential (GJ.yr^{-1})
Rice	96	0.725	Straws	1.11±1.21	0.80±0.87	178±193	6.40±6.95
			Husks	0.26±0.29	0.16±0.18	35±38	1.26±1.37
Maize	87	0.249	Stalks	0.50±0.77	0.40±0.62	91±140	3.27±5.06
			Husks	0.05±0.80	0.05±0.80	11±16	0.38±0.59
			Cobs	0.07±0.12	0.07±0.12	24±37	0.86±1.33
Potato	82	1.291	Stem & leaves	0.69±1.72	0.55±1.37	48±118	1.73±4.27
			Peelings	0.97±2.4	0.77±1.92	89±220	3.21±7.95
Cassava	20	0.406	Stalks	0.05±0.04	0.04±0.04	6±5.8	0.22±0.21
			Peelings	0.10±0.01	0.02±0.02	3±2.5	0.09±0.09
Soybean	29	0.076	Straw & pods	0.17±0.20	0.14±0.16	26±30	0.93±1.1
Beans	64	0.053	Straws	0.12±0.19	0.09±0.15	16±26	0.58±0.93
Sweet potato	48	0.514	Peelings & leaves	0.23±0.27	0.19±0.21	19±22	0.70±0.80
			Straw	0.26±0.30	0.21±0.24	24±27	0.85±0.98
Taro	24	0.536	Peelings	0.11±0.10	0.09±0.08	7±6.3	0.25±0.23
			Straw	0.27±0.25	0.21±0.20	21±20	0.77±0.72
Tobacco	13	0.270	Stalks	0.40±0.90	0.40±0.90	76±173	2.75±6.25
Cabbage	1	0.760	Foliage & stem	1.90±0.82	1.81±0.78	72±31	2.58±1.12

Note: HH represents 'households'. FM*= Fresh Matter. Results are expressed in mean ± standard deviation.

The recoverable residues for energy production are obtained by subtracting the amount used for other purposes from the gross crop residue generated. The estimates display that the average total amount of potentially available residues from crop production for the production of biogas is approximately 6 t, per year per smallholder farming household cultivated with a respective crop, i.e. 83% of gross residues are available as recoverable in rural Vakinankaratra. At an individual level, potato contributed the maximum quantity of recoverable residue at approximately 1.33 t (22%), followed by rice and maize residues at approximately 0.96 and 0.52 t (16 and 9%) to the total recoverable residue per farming household farmed with a respective crop. At crop level, cassava residue has the highest competing uses, and only 39% are considered available for energy generation purposes as the peels are fed to animals (only 20% recoverable) or dumped into solid waste [2]. On the other hand, tobacco stems and stalks have the lowest competing uses for energy generation among the considered crop residues.

The potentially recoverable residue resources can be exploited for anaerobic digestion to generate biogas. The overall methane potential estimated from recoverable crop residues is 745 Nm^3 methane per year, equivalent to 26.8 GJ per year of heat energy per smallholder farming household in the study area. The available total methane potential from crop residues are mainly from rice, potato, and maize with 213, 137, and 125 Nm^3 per annum of methane respectively, equivalent to 29, 18, and 17% of the total crop residue considered, as shown in (**Fig. 4**). This corresponds to 7.7, 4.9, and 4.5 GJ per annum of heat energy from rice, potato, and maize residues respectively, as shown in (**Fig. 5**).

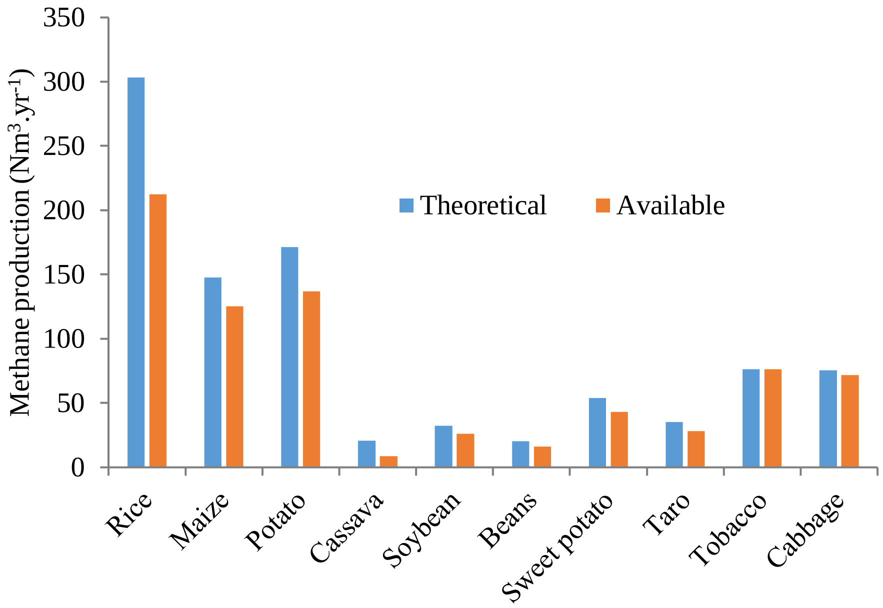

Fig. 4 Theoretical and available potential methane production of crop residues.

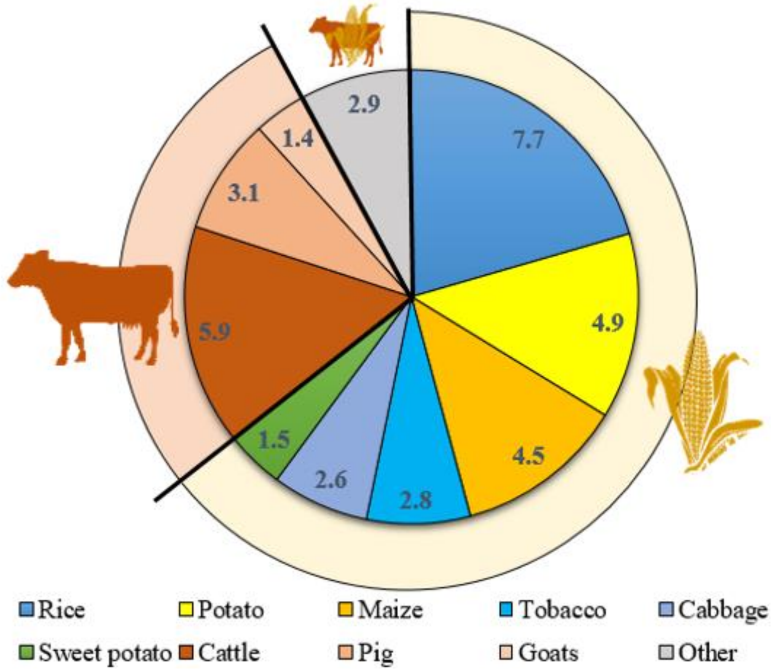

Fig. 5 Energy potential (GJ) of each agricultural biomass residue per year per household farmed with respective crop or animal.

Animal manure biomass and energy potential

The most common livestock in farming systems of rural Vakinankaratra highlands are poultry, cattle, and pigs, owned by 78%, 66%, and 60% of all households, respectively. Among those that farmed with poultry, the mean number owned per farming household were 13, followed by cattle (3), and pigs (3). **Table 5** presents the mean number of livestock per smallholder farming household, the estimated manure generation, and the methane equivalent and its energy potentials. The mean number of animals per farming household is small. From the manure produced by the four animal categories listed above, the gross animal manure produced is estimated to be 19.4 t on a fresh weight basis per year per smallholder farming household as presented in (**Table 6**). The highest gross quantity of manure contributed is by cattle, 13.14 t per smallholder household per year at an individual level.

Table 5 Animal manure estimate and the corresponding energy potential per smallholder farming household.

Type of livestock	HH (%)	Average P_{live} (Head)	Gross manure generated **FM*** ($t.yr^{-1}$)	Manure recoverable **FM*** ($t.yr^{-1}$)	Methane potential ($Nm^3CH_4.yr^{-1}$)	Energy potential ($GJ.yr^{-1}$)
Cattle	66	3	13.14±7.57	6.57±3.79	163±94	5.88±3.39
Goats and sheep	1	3	2.19±1.03	0.72±0.34	40±19	1.43±0.67
Pigs	60	3	3.94±4.21	3.15±3.37	86±91	3.08±3.30
Poultry	76	13	0.09±0.10	0.05±0.05	3±2.74	0.09±0.10

Note: HH represents 'households'. FM*= Fresh Matter. Results are expressed in mean ± standard deviation.

With regards to total recoverable livestock manure, 10.5 t on a fresh weight basis per smallholder farm household per year is estimated, i.e. 54% of gross manure generated are available as recoverable. Livestock (usually cattle, goats, and sheep) are allowed free-range during the day as most family farms are situated in rural areas. Thus, it is assumed that for half the day, the amount of produced manure from most cattle, sheep and goats is not recoverable. However, animals are mostly kept close to the house throughout the day to prevent animal theft, which provides a good opportunity to facilitate manure recovery. Pigs are commonly kept in agricultural system enclosures that facilitate the easy recovery of animal manure. Poultry was found in the highest numbers in the studied area, however it generates the smallest amount of manure per head because they are free-roaming by day and only spend the night in an enclosure.

From the recoverable fraction of animal manure, approximately 291 Nm^3 of methane can be produced: this is equivalent to a total of 10.5 GJ per year of heat energy in the rural Vakinankaratra region, as presented in (**Table 6**). The total methane potential available from the recoverable livestock manure is largely from cattle, about 163 Nm^3 of methane (56%) as presented in (**Fig. 6**). This high potential is because of the relatively large quantity of manure produced by cattle (approximately 12 kg FM per head per day on average), leading to a large recovery of cattle manure. Furthermore, the majority of surveyed households owned cattle as part of their production system, with an average of three heads of cattle per farmer.

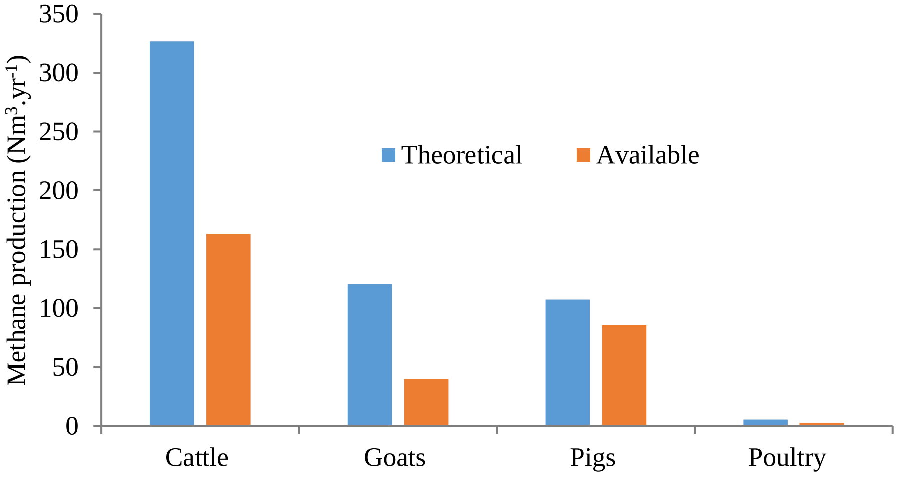

Fig. 6 Theoretical and available potential methane production of animal manure.

Table 6 Summary of biomass residue resources availability and biogas production potential.

	Unit	Crop residue	Animal manure
Gross residue potential **FM***	[$t.yr^{-1}$]	7.3±1.08	19.4±7.41
Recoverable residue potential **FM***	[$t.yr^{-1}$]	6.0±0.85	10.5±3.74
Methane potential	[$Nm^3CH_4.yr^{-1}$]	745.0±122	291.0±92.65
Energy potential	[$GJ.yr^{-1}$]	26.8±4.28	10.5±3.34
Firewood equivalent of 80% of methane	($t.yr^{-1}$)	3.3±0.55	1.3±0.41
Kerosene equivalent of 20% of methane	($m^3.yr^{-1}$)	0.2±0.03	0.07±0.02
Total amount of digestate **DM***	[$t.yr^{-1}$]	1.6±0.26	0.7±0.26

FM*=fresh matter. DM*=dry matter.

Digestate production potential

From the use of recoverable agricultural biomass resources in AD, it is estimated that the generation of approximately 2.3 dry tons total amounts of digestate from all residues per year per smallholder farming household in the studied area, as summarized in the supplementary material (**Table S5-7**). The estimated total digestate contains nutrient contents that were estimated to be 121, 98, and 101 kg of total-N, total-P_2O_5, and total-K_2O per year, respectively.

Discussion

Animal manure and crop residues availability estimate for AD purposes is crucial for biomass supply sustainability. The estimated results display an important residue biomass potential for the generation of biogas in small-scale farming systems, which can substantially improve energy access and minimize biomass use in conventional ways. The estimated gross animal manure and crop residue biomass resources potential were approximately 19.4 and 7.3 t on a fresh weight basis per smallholder household, of which 10.5 t (54% of gross) and 6 t (83% of gross) are available as recoverable for the generation of biogas, respectively, as summarized in (**Table 6**). This indicates that crop residues have lower competing uses than animal manure. Manure is usually applied to the farming fields to act as fertilizer. Anaerobic digestion could be a good alternative to provide both high-quality organic fertilizer and bioenergy, thereby decreasing the competing uses of manure.

From the available crop residue and animal manure biomass resources the total methane potential is 745 and 291 Nm^3 of methane per annum per farming household, equivalent to 26.8 and 10.5 GJ of heat energy, respectively. The energy potential of each agricultural biomass residues per year per household, for the different types of residues available, are presented in (**Fig. 5**). Crop residues show both higher methane potential and energy potential from available agricultural residues than animal manure. This is a result of the low numbers of animal types and the low quantities of each type owned by the surveyed farming households, and of the higher competing uses for manure in the farming systems. Overall, the residues that have the highest biogas potential are those from cattle among animals and from rice, potato, and maize among crops. Biomass production is important during the rainy season (November to April). With irrigation there is some production during the dry season, but this is much lower. Thus, the seasonal availability of the crop residues should be carefully considered for farmers in areas relying on a dryland production system as all crop residues are not available all year round. Additionally, other factors that could affect agricultural biomass resource availability, for example, animal breed types (manure) or changes in crop cultivars (crop residue), were not considered.

This study revealed that anaerobic digestion based on animal manure and crop residues can make a substantial contribution to meeting the energy demands of agricultural households in the rural highlands of the Vakinankaratra region of Madagascar. It is estimated that the methane generated has the potential to replace 4.6 t of firewood and 0.26 m^3 of kerosene per year. These findings revealed that, if more priority will be given to bioenergy production from animal manure and crop residues the existing problem of energy access to several regions of Madagascar can be eliminated so long as the quantity of residues required for the animal feed and soil fertility is maintained. Moreover, proper utilization of animal manure and crop residues biomass resources for the production of bioenergy in rural areas of Vakinankaratra can also replace a high percentage of traditional cooking fuel that is represented by firewood and straw (about 83.3% of households in the rural area) [43]. Switching from these conventional solid fuels (such as wood, straw, charcoal, etc.) to more efficient modern fuels like biogas, can lead to substantial reductions in household air pollution as well as reduce pressure on natural resources.

Biogas is currently not being utilised to a significant extent by any households in the rural areas of Madagascar. In Madagascar the electricity supply does not cover the entire territory: there are three interconnected networks, around the towns of Antananarivo-Antsirabe (RIA), Fianarantsoa (RIF) and Toamasina (RIT). The total length of the current transmission lines is approximately 1,000 km. However, a large part of these transmission and distribution networks are obsolete and are increasingly causing incidents. Most of the lines and equipment are overloaded. In the Vakinankaratra region, only 9% of urban dwellers and less than 2.5% of rural dwellers have access to electricity through the grid in 2019 according to the Ministry of Energy, Water and Hydrocarbons (MEEH). So, it seems difficult with so few rural people having access to electricity and such an underdeveloped grid, to consider connections from biogas production. The energy produced should be consumed on-site.

The estimated energy potential from the AD of estimated agricultural residues in this study is higher than the energy demand estimated for cooking. To satisfy the cooking needs per capita per day, 0.33 m^3 of biogas is required as it has been estimated for Nepal [44]. Haladová et al [3] estimated 1 m^3 of biogas for meal preparation only for the average Malagasy family per day. The estimation was done based on 200 liters of biogas (with 60% of methane content) needed for cooking three meals for one person per day, with a mean Malagasy household size of 4.9

persons. This biogas quantity is lower than the one reported for Nepal. For Vietnam, it has been estimated that 0.8 to 1 m^3 of biogas is needed for a typical farming household of six people per day, which is comparable [45]. However, Bond and Templeton [46] stated that the production of biogas to provide a five-member family with two cooked meals a day is about 1.5–2.4 Nm^3 biogas in developing countries. Similarly, Tolessa et al [18] reported 0.5 Nm^3 per day per person of biogas for cooking and 1.25 Nm^3 per day per person of biogas for complete replacement of traditional fuels for low-income South African households. Based on these reports, biogas generation to meet the energy demands for cooking with biogas is approximately 0.8-2.5 Nm^3 biogas (0.44-1.5 Nm^3 methane) per day per average household in developing countries. This is equivalent to 5.8-19.7 GJ heat energy per year (which corresponds to 3.2-10.8 $GJ.yr^{-1}$ available energy demand for cooking with biogas by assuming an average of 55% biogas thermal efficiency).

After cooking, lighting is the second most usual end-use of biogas, particularly in the areas that lack connection to the electrical grid. Biogas is used for lighting with the aid of exclusive gas mantle lamps which consume around 0.07–0.14 Nm^3 of biogas per hour [44]. Biogas lamps are less efficient than electric-powered lamps but more efficient than kerosene-powered lamps [45]. Farming households normally prefer biogas for cooking instead of lighting. Thus, the use of other lighting technologies is recommended, for example, home photovoltaic systems consisting of solar panels, light-emitting diode lights, battery and charger for a cell phone.

Digestate is a high-quality fertilizer for crops with significant contents of nitrogen, phosphorus, and potassium. As described in the methodology section, the mean nitrogen content of digestate is 5.2% (4.2% P and 4.3% K) on a dry weight basis. After AD, ammonium (NH_4^+) accounts for about 65-80% of the total nitrogen in the digestate, which is highly bioavailable and immediately available for crop uptake [12]. In digestate, the content of ammonium is directly associated with the total N content in the substrate. The higher the NH_4-N contents in the digestate, the higher the efficiency of the digestate as nitrogen fertilizer. However, during the AD process, the increases in the concentration of NH_4^+ promote losses of gaseous N after digestate is applied to the soil and increased the short-term availability of plant N [15]. Thus, to improve the use efficiency of N and promote digestate with a greater NH_4^+ share on total N, caution should be given to vegetation periods, application methods, and season to minimize losses of N such as by mixing the digestate instantly with soil. One ton of dry digestate contains approximately 52 kg N on average, which corresponds to 115 kg urea fertilizer. From the estimated 2.3 t total quantities of digestate generated from all residue types, N content is 121 kg per year per agricultural household in the rural Vakinankaratra region of Madagascar. This corresponds to 268 kg urea fertilizer per year for those farmers who have all the residues, and which can then be used for crop fertilization.

Digestate can be utilized as organic fertilizer and is indicated to be more appropriate than raw agricultural residues (e.g. manure, slurry) for fertilizer application. It has greater organic carbon retention and increased bioavailability of nitrogen due to decreased losses of N during decomposition. Degradable organic matter is easily transformed into methane and carbon dioxide during anaerobic digestion, whereas complex organic matter, for example, lignin remains in the digestate, thus increasing its quantity of effective organic carbon, which remains in the soil for at least one year. Therefore, this contributes to the humus build-up in soil (in digestate 33.7 kg per ton on average vs. in pig manure 20.0 kg per ton on fresh weight) [12]. High humus status enhances the infiltration of soil microorganisms and the holding capacity of water is fair enough for rain-fed crops [47].

The utilization of residue biomass resources to provide clean renewable energy to smallholder farmers can alleviate the problems that arise from the absence of modern clean energy facilities. It also enhances the farming households' productive capacity. Livestock manure is either applied directly to crops as manure, left unused, or utilized for cooking in dried form, whereas the unused portion of crop residues are left and/or burn in the fields, which leads to loss of nutrients present in the residues as well as air pollution.

If utilized properly with appropriate processing technology, animal manure and crop residues can be a source of biogas. The production of biogas through anaerobic digestion technology is well suited to small-scale farmers as both an alternative energy source and recycle nutrients as well as a management practice for residues. Biomass resources are the main factors that affect the development of small-scale anaerobic digestion technology in rural parts of developing African countries. The development of small-scale anaerobic digestion technology is influenced not only by biomass resources but also by the level of rural social economy and other factors [48]. The income of the consumers and the consumer's area energy condition is vital in selecting biogas as an energy source or not. In some poor rural areas, farmers do not have available capital to fund digester installation. This may require government support during the initial phase so that the cost of installing and maintaining a biogas system does not prevent farmers from using this source of energy. A smaller household type design digester with a volume of 4 m^3 to 12 m^3 might be more affordable for a family farm with two or three cows (other equivalent substrates) [49,50], such as in rural Vakinankaratra areas. The household-scale type digester appears more valuable for small farmers to produce biogas and organic fertilizers with lower investment and maintenance costs [51]. A household-scale type digester might be more attractive for a small-scale farm as feedstock are available at a certain distance without transport and storage issues. Moreover, the farms are small, so the quantities to be stored are not very important. However, this constitutes a point of improvement: to reinforce the storage capacities so that this one is done in good conditions, it is besides one of the techniques popularized for the improvement of the quality of the manure. Therefore, investments must be planned in addition to the digester.

Finally, this study proposes that small-scale anaerobic digestion technology should be adapted or developed according to local situations (including biomass and water availability). This could be done to explore possible strategies that will identify ways to enhance biomass potential and utilize the resources feasibly (e.g, investigation on whether the use of a smaller digester or a community digester shared by households is more feasible in local situations). Further study is also recommended on the adverse effect of utilizing digestate as a fertilizer as well as about digestate storage and utilization mechanisms after the AD process in a local context that did not form part of this study in biomass estimation.

Future studies would be of great value to future project assessments relating to the effective use of the available resources for AD application in rural communities. Particularly, future investigations relating to alternative usages and approaches such as natural biogas/bio-natural gas for vehicles, BioNGV (e.g., for replacement of conventional fuels) in the circular economy and economic development context to realize the full potential of AD and help farmers to better use their farm residues. This could also allow farmers to diversify their income and improve their socio-economic development.

Conclusion

Using data from agricultural household surveys combined with literature models, and publicly available data enabled us to estimate biomass resources availability for anaerobic digestion (AD) in small farms in the Vakinankaratra region of Madagascar. The estimation of agricultural biomass residue has revealed that there is an important potential of biomass feedstock for AD application in the region. Small-scale biogas technologies could be utilized near the source of feedstock in small farming systems and supply energy off the grid. This can make an important contribution in meeting the energy need in rural areas of the country, where the government has been unable to supply modern energy applications. Besides, a stabilized organic fertilizer produced from livestock manure and crop residues through AD can improve the soil quality and fertility and improve crop productivity within an agroecological small production system. The established baseline for biomass resource estimation at the small farming system level can be used for other provinces in Madagascar and elsewhere, to establish a similar baseline and quantify the potential for bioenergy generation from locally available biomass resources. Further studies are recommended to assess the ecological and economic value of biomass feedstock collection and conversion at a national level to integrate into the mainstream energy sector.

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Supplementary information

Table S1: The numbers of inhabitants, farms and animals in the study region.

Vakinankaratra region	In 2018
Population total	2 079 659
Agricultural population*	1,994,049
Number of farm households*	433,489
Cattle**	772,253
Pigs**	690 907
Poultry**	4,413,025

***Source: [17], ****Source: Authors estimations.

Table S2: Coefficients used for calculation for fuel equivalent potential of biogas.

Parameters	Unit	Values	References
Calorific value of biogas	$kcal.l^{-1}$	5.13	[16]
Calorific value of methane	$kcal.l^{-1}$	8.55	
Calorific value of firewood	$kcal.kg^{-1}$	3824	
Calorific value of kerosene	$kcal.l^{-1}$	8365	
Burning efficiency of firewood	%	40	
Burning efficiency of kerosene	%	80	
Methane content in biogas	%	60	
Methane leakage from the digester	%	10	
Density of methane	$kg.m^{-3}$	0.72	[40]
Density of carbon dioxide	$kg.m^{-3}$	1.96	
Density of biogas	$kg.m^{-3}$	1.22	a

[a] Calculated

Table S3: Crop residue substrate conversion to biogas.

Crop	Residue type	Y_{biogas} ($Nm^3.kgTS^{-1}$)	Substrate conversion into biogas ($kg.kgTS^{-1}$)
Rice	Straws	0.440	0.535
	Husks	0.387	0.470
Maize	Stalks	0.447	0.543
	Husks	0.397	0.482
	Cobs	0.580	0.705
Potato	Stem &leaves	0.240	0.292
	Peelings	0.548	0.667
Cassava	Stalks	0.320	0.389
	Peelings	0.538	0.655
Soybean	Straw & pods	0.375	0.456
Beans	Straws & pods	0.315	0.383

Sweet potato	Straw	0.240	0.292
	Peelings & leaves	0.495	0.602
Taro	Peelings	0.458	0.557
	Straw	0.278	0.338
Tobacco	Stalks	0.377	0.458
Cabbage	Foliage & stem	0.442	0.537

Table S4: Animal manure substrate conversion to biogas.

Type of livestock	Y_{biogas} ($Nm^3.kgTS^{-1}$)	Substrate conversion into biogas ($kg.kgTS^{-1}$)
Cattle	0.345	0.420
Goats	0.367	0.446
Pigs	0.412	0.501
Poultry	0.367	0.446

Table S5: Digestate potential of the available crop residue.

Crop residue type	Recoverable residue (dry $kg.yr^{-1}$)	Digestate production (dry $kg.yr^{-1}$)	N equivalent of fertilizer (dry $kg.yr^{-1}$)	P equivalent of fertilizer (dry $kg.yr^{-1}$)	K equivalent of fertilizer (dry $kg.yr^{-1}$)
Rice	824	393	20	17	17
Maize	452	198	10	8	9
Potato	604	326	17	14	14
Cassava	40	23	1	1	1
Soybean	115	63	3	3	3
Beans	85	53	3	2	2
Sweet potato	230	142	7	6	6
Taro	154	96	5	4	4
Tobacco	338	183	10	8	8
Cabbage	271	125	7	5	5
Total	*3112*	*1602*	*83*	*67*	*69*

Table S6: Digestate potential of the available animal manure.

Type of livestock	Dry Manure recoverable (dry $kg.yr^{-1}$)	Digestate production (dry $kg.yr^{-1}$)	N equivalent of fertilizer (dry $kg.yr^{-1}$)	P equivalent of fertilizer (dry $kg.yr^{-1}$)	K equivalent of fertilizer (dry $kg.yr^{-1}$)
Cattle	788.4	457.7	23.8	19.2	19.7
Goats/Sheep	180.7	100.1	5.2	4.2	4.3
Pigs	346.9	173.2	9.0	7.3	7.4
Poultry	11.9	6.6	0.3	0.3	0.3

Total	*1328*	*738*	*38*	*31*	*32*

Table S7: Summary of the estimated digestate potential of the available crop residue and animal manure.

Residue type	Recoverable residue (dry kg.yr^{-1})	Digestate production (dry kg.yr^{-1})	N equivalent of fertilizer (dry kg.yr^{-1})	P equivalent of fertilizer (dry kg.yr^{-1})	K equivalent of fertilizer (dry kg.yr^{-1})
Crop	3112±489	1602±260	83±13.51	67±10.91	69±11.17
Animal	1328±445	738±257	38±13.41	31±10.83	32±11.09
Total	4440±484	2340±261	121±13.55	98±10.95	101±11.21