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Potential of livestock manure and agricultural wastes to mitigate the use of firewood for cooking in rural areas. The case of the department of Cordoba (Colombia)

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ABSTRACT

Modern energy services are essential to replace the extensive use of traditional biomass fuels driving several environmental, health, and social issues affecting the welfare of low-income citizens. Particularly, in Colombia, 11% of the households rely on inefficient firewood cooking systems, while two million people have either intermittent access or no access to electricity. This is particularly important in the department of Cordoba, where an average of 32% of the households relies on firewood for cooking, increasing to 66% of the households in rural areas. Furthermore, 20% of the rural population lack access to electricity. Therefore, this study aims at defining the biogas-based energy potential of the available agricultural and manure wastes in the department. To this end, governmental data is used to estimate the demand for firewood for cooking, the resulting GHG emissions, and the available agricultural and manure wastes. Overall, there are around 1.2 million t of agricultural wastes and 2.2 million t of manure yearly available in the department, representing an energy potential of 6687 TJ. Using 26% of the biogas-based energy potential identified suffices to support the 1334 TJ of biogas needed to replace cooking firewood and to supply the 390 TJ needed for household electricity generation. The use of biogas can reduce GHG emissions to 11% of the emissions resulting from cooking firewood. Polyethylene tubular digesters appear as the most indicated household technology, contrasted to geomembrane tubular digesters that need 2.4 times the initial capital investment while fixed dome digesters need 7.9 times the initial capital investment. Implementing household digesters to support the energy demand for cooking in the department, necessitates a minimum of 18 million USD, while the implementation of ‘digester + electric generator’ needs between 1.7 and 5.7 million USDdepending on the monthly demand of electricity of 60 kWh or 187 kWh.

1. Introduction

Access to modern energy is instrumental for welfare, guarantee adequate health conditions, protect the environment, and promote socio-economic development (Rahut et al., 2019), which impacts directly on sustainable development (Ki-moon and Yumkella, 2010). However, poor and developing countries face a persistent deficit of electricity and a significant share of the population has little access to modern energy and technologies (Sarkodie and Adams, 2020). Currently, worldwide some 1.1 billion people (i.e. 14% of the global population) have no access to electricity, while 2.8 billion lack access to clean cooking fuels (Rahut et al., 2019). Other people, mainly from rural areas, rely on poor-quality electricity and frequent blackouts (Hountalas and Mavropoulos, 2010; Kamalimeera and Kirubakaran, 2021).

The limited and unreliable access to clean energy in poor and developing countries, drives the extensive use of traditional biomass fuels that represents a daily economic burden in rural areas, additionally increasing deforestation (which makes it harder to find firewood increasing the economic costs and collection time) and greenhouse gas (GHG) emissions (Rahut et al., 2019; Smith and Avery, 2014). Currently, traditional biomass fuels support 80% of the rural energy demand (Kamalimeera and Kirubakaran, 2021), driving different environmental, social, economic, and public health issues (Surendra et al., 2014). While firewood is renewable, its traditional use for cooking is unsustainable

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with severe environmental consequences (Sagastume et al., 2020).

In Africa, where the demand for firewood accounted for 70% of deforestation in 2010 and is estimated to increase to 83% by 2030, the use of small-scale digesters could reduce firewood-based deforestation by 4–26% by 2030 (i.e. 9–35% of the deforestation projected for 2030) (Subedi et al., 2014). Likewise, in rural China, where the lack of affordable and reliable energy is a barrier to economic growth, firewood demand-driven the exploitation of forests beyond their sustainable capacity (Ding et al., 2012). Moreover, in Colombia, low-income rural households rely on the more accessible and affordable firewood for cooking with high health, environmental, economic, and social costs (Pizarro-Loaiza et al., 2021).

Household biogas production from biomass wastes is a rather secure energy source unaffected by fuel price fluctuations as compared to fossil fuels (Ioannou-Ttofa et al., 2021). Household digesters can be a circular economy and food security strategy, additionally upgrading health and sanitation by addressing solid waste management (Kamalimeera and Kirubakaran, 2021). Particularly, in isolated rural communities with limited or inexistent energy infrastructure, small-scale household digesters are a simple and effective way towards more holistic farming systems that reduce the demand for traditional biomass fuels and chemical fertilizers, while improving welfare by providing clean energy for cooking, lighting, food preservation, heating, indoor air quality and health (Hijazi et al., 2019; Orskov et al., 2014; Smith and Avery, 2014). Decentralized and hybrid technologies have already provided access to electricity for an estimated 1.6 to 2 billion people in remote areas not connected to central electric grid systems (Kamalimeera and Kirubakaran, 2021; Mandal et al., 2018). However, a wider implementation of small-scale digesters has been precluded by environmental, socio-economic, and cultural barriers (Mwirigi et al., 2014).

The biogas potential of organic wastes has been discussed in different studies. In Iran, the biogas potential from livestock manure coincides with an estimated 3–34% of the natural gas demand in seven provinces (Noorollahi et al., 2015). Moreover, in Nigeria, in urgent need to address the highly erratic electric system causing daily blackouts up to 20 h, livestock manure stands as an opportunity for biogas-based electricity production (Adeoti et al., 2014). In China, an estimated 50–66% of the renewable energy target could be supported by the biogas potential identified for 60% of the unused livestock manure (Bao et al., 2019).

Different studies discussed the implementation of small-scale digesters in rural areas worldwide. In Ecuador, the biogas potential from livestock manure in rural areas, can potentially replace the demand for LPG and support 90% of the rural electrification target, while mitigating GHG emissions (Cornejo and Wilkie, 2010). Moreover, in Colombia, a small-scale digester implemented in rural areas with daily input of 50 kg of cow manure (i.e. the manure produced from 3 cows corralled 60% of the time), provided enough biogas to support the cooking needs of five people (Castro et al., 2017). In Cajamarca (Peru), nearly 100 digesters were installed for cooking and lighting in different biogas programs since 1988, although different barriers led to abandoning the program and most digesters after a few years (Garfí et al., 2014). A new project in 2007 implemented plastic tubular digesters that, even under suboptimal operation, produced enough biogas to support 60% of the cooking needs, reducing firewood consumption, deforestation, and GHG emissions by 50%–60% while increasing income by 3%–5.5% (Garfí et al., 2012, 2014). In the Peruvian Andes, the implementation of rural household biogas digesters led to poverty alleviation, upgrading health conditions and agricultural yields, while reducing the demand for firewood, deforestation, and GHG emissions (Ferrer-Martí et al., 2018; Garfí et al., 2012, 2014). In China, governmental policies promoting household digesters in rural areas since the 1970s lead to some 10% of the rural families relying on biogas by 2005, reducing the per capita rural household energy by 10% and the demand for chemical fertilizers by 51% (Ding et al., 2012; Yu et al., 2008).

The use of LPG (liquified petroleum gas) has been suggested to reduce the demand for traditional biomass fuels (World Bank, 2014), but high acquisition and transporting costs prevented the expansion of this alternative (Garfí et al., 2019). Thus, household digesters rise as a significant alternative to reduce the demand for traditional biomass fuels. Addressing barriers to small-scale digesters necessitates the standardization of efficient technologies, higher public awareness of the integrated production of biogas and biofertilizer, and access to funding and adequate policies (Smith and Avery, 2014). Currently, the economic performance of household digesters strongly depends on subsidies (Wang et al., 2016). Therefore, policies must consider that the use of traditional fuels in households is influenced by income, tradition, gender, etc., being predominant in low-income families making subsidy important (Rahut et al., 2019). In general, the successful development of biogas projects in developed countries highlights the potential to replicate these outcomes in developing countries, where, regardless of the abundance of feedstock, biogas projects are frequently economically unfeasible (Khan and Martin, 2016).

In Colombia, electricity is available in 48% of the national territory providing access to 96% of the population (Gómez-Navarro and Ribó-Pérez, 2018), while two million people live in non-interconnected areas (52% of the national territory) including 1.2 million people with no access to electricity (Gaona et al., 2015). Other people are provided with costly, intermittent, and poor-quality electricity that can be limited to 4–8 h daily (UPME, 2016a). Particularly, cooking accounts for 66% of the end-use energy in the residential sector, where 11% of the 1.7 million households rely on firewood that represents 41% of the end-use energy (i.e. between 7% in urban areas and 83% in rural areas) using cooking systems with energy efficiencies around 3% (UPME, 2020a). Additionally, artisanal industries in rural areas further promoted the demand for firewood, contributing to deforestation (Hoffmann et al., 2018). In the country, the health costs associated with the use of firewood are estimated at 0.22% of the GDP (GASNOVA, 2018). Therefore, Colombia is challenged to provide access to electricity and clean energy to upgrade the welfare of rural and low-income families. In the country, biomass account for the highest renewable potential estimated in 58, 611 GWh excluding forestry, from which some 10,000 GWh could be technically exploited (Gonzalez-Salazar et al., 2014a). A different study estimated that the anaerobic digestion of agricultural, livestock, and slaughterhouse wastes can yield some 63,000 GWh of energy (66% of the potential obtained from agriculture and agro-industrial wastes) (Sagastume et al., 2020). This potential could replace 25% of the national electricity generated in 2018 and 90% of the demand for natural gas and LPG in Colombia.

The department of Cordoba has large areas of an unmanaged forest threatened by deforestation (Delgado et al., 2020; UNDP, 2019). In the department, around 32% of the households (i.e. 4% in urban areas and 66% in rural areas) rely on firewood for cooking, using the traditional three-stones system with thermal efficiencies around 3% (Consorcio Estrategia Rural Sostenible, 2019; UNDP, 2019). Other fuel sources used for cooking in rural areas include LPG (28%), natural gas (4%), and electricity (1%) (with thermal efficiencies of 35–50%) (Kurchania et al., 2010; Ltodo et al., 2007; Shen et al., 2018; UNDP, 2019; UPME, 2020a). On average, collecting firewood for cooking requires around 96 h per month contrasted to the 24 h needed to manage biogas digesters (Consorcio Estrategia Rural Sostenible, 2019). Therefore, anaerobic digestion can address the demand for firewood in rural households while mitigating GHGs and improving welfare.

The costs of LPG averaging 50 USD per month plus 25 USD of transporting costs from urban to rural areas, prevents a wider use (Garfí et al., 2019). Overall, 4% of the households lack access to electricity, increasing to 20% in some rural areas (UPME, 2020b), evidencing sharp differences in the access to public services between urban and rural areas (Delgado et al., 2020).

Livestock and agricultural wastes, widely available in Cordoba, can become a source of clean energy for cooking and electricity in rural areas (Sagastume et al., 2020). Furthermore, a total of 67% of the GHG emissions in the department result from the enteric fermentation of livestock, deforestation, manure management, and the use of cooking fuels (IDEAM, PNUD, 2016). Therefore, the use of livestock and agricultural wastes can mitigate GHG emissions by addressing the management of manure and reducing the demand for firewood reducing energy poverty, thus, reducing deforestation. However, before anaerobic digestion can become a reality for low-income and rural citizens, is necessary to identify the current potential of livestock and agricultural wastes for biogas production. Consequently, this study aims at defining the biogas-based energy potential of livestock and agricultural wastes in the department of Cordoba. This is a first step to promote household digesters in the department, by providing decision-makers with useful information to support the development of new projects, the implementation of the renewable policies available, and, if necessary, the development of new policies.

2. Materials and methods

This section explains the materials and methods used in this study. It includes the relevant information of the department of Cordoba and the methods to estimate the renewable potential from agricultural and biomass wastes.

2.1. Household digesters

Household biogas digesters are frequently built between 2 and 10 m^3 with 40–90 days retention time (Jegede et al., 2019; Nguyen et al., 2019). Anaerobic digesters include the Chinese dome, the Deenbandhu, the floating dome, the Taiwanese bag, and the prefabricated design (Jegede et al., 2019). The volumetric biogas production rate of household digesters usually ranges from 0.15 to 0.30 $\frac{m^3_{biogás}}{m^3_{digester}\cdot day}$, while the average cooking demand of biogas varies from 0.2 to 0.3 $\frac{m^3_{biogás}}{person\cdot day}$ (Deng et al., 2020). Household digesters lose between 1.7 and 8% of the CH_4 with fugitive emissions, contributing to global warming and climate change (Bruun et al., 2014; Flesch et al., 2011).

The most used household digesters include the fixed-dome in China, the floating drum in India, and the balloon/bag digester in Latin America (Figueroa et al., 2017; Ioannou-Ttofa et al., 2021). Floating drum designs have the highest capital costs with a lifespan of 15 years, contrasted with fixed dome digesters are less costly and have a lifespan of 20 years (Yasar et al., 2017). Moreover, tubular digesters have lower costs and lifespans between 5 and 10 years depending on the materials (Ferrer-Martí et al., 2018). Table 1 shows the capital investment and installation costs for the fixed dome and tubular digesters (i.e. polyethylene and geomembrane digesters).

The CAPEX and biogas production data were correlated to estimate the costs and biogas yields for different volumes of digesters (see Fig. 1).

Overall, fixed dome digesters have a higher cost than tubular digesters.

In Colombia, household digesters have little implementation, mostly limited to the installation of tubular polyethylene digesters in small-scale farms (Garfí et al., 2019). In Cordoba, the number of people per household averages 3.3 (DANE, 2018). Thus, an average of 0.7–1 $\frac{m^3_{biogás}}{household\cdot day}$ is needed to supply the cooking demand in the department, which requires a 3 m^3 digester.

The capital costs required to implement a digester on households relying on firewood is calculated as:

$$CAPEX_{TD} = H_f \cdot CAPEX_D \tag{1}$$

where:

$CAPEX_{TD}$ – Capital costs of digesters for households relying on firewood (USD)
$CAPEX_D$ – Capital costs of the digester (USD/digester)
H_f – Households relying on firewood

Moreover, there are 14,474 households with no access to electricity in the department. Using biogas to provide the basic subsystem consumption to these households requires small-scale generators. To this end, the use of biogas generator units in capacity to generate from 0.85 to 1 kW for 1000 USD per unit was considered (BISON, 2021).

$$CAPEX_{TE} = H_e \cdot (CAPEX_E + CAPEX_D) \tag{2}$$

$CAPEX_{TE}$ – Capital costs of electric generator units for households without access to electricity (USD)
$CAPEX_E$ – Capital cost of biogas generator (USD/generator)
H_f – Households without access to electricity

In this case, the capital costs depend on the investment in the digester needed to support the biogas production required by the generator.

2.2. Departament of Cordoba

There are 1.56 million people in the department, of which 47% reside in rural areas (DANE, 2018). Moreover, there are 466,615 households, with 43% located in rural areas and 28% located in the capital city (Montería) (DANE, 2018). Furthermore, an average of 7% of the rural population lack access to electricity, which increases to 28% in some municipalities. Moreover, over half of the rural population depends on firewood for cooking. On the other hand, there are important amounts of agricultural and livestock wastes available in the department, which combined with deforestation, account for a significant amount of the departmental GHG emissions.

2.2.1. Firewood demand

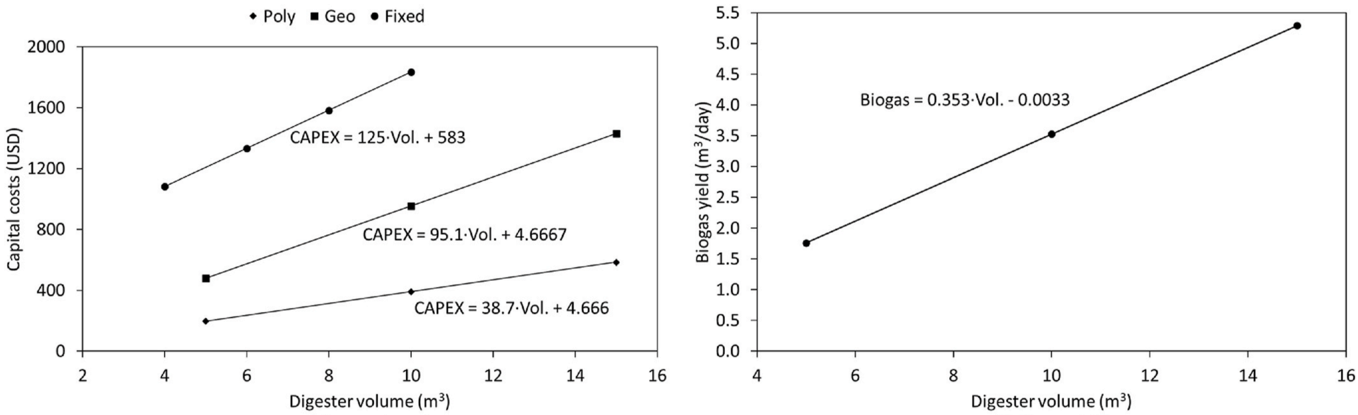
In the department, firewood is used in open fire systems, with thermal efficiencies ranging from 1 to 17% (Carranza and Gutiérrez, 2012), which averages 4.4% in Colombia (Consorcio Estrategia Rural Sostenible, 2019). As compared, standard gas stoves that are fueled with LPG or natural gas, operates with thermal efficiencies ranging from 35 to 50% (Kurchania et al., 2010; Ltodo et al., 2007; Shen et al., 2018; UPME, 2020a), while biogas stoves operate with thermal efficiencies around 37.2% (i.e. around 12% of the total energy from firewood).

In total, an estimated 150,717 households rely on firewood for

Table 1
The capital cost of the fixed dome and tubular digesters (FAO, 2021; Ferrer-Martí et al., 2018).

Digester size (m^3)	CAPEX (USD)			OPEX (USD/year)			Total (USD)		
	Poly.	Geo.	Fixed	Poly.	Geo.	Fixed	Poly.	Geo.	Fixed
4	–	–	1083	–	–	43	–	–	1949
5	198	480	–	794	961	–	992	1441	–
6	–	–	1333	–	–	53	–	–	2399
8	–	–	1583	–	–	63	–	–	2849
10	392	956	1833	1568	1912	73	1960	2868	3299
15	585	1431	–	2341	2863	–	2926	4294	–

*Poly. – Polyethylene, Geo. – Geomembrane.



a) Economic costs

b) Biogas yield

Fig. 1. Digester cost and biogas yield (own elaboration with data from Table 1).

cooking, accounting for 4.1% of the urban households (i.e. around 10,458 households) and 66.3% of the rural households (i.e. around 140,259 households) (UNDP, 2019). Fig. 2 shows the estimated distribution of urban and rural households consuming firewood.

Nine municipalities with over 6000 households relying on firewood account for 56% of the total households (i.e. Cereté, Ciénaga de Oro, Lorica, Sahagún, San Andrés, San Pelayo, Tierralta, Tuchín). Considering a monthly average demand of 367 kg of firewood per household (Consorcio Estrategia Rural Sostenible, 2019), the demand for firewood in the department is estimated at 663,762 t per year. Based on a biomass yield of 96.2 t per ha for natural forests in Cordoba, the demand for firewood drives the deforestation of some 6900 ha per year (Yepes et al., 2011). Given a firewood heating value of 16.9 MJ/kg, the firewood demand for cooking is equivalent to some 11,279 TJ/month (UPME, 2016b). Contrasted, the use of gas stoves would require between 993 and 1418 TJ/year (i.e from 9 to 13% of the energy from firewood), while the use of biogas requires some 1334 TJ (i.e. around 12% of the energy from firewood).

2.2.2. Access to electricity in Cordoba

In Colombia, the government defined a basic subsistence consumption (BSC, i.e. the electricity threshold monthly required to satisfy the basic needs of the average household) (UPME, 2011). Currently, the BSC is defined between 130 kWh/month per average household for lower temperature regions and 187 kWh/month for tropical weather regions (Superservicios, 2017). However, in several rural areas countrywide the electricity consumption averages 60 kWh/month per household (Minenergía, 2019; UPME, 2012). Moreover, the United Nations defined an energy threshold to meet basic human needs in 100 kWh of electricity and 100 kg of oil equivalent of modern fuels per year, which coincides with the emissions of 0.41 $t_{CO2eq.}$ per capita (Chakravarty and Tavoni, 2013; González-Eguino, 2015; Ki-moon and Yumkella, 2010).

The demand for electricity varied from 1477 to 1426 GWh between 2016 and 2017 (Ramírez et al., 2018). While the average access to electricity varies from 93% in rural areas to 99% in urban areas, there are eight municipalities (i.e. Ayapel, Montelíbano, Puerto Libertador, San Andrés, San José de Uré, Tierralta, Tuchín, Valencia) where the access ranges from 72% to 86%. These data show the limited access to electricity in some areas of the department.

2.2.3. Agriculture in Cordoba

Agriculture is one of the main economic activities of the department. In total, 40 annual, permanent, and short period crops are harvested in the department, while most of the production results from seven crops (MINAGRICULTURA, 2017). Fig. 3 shows the agricultural production of these crops in the department.

In total, the agricultural production of the main crops accounts for 0.9 to 1.2 million t of products per year. In this case. The seven largest

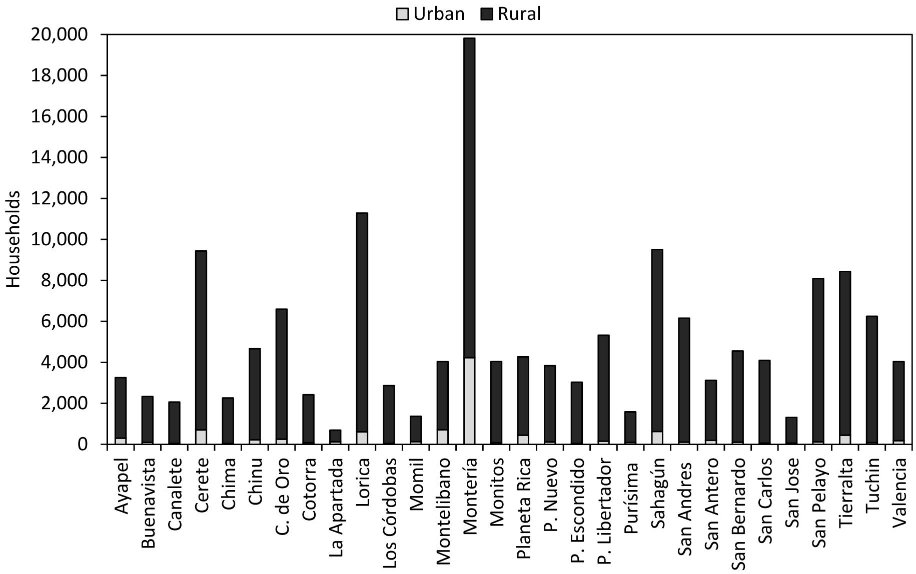


Fig. 2. Estimated households depending on firewood in urban and rural areas (Own elaboration with data from (DANE, 2018; UNDP, 2019)).

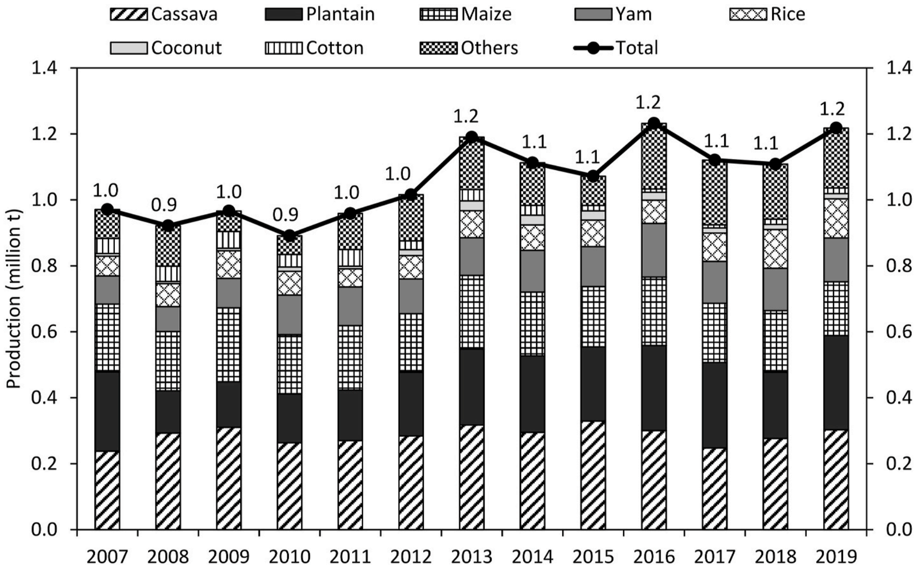


Fig. 3. Agricultural production in Cordoba (MINAGRICULTURA, 2021).

crops average 88% of the agricultural production in the department.

Agricultural production in the different municipalities is shown in Fig. 4.

In total, the production from Tierralta, C. de Oro, and Lorica account for 34% of the departmental production, while Momil, Purísima, and San José account for a low 1%.

2.2.4. Livestock in Cordoba

Cordoba is one of the main producers of bovine livestock in Colombia. Fig. 5 shows the heads of livestock under production in the different municipalities.

In total, there are 2.1 million heads of bovine livestock, 0.3 million heads of porcine livestock, and 3.5 million heads of poultry livestock. The municipalities of Lorica, Montería, and Sahagún account for 39% of the livestock in the department, while La Apartada, San Antero y San Jose account for a limited 1%.

2.2.5. GHG emissions

The department of Cordoba accounted for the emission of 6.7 million $t_{CO2eq.}$ in 2012 (IDEAM, 2016; UNDP, 2019). Table 2 shows the share of emissions by source in the department.

In total, livestock and forestry account for some 70% of the departmental GHG emissions, mostly affected by the enteric fermentation of bovine livestock, removals of firewood and carbon from soils in natural forests, direct and indirect emissions from manure and urine during livestock grazing, fuel combustion in the residential and commercial sectors, bovine manure management, and deforestation of natural forests (IDEAM, 2016). Countrywide, deforestation account for 98% of the emissions from forestry. Moreover, the carbon balance and regeneration of natural forests, seasonal crops, and grasslands account for 76% of the 0.9 million $t_{CO2eq.}$ absorbed in the department. Overall, livestock manure, agriculture, and forestry have a large influence on the net GHG emissions of the department.

The emissions of GHGs in this study were calculated as:

$$GHG = BW_i \cdot EF_i \tag{3}$$

where:

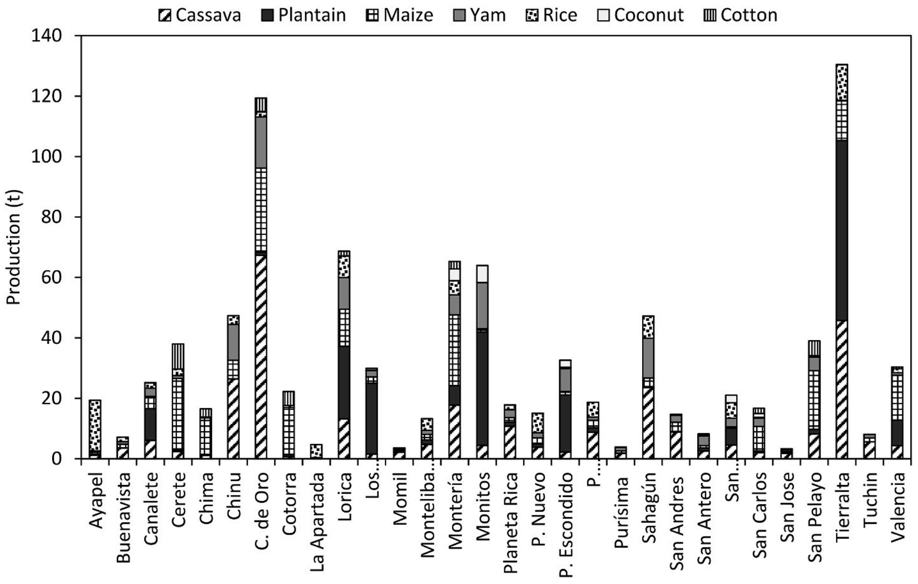


Fig. 4. Average agricultural production by municipalities in the department of Cordoba between 2010 and 2019 (MINAGRICULTURA, 2021).

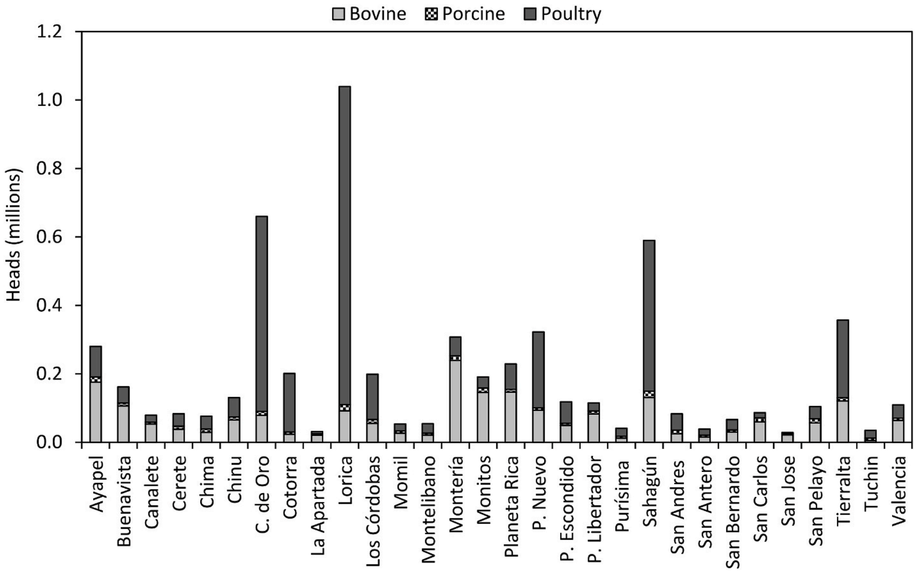


Fig. 5. Heads of livestock in the department (MINAGRICULTURA, 2021).

Table 2
GHG emission in the department of Cordoba (IDEAM, PNUD, 2016; UNDP, 2019).

Source	Emissions (%)
Livestock	49.24
Forestry	20.92
Manufacturing industry	14.24
Transport	8.36
Others	7.24

BW_i – Biomass waste i
EF_i – Emission factor of GHGs for biomass waste i

Table 3 shows the heating value and GHG emission factor for different cooking fuels used in the residential sector.

The table shows that firewood account for the highest specific GHG emissions, which is aggravated by the inefficient use of firewood for cooking. Moreover, natural gas and electricity account for the lowest specific emissions.

Based on the emission factor of firewood and using the average demand for firewood in Colombia, the GHG emissions resulting from the use of firewood for cooking are estimated for the municipalities in Cordoba (see Fig. 6).

Table 3
Characteristics and emission factor of selected cooking fuels (UPME, 2016b).

Parameters	Biogas (m^3)	Natural gas (m^3)	Electricity (kWh)	LPG (kg)	Firewood (kg)
HHV (MJ/unit)	24.4	39.5	–	49.1	18.3
LHV (MJ/unit)	22.0	35.7	–	45.4	16.9
Emission factor (t_{CO2}/TJ)	84.4	55.5	55.3	67.2	89.5
Emission factor (kg_{CH4}/TJ)	1	1	3	1	30
Emission factor (kg_{N2O}/TJ)	0.1	0.1	1	0.3	4
Emission factor ($t_{CO2eq.}$/TJ)	84.4	55.6	55.4	67.2	91.4

*Equivalent CO_2 of CH_4 (28 $kg_{CO2eq.}$) and N_2O (265 $kg_{CO2eq.}$) (CML - Department of Industrial Ecology, 2016)

In total, GHG emissions from firewood are estimated at 1 million $t_{CO2eq.}$. The capital Montería (the largest municipality), with the highest urban and rural populations in the department, accounts for 13% of the GHG emissions, while five other municipalities emit over 50,000 $t_{CO2eq.}$.

2.3. Biomass-to-energy potential

The process of anaerobic digestion results in the production of biogas (i.e. a mix of CH_4 and CO_2). In households, this process is developed in small-scale digesters using the substrates available. While biogas is a fuel used for heat and power production, the digestate byproduct serves as fertilizer (Mayer et al., 2019).

The biochemical methane potential (i.e. the methane yield from anaerobic digestion) for lignocellulosic biomass is calculated like (Thomsen et al., 2014):

$$BMP_i = 378 \cdot x_{C_i} + 354 \cdot x_{H_i} - 194 \cdot x_{L_i} + 313 \cdot x_{R_i} \quad (4)$$

where:

BMP_i – Biochemical methane potential of biomass source i $\left(\frac{L}{kg_{VS}}\right)$
x_{C_i} – Cellulose fraction of biomass source i
x_{H_i} – Hemicellulose fraction of biomass source i
x_{L_i} – Lignin fraction of biomass source i
x_{R_i} – Fraction of the remaining biomass constituents of biomass source i

Moreover, for manure (i.e. non-lignocellulosic biomass), the BMP is calculated like (Sagastume et al., 2020):

$$BMP_i = BMP_{(VS)_i} \cdot M_{manure} \cdot TS \cdot VS_{d.b} \quad (5)$$

where:

$BMP_{(VS)_i}$ – Specific biochemical methane potential of biomass source i $\left(\frac{m^3}{kg_{VS}}\right)$
M_{manure} – Mass of manure (kg)
TS – Total solids
$VS_{d.b}$ – Volatile solids on a dry basis

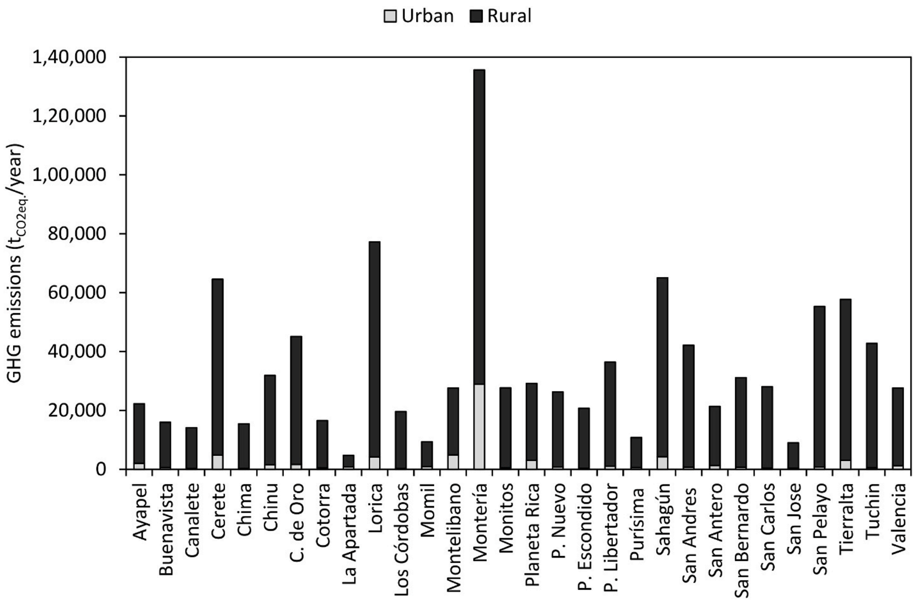


Fig. 6. Estimated GHG emissions from firewood in Cordoba (DANE, 2018).

Finally, to calculate the technical methane potential (TMP) that account for the biomethane that can be technically exploited, is calculated as (Wang et al., 2018):

$$TMP_i = BMP_i - \frac{\sum_1^j 1.1 \cdot M_i \cdot c_P \cdot (T_R - T_o)}{LHV_{CH_4}} \tag{6}$$

were:

TMP_i – Technical methane potential of biomass source i $(m^3/t_{biomass})$
c_P – Feedstock specific heat $\left(4.2\,kJ/_{kg\cdot°C}\right)$.
T_R – Digester operational temperature (°C)
T_o – Average atmospheric temperature (°C)
LHV_{CH_4} – Low heating value of methane (kJ/m^3)

Finally, the BMP for each source of biomass is calculated like:

$$W_i = M_i \cdot TMP_i \cdot LHV_{CH_4} \tag{7}$$

where:
W_i – Biomethane energy potential from biomass source i (TJ).

Finally, the total BMP for the biomass sources available is calculated like:

$$W = \sum_1^i W_i \tag{8}$$

The cooking potential of a biomass source is:

$$W_{cook_i} = W_i \cdot \eta_{cook} \tag{9}$$

where:

W_{cook_i} – Cooking energy potential from the biomethane for biomass source i (TJ)
η_{cook} – Cooking efficiency (%)

The total cooking potential is then calculated like:

$$W_{cook} = \sum_1^i W_{cook_i} \tag{10}$$

where:

W_{cook} – Total cooking energy potential from the available biomass sources (thermal efficiencies of 35–50% are considered for LPG and natural gas) (TJ).

To calculate the electric potential of biomethane it is considered an electricity efficiency of 30% for biogas systems (Pöschl et al., 2010), with a self-consumption of 20% for the technology used to produce electricity (Dong et al., 2018):

$$W_{elect_i} = 0.8 \cdot (W_i \cdot \eta_{elect}) \tag{11}$$

where:

W_{elect_i} – Electricity potential from biomass source i (TJ)
η_{elect} – Electricity efficiency

The total electricity potential is then:

$$W_{elect} = \sum_1^i W_{elect_i} \tag{12}$$

W_{elect} – Total electricity potential from biomass sources (TJ)

2.4. Demand for biogas energy

The biogas-based energy required to replace the consumption of firewood in the average household (i.e. consuming 367 $kg_{firewood}$/month) is calculated as:

$$e_{biogas} = \frac{(12 \cdot m_f \cdot LHV_f) \cdot \eta_f}{\eta_{biogas}} \cdot 10^{-9} \tag{13}$$

where:

e_{biogas} – Specific biogas-based energy required to replace the consumption of firewood $\left(\frac{TJ}{Household \cdot year}\right)$
m_f – Mass of firewood (367 kg/month)
LHV_f – Low heating value of firewood (16.9 MJ/kg)
η_f – Efficiency of firewood cooking system (4.4%)
η_{biogas} – Efficiency of biogas cooking system (37.2%)

Moreover, the biogas-based energy demand required at municipal and departmental levels is calculated as:

$$E_{cook} = H_f \cdot e_{biogas} \tag{14}$$

where:

E_{cook} – Biogas-based energy required to replace the consumption of firewood $\left(\frac{TJ}{year}\right)$

The biogas-based energy demand to meet the BSC at municipal and departmental is calculated as:

$$E_{elect.} = H_{we} \cdot (BSC \cdot 12) \cdot 3600 \cdot 10^{-9} \tag{15}$$

$E_{elect.}$ – Biogas-based energy required to support the generation of electricity $\left(\frac{TJ}{year}\right)$

H_{we} – Households without access to electricity

2.5. Characteristics of biomass

Table 4 shows the waste factors and other characteristics of the biomass wastes considered in this study.

Pseudo-stem from plantain production shows the highest moisture and waste factor, while waste yam and cassava stalks show the lowest waste factors. Moreover, most wastes show TMP values higher than 110 m^3/t, except for waste yam and plantain pseudo-stem.

Table 5 shows the waste factors and other characteristics of the manure wastes considered in this study.

Bovine heads show the highest TMP per head, except for breading and replacing sows, and boars which account for a little share of the livestock in pig breeding systems. Moreover, while the TMP per head of poultry is low compared to bovine and porcine livestock, poultry breeding systems include more heads per surface area as compared to bovine and porcine systems.

3. Results

The results describe the available biomass for biogas production and its energy potential.

3.1. Available agriculture and livestock biomass

Fig. 7 shows the agricultural wastes resulting from the production of the main crops in the department.

In total, 1.2 million t of wastes result from agriculture on yearly basis. Some 38% of the crop wastes are generated in Lorica, Monitos, and Tierralta. Plantain, maize, and cassava account for the highest production of crop wastes in the department.

Fig. 8 shows manure available in the municipalities for the livestock considered. In the case of bovine livestock, it is considered that the livestock is corralled 60% of the time (Castro et al., 2017).

In total, bovine manure accounts for 41–92% of the available manure in the municipalities, while porcine manure represents from 5 to 51%, and poultry manure accounts for 1–23%. In the department, bovine accounts for 84% of the 2.2 million t of manure available, while porcine accounts for 10% and poultry manure account for 6%.

Table 6 summarizes the waste products from agriculture and livestock in the department.

3.2. Biochemical methane potential for cooking and electricity

Fig. 9 shows the BMP estimated for the agricultural wastes available for energy applications in the department.

In total, crop wastes account for a BMP of 104 million m^3. The highest BMP was identified in C. de Oro, Montería, Tierralta, and Cerete accounting for 42% of the departmental potential. Moreover, the BMP estimated for the available manure for energy applications is shown in Fig. 10.

In total, manure account for a BMP of 82 million m^3, with the highest potentials identified in Montería, Ayapel, Planeta Rica, and Monitos accounting for 32% of the departmental potential.

Table 7 summarizes the biogas potential from agriculture and livestock in the department.

Fig. 11 shows the bioenergy potential from crop wastes and manure and the biogas-based energy demand to replace the use of firewood and to support the demand for electricity to meet the BSCin households without access.

In total, around 1334 TJ/year are required to replace the consumption of firewood in the department, while guarantying the BSC in households without access to the electricity needs some 390 TJ/year of biogas-based energy, providing the ARC needs some 125 TJ/year, and 17 TJ/year are sufficient to provide access to the ET. The figure shows that, except for Tuchin, all the municipalities have enough crop wastes and manure to guarantee a biogas production to replace firewood and support the BSC.

Since the specific emissions of firewood combustion are higher than for biogas (see Table 3), replacing firewood with biogas can reduce GHG emissions (see Fig. 12).

The use of biogas can reduce GHG emissions from firewood in the department from the calculated 983,652 t_{CO2eq}./year to some 112,624 t_{CO2eq}./year (i.e. reducing GHGs resulting from firewood combustion to 11% with the use of biogas). Reducing the demand for firewood with household digesters, reduces GHG emissions resulting from the change of land use, while additionally mitigating emissions from the inadequate management of manure. Particularly, households using digesters show lower GHG emissions than households using firewood, even when considering the fugitive emissions (Dhingra et al., 2011). Fugitive emissions from household digesters, accounting for 1.7–8% of the CH_4 production, could turn them from a GHG mitigation alternative to a potential climate bomb (Bruun et al., 2014; Flesch et al., 2011). However, even when emitting 40% of the CH_4 obtained, household digesters

Table 4
Waste factors, characteristics, and TMP from crop wastes.

Crop	Waste	Moisture (%)	X_C (%)	X_H (%)	X_L (%)	VS_{db} (%)	Waste factor ($t/t_{product}$)	$BioCH_4$ (m^3/t_{VS})	BMP (m^3/t)	TMP (m^3/t)
Cassava	**Stalks**	16	23	29	22	80	0.09	227.6	153.6	151.9
	Rhizome	8	34	17	28	77	0.49	198.7	140.3	138.6
Plantain	**Pseudo-stem**	90	54	16	21	89	3.00	248.2	22.0	20.4
Maize	**Stubble**	8	45	25	15	73	0.93	276.5	185.8	184.2
	Cob	7	28	26	19	74	0.27	245.5	170.1	168.5
	Stover	7	40	25	14	75	0.21	278.3	194.8	193.2
Yam	**Waste yam**	12	40	30	67	66	0.07	11.4	6.7	5.0
Rice	**Husk**	23	35	25	20	69	0.20	244.6	130.2	128.5
Coconut	**Husk**	10	39	20	37	81	0.34	159.0	115.4	113.7
Cotton	**Stalks**	7	38	32	21	74	1.77	244.4	168.6	166.9

*X_C – cellulose, X_H – hemicellulose, X_L – Ligning, VS_{db} – Volatile solids on dry basis.

Table 5

Waste factors, characteristics, and biomethane yields from manure.

Livestock		Manure $\left(\frac{\mathbf{kg}}{\mathbf{head \cdot year}}\right)$	TS (%)	VS_{db} (%)	BMP $\left(\frac{\mathbf{Nm^3}}{\mathbf{kg_{VS}}}\right)$	VS $\left(\frac{\mathbf{kg_{VS}}}{\mathbf{head}}\right)$	BMP $\left(\frac{\mathbf{m^3}}{\mathbf{head \cdot year}}\right)$	TMP $\left(\frac{\mathbf{m^3}}{\mathbf{head \cdot year}}\right)$
Bovine	**< 1 year**	1460	10.5	74.7	0.18	114.5	20.6	18.5
	1–2 years	3285				257.7	46.4	41.5
	2–3 years	5110				400.8	72.1	64.6
	> 3 years	6570				515.3	92.8	83.1
Porcine	**Piglets (1–60 days)**	102	26.8	74.2	0.21	20.3	4.3	4.1
	Growers (61–120 days)	445				88.5	18.6	17.9
	Finisher (121–180 days)	799				158.9	33.4	32.2
	Replacing sows (120–240 days)	1971				391.9	82.3	79.4
	Breading sows (> 240 days)	2694				535.7	112.5	108.5
	Boars (> 180 days)	2051				407.9	85.6	82.6
	Backyard pigs	799				159.0	33.4	32.2
Poultry	**Fattening**	26	32.2	65.2	0.23	5.4	1.2	1.2
	Growing	38				8.0	1.8	1.8
	Egg production	38				8.0	1.8	1.8
	Reproduction	38				8.0	1.8	1.8
	Backyard chicken	38				8.0	1.8	1.8

*TS – Total solids.

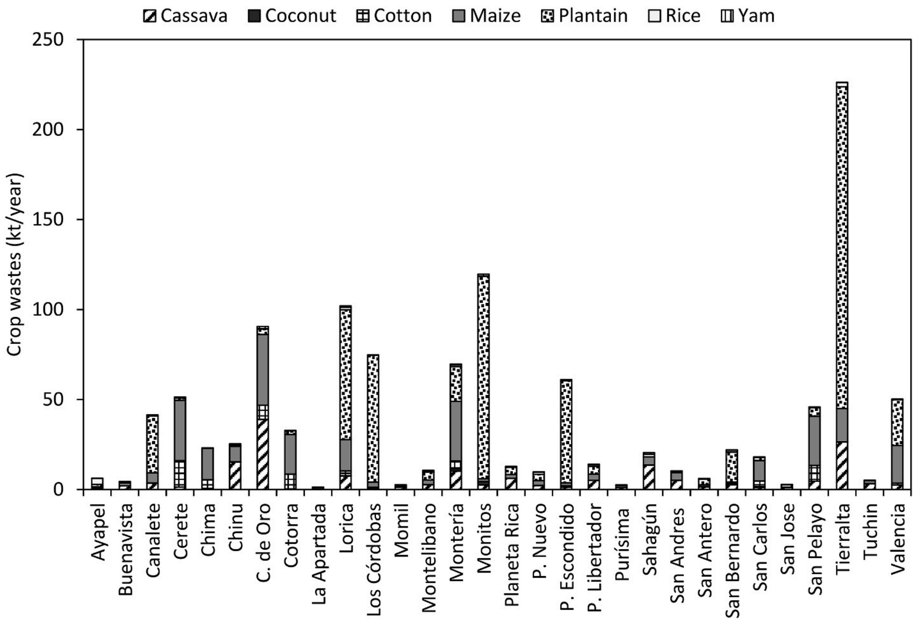


Fig. 7. Crop wastes in the department.

reduced GHG emissions by 10–13% (Jelínek et al., 2021). For digesters to emit as much GHGs as the emitted from the traditional use of firewood, fugitive emissions in household digesters need to be as high as 53–55% (Jelínek et al., 2021).

In total, livestock and forestry account for some 70% of the departmental GHG emissions, mostly affected by the enteric fermentation of bovine livestock, removals of firewood and carbon from soils in natural forests, direct and indirect emissions from manure and urine during livestock grazing, fuel combustion in the residential and commercial sectors, and deforestation of natural forests (IDEAM, 2016). Countrywide, deforestation account for 98% of the emissions from forestry. Moreover, the carbon balance and regeneration of natural forests, seasonal crops, and grasslands account for 76% of the 0.9 million $t_{CO2eq.}$ absorbed in the department. Overall, livestock manure, agriculture, and forestry have a large influence on the net GHG emissions of the department.

3.3. *Estimation of capital investment required*

In total, 150,718 households are relying on firewood in the department. Based on the average of 3.3 people per household, a digester of 3 m^3 is needed. This requires an estimated capital investment per digester of 121 USD for polyethylene digesters, 290 USD for geomembrane digesters, and 958 USD for fixed dome digesters. Thus, a capital investment of 18.2 million USD would be necessary to implement polyethylene digesters in these households, while 43.7 million USD would be required for geomembrane digesters, and 144.4 million USD would be needed for fixed dome digesters. It is also required to define repairing and maintenance costs during the lifespan of digesters to consider aspects that currently drive the limited success of this technology in rural households globally. It is probable that in some cases the availability of organic wastes justifies considering large-scale communal digesters to supply several households.

Moreover, the 14,474 households lacking access to electricity in the department. Considering supporting either the average electricity consumption of 60 $kWh_{electricty}$/month or the BSC of 187 $kWh_{electricty}$/

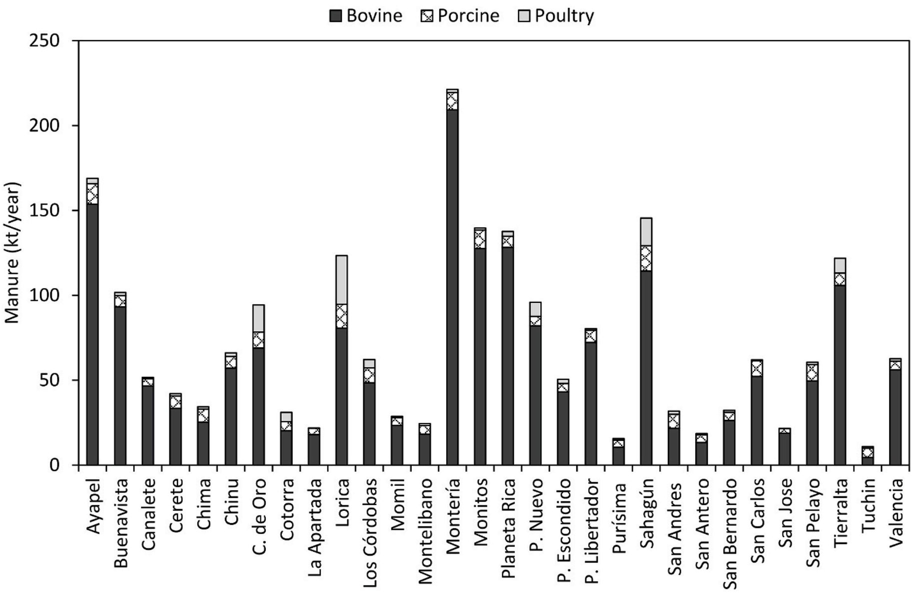


Fig. 8. Livestock manure available for recollection in the department.

Table 6
Agriculture and manure waste products in the department of Cordoba.

Municipality	Wastes (kt/year)										
	Cassava	Coconut	Cotton	Maize	Plantain	Rice	Yam	Bovine	Poultry	Porcine	Total
Ayapel	0.7		0.1	0.9	1.4	3.4	0.1	153.7	12.1	3.2	**176**
Buenavista	2.1			1.7	0.4	0.4	0.1	93.2	6.8	1.9	**107**
Canalete	3.6		0.2	5.7	31.6	0.4	0.2	46.7	4.3	0.8	**94**
Cerete	1.4	0.1	14.7	33.6	1.3	0.5	0.1	33.5	7.3	1.4	**94**
Chima	0.7		4.8	17.6	0.1	0.1	0.1	25.3	7.7	1.4	**58**
Chinu	15.3		0.1	8.7		0.6	0.9	57.1	7.0	2.1	**92**
C. de Oro	39.0	0.1	7.9	39.4	3.0	0.4	1.2	69.0	9.5	16.1	**186**
Cotorra	0.4	0.1	8.2	22.1	2.1	0.2		20.3	5.4	5.5	**64**
La Apartada	0.1			0.3	0.1	0.9	0.1	18.0	3.8	0.3	**24**
Lorica	7.6	0.1	2.8	17.3	72.2	1.5	0.8	80.7	14.1	28.7	**226**
Los Córdobas	0.9	0.2	0.2	3.0	70.5	0.1	0.2	48.5	8.9	4.9	**137**
Momil	1.3	0.1	0.1	0.8	0.4	0.1	0.1	23.4	4.6	0.8	**32**
Montelibano	2.8			2.6	4.5	0.8	0.1	18.3	5.2	1.1	**35**
Montería	10.3	1.4	4.4	33.1	19.4	1.0	0.5	209.3	10.2	1.9	**292**
Monitos	2.6	1.9	0.1	1.6	112.6	0.1	1.1	127.6	10.9	1.3	**260**
Planeta Rica	6.3	0.1	0.1	2.2	4.0	0.4	0.2	128.3	6.6	2.9	**151**
P. Nuevo	2.2	0.1	0.1	2.8	3.5	1.3	0.2	82.0	5.7	8.4	**106**
P. Escondido	1.3	0.8	0.1	1.6	56.8	0.1	0.6	43.2	5.0	2.4	**112**
P. Libertador	5.1			3.5	4.4	1.0	0.1	72.3	7.2	0.9	**95**
Purísima	1.1		0.1	1.1	0.5	0.1	0.1	10.6	4.2	1.0	**19**
Sahagún	13.7		0.1	4.5		1.5	1.0	114.3	15.0	16.3	**166**
San Andres	5.2		0.1	4.3	0.8	0.1	0.2	21.8	8.3	1.9	**43**
San Antero	1.5	0.2	0.1	1.1	3.3	0.1	0.3	13.3	4.6	0.7	**25**
San Bernardo	2.7	0.9		0.7	16.7	1.1	0.3	26.3	4.8	1.2	**55**
San Carlos	1.2	0.5	3.1	11.4	1.8	0.1	0.2	52.3	9.2	0.6	**80**
San Jose	1.1	0.1		0.3	1.4	0.1	0.1	18.9	2.7	0.2	**25**
San Pelayo	4.8	0.1	8.7	27.4	4.8	0.1	0.4	49.6	9.7	1.4	**107**
Tierralta	26.5		0.1	18.6	178.8	2.4	0.1	105.9	7.4	8.7	**349**
Tuchin	3.3			1.9		0.1	0.1	4.5	5.6	0.9	**16**
Valencia	2.6		1.1	21.0	25.5	0.3	0.1	56.2	5.1	1.5	**113**
Total	**167**	**7**	**57**	**291**	**622**	**19**	**10**	**1824**	**219**	**120**	**3337**

In total, there are 3.3 million t of agricultural and manure wastes available in the department, with manure accounting for 65% of the wastes.

month needs for digesters of 3 and 10 m^3. These digesters need investments of 121 USD to 1833 USD per digester, depending on the volume and the digester type. Therefore, an investment of 1.7–5.7 million USD is necessary for polyethylene digesters, 4.2 to 13.8 million USD for geomembrane digesters, and 13.9 to 26.5 million USD when considering fixed dome digesters. Moreover, biogas generators with a power of 0.85–1 kW are available at an average cost of 100 USD per unit (BISON, 2021). Consequently, an estimated investment of 3.2–28.0 million USD is needed to implement the ‘digester + electric generator’ system in households lacking access to electricity. A more detailed assessment is needed to identify the cases needing biogas for both, cooking and electricity.

In total, 21.4 to 172.4 million USD are needed (i.e. depending on technology and biogas demand) to address the access to clean energy for cooking and electricity for the low-income and rural population without access to clean and modern energy services in the department.

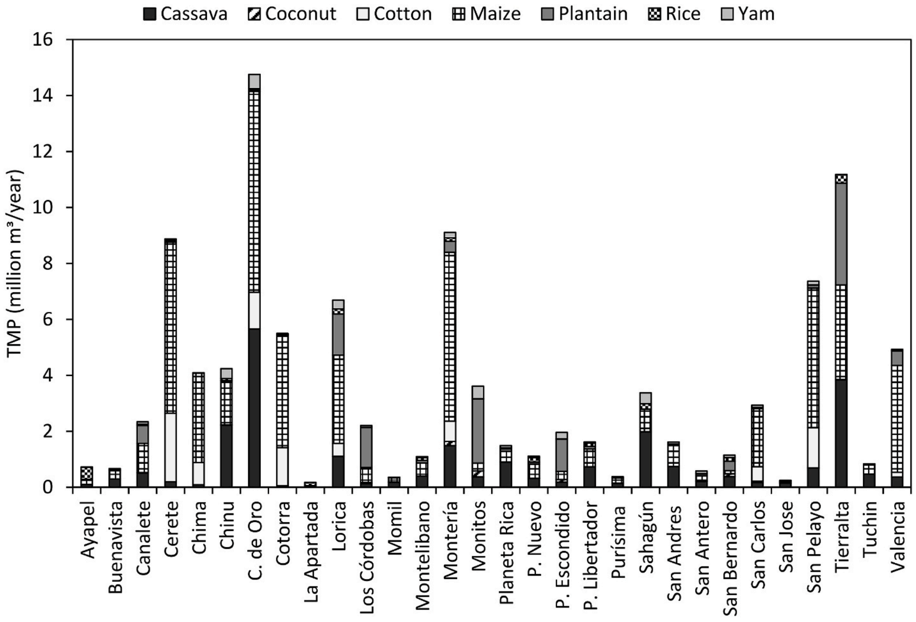


Fig. 9. Biochemical methane potential from crop wastes.

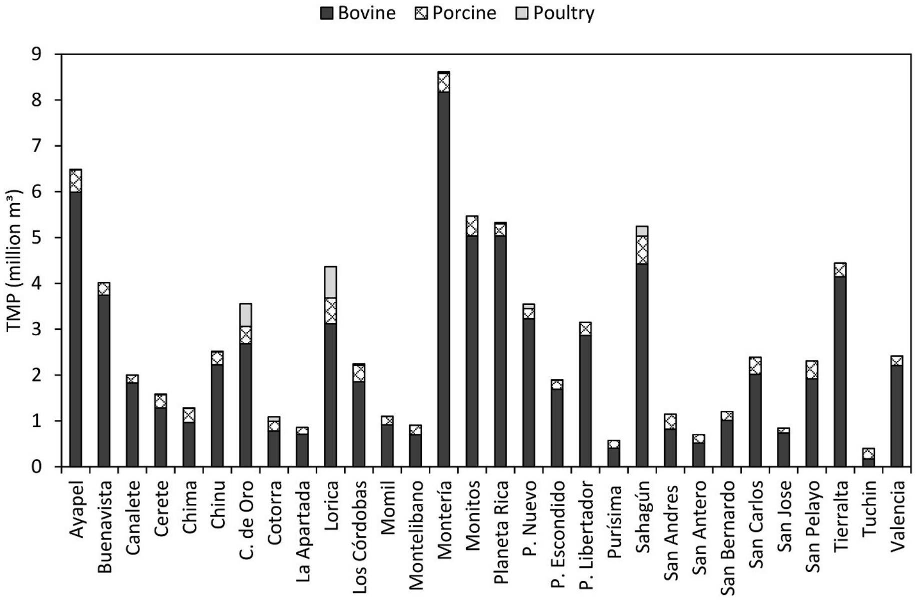


Fig. 10. Biochemical methane potential from manure.

Additional costs might be required for training families and the operation and maintenance of digesters and generators.

4. Discussion

Some studies in Colombia discussed the theoretical bioenergy potential of biomass (Gonzalez-Salazar et al., 2014a; 2014b), without discussing specific applications. Moreover, the potential of biomass in Colombia was discussed focused on the application of direct combustion and anaerobic digestion (Sagastume et al., 2020). The results show that the anaerobic digestion of biomass wastes can replace 90% of the demand for natural gas and LPG, 100% of the demand for solid fuels, and 25% of the electricity generated in 2018. However, this is a general study for the country and does not discuss the particularities of the different departments. In addition, the potential of anaerobic digestion to replace firewood for cooking was not discussed.

Currently, there is sufficient biomass available in the department to supply the energy demand for cooking in households relying on firewood and for electricity in households without access in the department. In total, 43% of the agricultural wastes are obtained from seasonal crops, while 57% of the wastes are obtained from perennial crops. All in all, the TMP from agricultural wastes accounts for 56% of the total potential identified, while manure accounts for 44% of the potential. It must be highlighted that, while the production of livestock manure and biomass wastes from perennial crops is stable through the year, biomass wastes from seasonal crops are produced during the harvest period and are thus available during specific periods of the year. However, when considering the harvest season for the different crops, biomass wastes are available throughout the year in the municipalities, although at the local scale agricultural wastes might become scarce in some periods of the year. Therefore, the suitability of seasonal agricultural wastes for energy valorization must be assessed in more detail, considering the availability

Table 7
Biochemical methane potential from agriculture and manure wastes in the department of Cordoba.

Municipality	Wastes (thousand m^3/year)										
	Cassava	Coconut	Cotton	Maize	Plantain	Rice	Yam	Bovine	Poultry	Porcine	Total
Ayapel	94		0.1	156	27	429	12	5989	485	11	**7204**
Buenavista	288			299	8	39	24	3743	271		**4671**
Canalete	494		19	1039	643	45	81	1829	171	0.2	**4321**
Cerete	193	1	2445	6120	26	54	29	1282	292	13	**10,454**
Chima	89		794	3194	2	4	4	965	310	7	**5369**
Chinu	2148		11	1583		74	353	2222	281	18	**6690**
C. de Oro	5470	7	1309	7179	60	41	505	2682	380	490	**18,124**
Cotorra	51	1	1364	4019	43	17		779	215	94	**6584**
La Apartada	10			45	1	112	1	707	150		**1026**
Lorica	1068	4	460	3156	1470	182	313	3117	568	677	**11,015**
Los Córdobas	126	22	18	538	1434	3	63	1857	358	30	**4447**
Momil	174	2	14	138	8	7	13	916	182	1	**1455**
Montelibano	386			468	91	99	40	700	206		**1991**
Montería	1441	150	725	6033	393	121	197	8174	410	28	**17,672**
Monitos	359	213	1	281	2291	2	455	5031	437		**9071**
Planeta Rica	874	0.2	0.4	387	81	39	80	5035	264	29	**6790**
P. Nuevo	309	1	3	503	70	164	52	3228	226	92	**4648**
P. Escondido	178	91	4	292	1155	10	227	1689	201	8	**3854**
P. Libertador	712			636	89	126	33	2863	287		**4745**
Purísima	142		1	185	9	1	35	407	168		**947**
Sahagún	1915		10	808		188	393	4427	602	217	**8559**
San Andres	717		5	778	14	8	69	817	332		**2739**
San Antero	206	12	2	186	65	8	96	518	183		**1276**
San Bernardo	372	97		112	340	132	85	1011	193		**2340**
San Carlos	165	50	516	2075	37	6	82	2016	370		**5317**
San Jose	143	1		47	28	8	17	738	108		**1088**
San Pelayo	665	1	1445	4991	96	12	134	1918	388		**9650**
Tierralta	3716		11	3381	3639	304	4	4145	294	3	**15,497**
Tuchin	455			333		0.00	36	174	224		**1221**
Valencia	354		170	3817	517	34	24	2209	205		**7332**
Total	**23,312**	**652**	**9329**	**52,778**	**12,638**	**2268**	**3456**	**71,187**	**8759**	**1718**	**186,097**

In this case, agricultural wastes account for 56% of the biochemical methane potential.

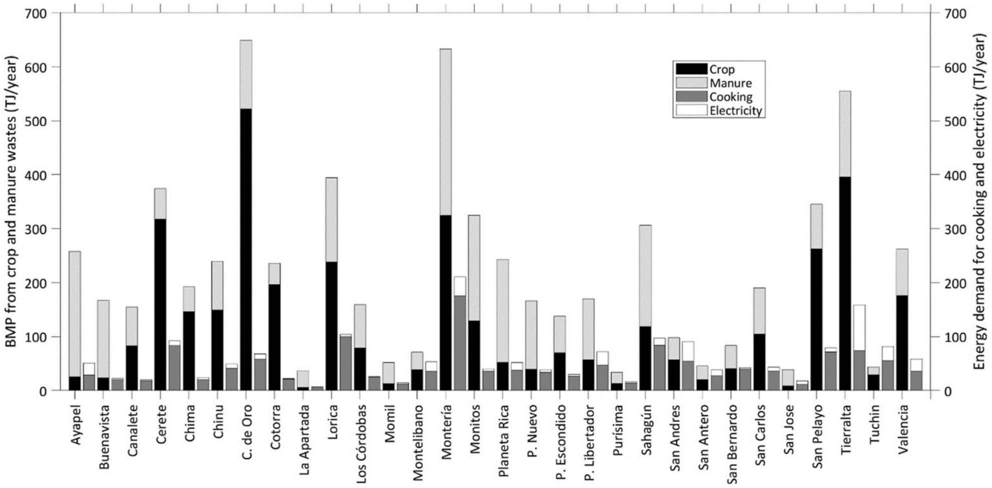


Fig. 11. Available BMP from crop wastes and manure compared to the energy demand for cooking and electricity.

during the year, the possibility to be stored, the geographical location, etc. In general, more research is required to characterize this situation at the local level, using tools like the Geographic Information System (GIS). This is essential to successfully develop the household biogas potential, which strongly depends on the context (i.e. geography, energy access, socio-economic level, etc.) (Bond and Templeton, 2011; Zhang et al., 2013).

The results indicate that tubular digesters (i.e. polyethylene and geomembrane designs) are economically more viable than the more robust fixed dome design. The implementation of polyethylene tubular digesters require 42% of the initial capital investment needed for geomembrane tubular digester, and 13% of the initial capital investments required for fixed dome digesters. When considering the capital investment over 20 years, polyethylene tubular digesters (with 5 years of lifespan) need 83% of the capital investment required for geomembrane tubular digesters (with 10 years of lifespan) and 51% of the capital investment needed for fixed dome digesters (with 20 years of lifespan). Although polyethylene tubular digesters show a lower capital investment contrasted to geomembrane tubular designs, some authors point to their lower technical performance (Ferrer-Martí et al., 2018). All in all, the development of government programs to promote household digesters for cooking, will depend on the availability of capital for the initial investment. In general, subsidy policies are instrumental to achieving the regular operation of digesters, particularly for the

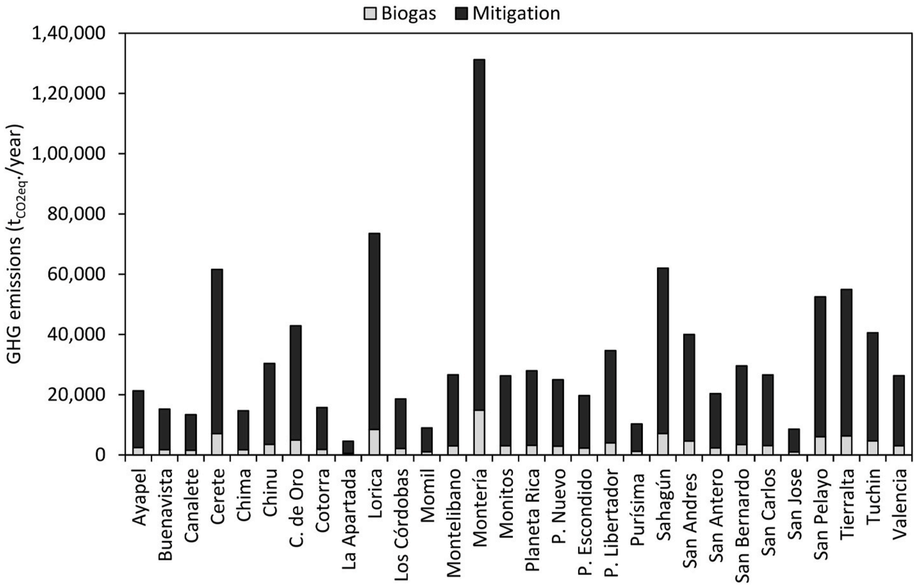


Fig. 12. Estimated GHG emissions from biogas-based cooking to replace firewood.

low-income farmers (Fan et al., 2011; Gunnerson and Stuckey, 1986; Ni and Nyns, 1996).

Moreover, the implementation of 'digesters + electric generators' to meet the demand for electricity in the 14,474 households lacking access to electricity, requires from one to over 3 times the demand of biogas needed for cooking. In practice, considering the availability of electro domestic equipment (or the lack of it), the demand will be closer to the rural average of 60 kWh/month than to the BSC of 187 kWh/month. However, the access to electricity will increase the demand for electro domestic equipment and thus, for electricity. Therefore, this needs a more detailed assessment to define the technical potential of household digesters for electricity generation in the department.

According to the results from this study, the use of biogas for household digesters can be a strategy to significantly reduce the emissions of GHGs. However, fugitive emissions of CH_4 in household digesters can be significant. Therefore, it is indicated a more detailed study assessing the net impact of household digester on the emission of GHGs as compared to the combined emissions from using firewood, and the traditional management of agricultural and manure wastes (Bruun et al., 2014; Flesch et al., 2011). Currently, the evidence suggests that the use of household digesters, even with fugitive emissions as high as 40%, results in lower emissions of GHGs as compared to the use of firewood (Dhingra et al., 2011; Jelínek et al., 2021).

Based on low operating and maintenance costs and little installing and operating difficulties, some studies point to small-scale digesters as suitable alternatives for rural households in low-income economies, (Ferrer-Martí et al., 2018). However, small-scale digesters remain too costly for poor families (Garfí et al., 2012). Additionally, drawbacks like low methane yields, incomplete bioconversion, process instability, and economic non-viability (Khan and Martin, 2016), further contribute to its limited success in developing countries (Lwiza et al., 2017; Mengistu et al., 2015; Mulinda et al., 2013). When possible, the use of larger digesters to supply biogas to several households can overcome some barriers, reducing the demand for labor, and improving the methane yield. One main challenge to larger digesters is the demand for qualified labor that might be unavailable in rural areas. In any case, governmental support is essential for the economic viability of digesters (Ioannou-Ttofa et al., 2021), and new public policies are needed to address the access to modern energy services for low-income and rural people to prevent an increased demand for traditional solid fuels (Surendra et al., 2014). The success of small-scale digesters programs in Asian countries proves their potential as a stable source of energy (Bedi et al., 2017; Bhat et al., 2001; Katuwal and Bohara, 2009). Small-scale digesters can be part of a national strategy to tackle the energy crisis while mitigating environmental issues (Li et al., 2016), which needs adequate incentives and policies (Ioannou-Ttofa et al., 2021).

5. Conclusions

The yearly demand for firewood to support cooking in the department of Cordoba is estimated at 663,762 t, which coincides with the deforestation of an estimated 6900 ha of woods. This study highlights that the use of the more efficient gas or biogas stoves can reduce the demand for cooking energy to between 9 and 13% of the energy demand from traditional firewood systems. Moreover, using 26% of the wastes available from agriculture and livestock production suffices to support the demand for cooking energy in the 150,718 households relying on firewood, and the demand for electricity in the 14,474 households lacking access to electricity. An assessment considering the local availability is recommended to further highlight the technical potential of the wastes available, considering more realistic scenarios.

Tubular digesters needing an initial capital investment equivalent to 13 and 30% of the investment required for fixed domes, look like the best alternatives. Particularly, the use of polyethylene digesters that results in the lowest investments over 20 years surfaces as the best alternative. A minimum of 18.2 million USDof initial capital investment is needed to implement polyethylene digesters to support the cooking needs in households relying on firewood, contrasted to the 43.7 million USDneeded for geomembrane digesters. Over 20 years, the investment for polyethylene digesters increases up to 72.8 million USD contrasted to the 87.4 million USD needed for geomembrane digesters.

This study concludes that GHG emissions resulting from the use of firewood for cooking can be reduced to 11% with the use of biogas. However, a more detailed study is necessary to assess the impact of fugitive emissions on the global warming potential of household digesters in the department.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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