Impact of agroecological technologies on energy efficiency and greenhouse gas emission in a livestock system in Chiapas, Mexico

Impacto de tecnologías agroecológicas sobre la eficiencia energética y la emisión de gases de efecto invernadero en un sistema ganadero en Chiapas, México

Impacto das tecnologias agroecológicas na eficiência energética e na emissão de gases de efeito estufa em um sistema pecuário em Chiapas, México

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Abstract

To mitigate greenhouse gas (GHG) emissions in the agricultural sector, it is necessary to propose alternatives based on a systemic vision and agroecological principles that allow for more efficient use of energy within the systems. The objective of this study was to evaluate three agroecological technologies by quantifying energy use and its relationship with GHG emissions and mitigation, to contribute to the sustainable management of a livestock system in Frailesca, Chiapas, Mexico. An ex-post facto study was conducted to establish five technological scenarios, based on combinations of the use of the three agroecological technologies, to calculate energy efficiency (EE) and estimate GHG, for which energy equivalences of the inputs and outputs of the production system were used. For the livestock system with conventional management, the energy efficiency was 0.63, generating a GHG emission of 93,153.96 kg of CO_2eq in a period of six months; By incorporating combinations of the three agroecological technologies (compost, bio slurry and silvopastoral system) the energy efficiency increased to 0.82 and the GHG emission decreased to 71,523.63 kg of CO_2eq. It is concluded that these agroecological technologies can be implemented in livestock systems in Chiapas, Mexico to contribute to the mitigation of GHG.

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Resumen

Para mitigar las emisiones de gases de efecto invernadero (GEI) en el sector agropecuario es necesario plantear alternativas fundamentadas con una visión sistémica y principios agroecológicos, que permitan hacer más eficiente el uso de la energía dentro de los sistemas. El objetivo de este estudio fue evaluar tres tecnologías agroecológicas a través de la cuantificación del uso de la energía y su relación con la emisión y mitigación de GEI, para contribuir al manejo sostenible de un sistema ganadero en la Frailesca, Chiapas, México. Se realizó un estudio ex-post facto para establecer cinco escenarios tecnológicos, basados en combinaciones del uso de las tres tecnologías agroecológicas, para el cálculo de la eficiencia energética (EE) y la estimación de GEI, para lo cual se utilizaron equivalencias energéticas de las entradas y salidas del sistema de producción. Para el sistema ganadero con manejo convencional la eficiencia energética fue 0,63, generando una emisión de GEI de 93.153,96 kg de CO_2eq en un periodo de seis meses; al incorporar combinaciones de las tres tecnologías agroecológicas (composta, biol y sistema silvopastoril) la eficiencia energética aumentó a 0,82 y la emisión de GEI disminuyó a 71.523,63 kg de CO_2eq. Se concluye que dichas tecnologías agroecológicas pueden ser implementadas en los sistemas ganaderos de Chiapas, México para contribuir a la mitigación de GEI.

Palabras clave: eficiencia energética, gases de efecto invernadero, ganadería.

Resumo

Para mitigar as emissões de gases de efeito estufa (GEE) no setor agrícola, é necessário propor alternativas baseadas em uma visão sistêmica e em princípios agroecológicos, que tornem mais eficiente o uso de energia dentro dos sistemas. O objetivo deste estudo foi avaliar três tecnologias agroecológicas através da quantificação do uso de energia e sua relação com as emissões e mitigação de GEE, para contribuir para a gestão sustentável de um sistema pecuário em La Frailesca, Chiapas, México. Foi realizado um estudo ex-post facto para estabelecer cinco cenários tecnológicos, a partir de combinações do uso das três tecnologias agroecológicas, para o cálculo da eficiência energética (EE) e a estimativa de GEE, para os quais as equivalências energéticas dos insumos e saídas do sistema de produção. Para o sistema pecuário com manejo convencional, a eficiência energética foi de 0,63, gerando emissão de GEE de 93.153,96 kg de CO_2eq no período de seis meses; Ao incorporar combinações das três tecnologias agroecológicas (compostagem, biol e sistema silvipastoril) a eficiência energética aumentou para 0,82 e a emissão de GEE diminuiu para 71.523,63 kg de CO_2eq. Conclui-se que estas tecnologias agroecológicas podem ser implementadas nos sistemas pecuários de Chiapas, México, para contribuir para a mitigação de GEE.

Palavras-chave: eficiência energética, gases de efeito estufa, pecuária.

Introduction

In countries where livestock farming is intensive, GHG mitigation efforts have focused on increasing productivity by improving feed quality and the genetic potential of animals (Gastelen *et al*., 2023). However, there are practices with a systemic view of livestock farming, applying sustainability criteria in the management of soil, water and biodiversity, based on agroecological principles. One alternative to reduce GHG emissions in livestock systems is to increase energy efficiency by optimising the recycling of nutrients through carbon sequestration in the soil and biomass of production systems, which would contribute to reducing energy losses that occur in conventional production systems (Cevallos *et al*., 2019). Some agroecological technologies allow these objectives to be achieved, such as silvopastoral systems that store carbon in biomass (Aryal *et al*., 2018) and the production of fertilisers, such as composts and biols, as an option for recycling livestock manure (Venegas-Venegas *et al*., 2023).

Despite this, these agroecological technologies are not implemented in most livestock systems in Chiapas, where the use of external inputs is widespread, and the amount of energy input and output in these systems, and how it contributes to GHG emissions, is largely unknown. In this context, the objective of this study was to evaluate the implementation of agroecological technologies through the quantification of energy use and its relationship with GHG emission and mitigation, in order to contribute to the sustainable management of a livestock system in Frailesca, Chiapas.

Materials and Methods

Description of the study area

The research was carried out in the ranch 'Los Flamboyanes', which is representative of local production systems and is located in the Frailesca region, municipality of Villaflores, Chiapas, Mexico. Municipality between the parallels 16° 14′ 1″ N, 93° 16′ 0″ W, at an altitude of 840 m above sea level and with an annual rainfall of 1200 mm. The rainy period is five months and the dry period is seven months, where cattle are stabled. During the dry period, the diet consists of providing the cattle with maize silage (*Zea mays*), sorghum sudan forage (*Sorghum* x *drummondii*) and ground dried grass (*Andropogon gayanus*). During milking, 1 kg of concentrated feed is offered for every 4 kg of milk produced and mineral salts are freely available. Other activities carried out are milking, cleaning of the milking parlour and pens, loading the biodigester with cattle manure and insemination of the cows. Inputs such as electricity, diesel, chemical fertilisers, agrochemicals and others are used for these activities.

Conceptualisation of the production system

Using the production systems approach, boundaries, components, interactions, inputs and outputs related to EE and GHG emissions of the livestock system were identified (Guevara-Hernández *et al*., 2018). Subsequently, a delimitation of the primary production area within the livestock system, which is the dairy herd, was carried out, specifying the interactions between the components of the system with respect to energy use and GHG emission. With this information, the livestock system and the dairy herd subsystem were schematized.

Data collection

Data collection was performed daily during the drought period (November to April), by means of registers and tours of the ranch, which allowed descriptions of the work, quantification of inputs and labour.

Calculation of energy efficiency

Energy equivalences were compiled for each input used in each component, as well as for the outputs of the livestock system

(Martínez-Aguilar *et al*., 2021). Subsequently, a database was created in a Microsoft Excel® spreadsheet, Version 16.77.1 (2019), where the measured variables were multiplied with their respective energy equivalence. Specific information on inputs, outputs and energy values were processed using the methodology and parameters proposed by Guevara-Hernández *et al*. (2018).

Greenhouse gas emission and mitigation of the livestock system. The GHG emission estimation was performed by segments, i.e. based on the components identified in the conceptualisation of the livestock system, in particular, those that are part of the dairy herd subsystem. The components assessed for GHG emissions were the agricultural components (maize, sudan sorghum and grain sorghum plots) and the livestock component (enteric fermentation and manure produced and stored). For GHG mitigation, the components silvopastoral system, biodigester (biol and biogas) and composting were considered.

Estimation of GHG emissions from agricultural components

With the previously obtained data, GHG emissions associated with agricultural production, transport and inputs were estimated. For these estimates, equivalences provided by Olesen *et al*. (2004) were used, which provides approximations of the implications of energy use in agriculture for GHG emissions.

Estimation of enteric methane production

Methane production was estimated based on dry matter intake of the dairy herd, with the regression equation proposed by Niu *et al*. (2021), $CH_4 = (107 + 14.5 \times DMI) \times 0.05565$, where; DMI is dry matter intake.

Estimation of GHG emission from stored manure

The daily manure production of the dairy herd was weighed in 15 random samples. This information was used to estimate the daily manure production per cow for 6 months. Based on the equivalences proposed by Hao and Laney (2017) on GHG emissions during cattle manure storage, the daily emissions from manure stored in the dairy herd subsystem were estimated.

Estimation of carbon storage in the silvopastoral system

For above-ground biomass, a forest inventory was carried out directly to quantify the number of trees, diameter at breast height (DBH) and height. For juvenile trees between 2.5 cm and 9.5 cm DBH, the methodology proposed by Gómez-Castro *et al*. (2010) was used. For trees with DBH less than 2.5 cm, destructive sampling was performed with 40 trees, generating the following regression equation:

$$Y = 81.91e^{1.0231DBH}$$

Where Y = biomass (kg.tree^{-1}) and DBH = diameter at breast height.

To determine the carbon stored, the biomass of juvenile trees and trees with DBH less than 2.5 cm were summed and multiplied by 0.47 (López-Hernández *et al*., 2023).

Estimation of methane and carbon dioxide generation in the biodigester

The daily biogas production was estimated by means of a gas flow meter, subsequently, by means of gas chromatography, the composition of the biogas (methane and carbon dioxide) was determined, which allowed the GHG to be calculated.

Estimation of energy efficiency and GHG mitigation with different agroecological scenarios

An ex-post facto study was carried out where five possible GHG mitigation technology scenarios were considered (table 1). Conventional management was considered as the one where practices requiring high use of external inputs and no agroecological practices are used.

Results and discussion

Conceptualisation of the livestock system and primary production subsystem

The study area was delimited to the dairy herd as a subsystem (figure 1). The ranch has an area of 62.5 ha, of which 39.5 % is forest area of oak (*Quercus peduncularis*) and holm oak (*Quercus acutifolia*), 36.3 % is pasture, 17.9 % is agricultural plots of maize, grain sorghum and forage, 3.6 % is intensive silvopastoral system, 2.2 % is facilities area and, finally, 0.5 % represents a small orchard. For feeding the dairy cattle, 79.1 t of maize silage, 44.35 t of sorghum sudan fodder, 21.76 t of sorghum fortuna fodder, 3.7 t of grain sorghum and 1.6 t of sorghum stubble were harvested within the system; 14.3 t of concentrate feed were purchased as external feed inputs. Nine hundred litres of diesel were used to operate the tractor and 6,585 kW of electric power for the irrigation system and the mechanical milking machine. The main output of the dairy herd was the production of 39.87 t of milk in six months and, as by-products of the cattle manure, compost, biol and biogas were generated. The analysis of the livestock system in the conceptualisation allowed it to be considered an agroecological ranch in transition, as it has characteristics of agroecological systems such as nutrient recycling and decreased soil degradation by producing manure, as well as the presence of forested areas and live fences (Cevallos *et al*., 2019).

Table 1. Scenarios proposed with agroecological technologies in the livestock system and dairy herd subsystem.

	Conventional (kg)	Scenario 1 biol (kg)	Scenario 2 compost (kg)	Scenario 3 SSP (kg)	Scenario 4 biol and compost (kg)	Scenario 5 biol, compost and SSP (kg)
Chemical fertilizer	3,300	943	200	3,300	335	335
Biol	0	434,713	0	0	178,670	178,670
Compost	0	0	62,939	0	39,519	39,519
Sudan sorghum fodder	44,350	44,350	44,350	14,969	44,350	14,969
SSP forage	0	0	0	29,361	0	29,361

SSP: Silvopastoral system.

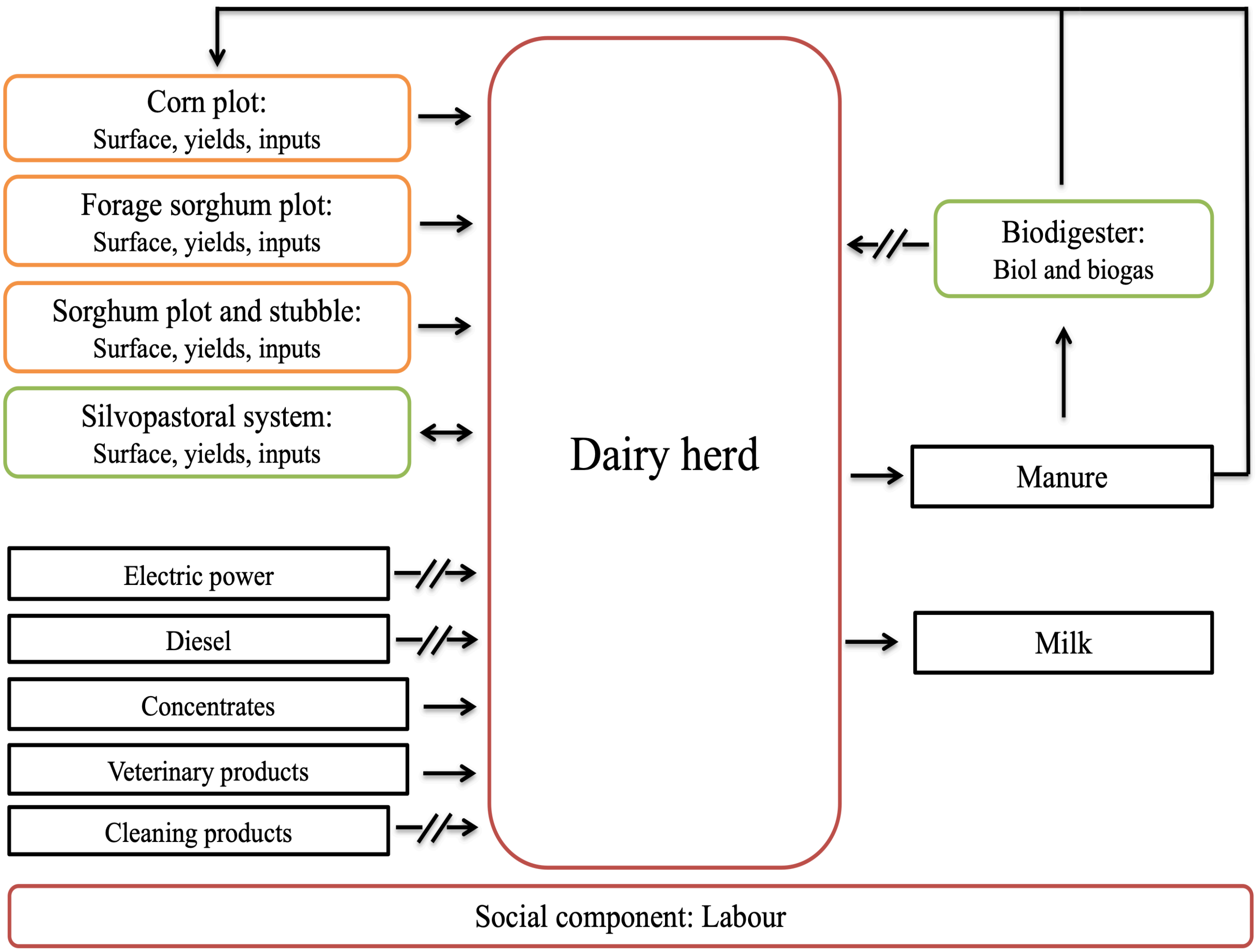

Figure 1. Conceptualization of the components and relationships of the dairy herd subsystem.

Energy efficiency of the maize plot component and the dairy herd subsystem with different agro-ecological scenarios

The results are presented in table 2. For the maize plot component, the first scenario involved the incorporation of biol, where the EE increased from 3.17 (conventional) to 4.58. For the second scenario using compost, the best EE was obtained, reaching 6.62, and in scenarios four and five the EE also improved reaching a value of 5.86.

The results in table 2, for the maize plot, are higher than those found by Guevara-Hernández *et al*. (2015), who obtained ES between 0.99 and 1.12 in maize production systems in the buffer zone of the 'La Sepultura' Biosphere Reserve in Chiapas, Mexico. Martínez-Aguilar *et al*. (2021), calculated EE between 9.87 and 17.37, in several types of maize production systems in the Frailesca, Chiapas, Mexico, characterised by the low use of external inputs, which prove to be highly efficient.

For the dairy herd subsystem, the EE increased by 30.15 % when incorporating agroecological technologies. The best result was obtained in scenario 5, with the use of biol, compost and SSP, reaching a value of 0.82, while with conventional management it was 0.63. These results are in agreement with Llanos *et al*. (2013), where they obtained energy efficiencies of 0.69, 0.94 and 1.53, in three different livestock strata in dairy farms in Uruguay. Moreover, they are higher than those reported by Gimenez *et al*. (2022), with EE between 0.26 and 0.64 in Argentinean dairies. The increase of EE in the maize plot, altered the efficiency in the dairy herd subsystem, since the maize silage was used for feeding the dairy herd, in addition to this, the SSP also makes an additional contribution to the increase in efficiency, because it is a forage produced with high EE (15.54), being the component with the highest efficiency within the livestock system.

Livestock enteric methane and GHG production from stored manure

The dairy herd consisted of 43 Jersey cows, the total enteric methane production during the six months of study was 2,572,402.86 L (1,546.91 kg CH_4), the daily production of enteric methane per animal was 330 $L.day^{-1}$ (198 $g.cow^{-1}$) with a consumption of 10.23 kg DM, slightly higher than that reported by Abarca-Monge *et al*. (2018), with Jersey and crossbred cows, where they mention that methane production in dairy cows was 265.7 $g.cow^{-1}.day^{-1}$, with an average consumption of 16 kg DM per day.

Table 2. Energy parameters with conventional management and incorporating agroecological technologies in the maize plot and dairy herd components.

Component	Scenario*	Energy efficiency	Input energy ($MJ.ha^{-1}$)	Energy cost of protein ($MJ.kg^{-1}$)	Labour energy productivity ($h.MJ^{-1}$)	Protein labour productivity ($h.kg^{-1}$)
Maize plot	Conventional	3.17	16,226.27	44.62	0.00265	0.37473
	Scenario 1	4.58	11,232.81	30.89	0.00354	0.50082
	Scenario 2	6.62	7,778.30	21.39	0.00286	0.40459
	Scenario 3**	3.17	16,226.27	44.62	0.00265	0.37473
	Scenario 4	5.86	8,780.93	24.14	0.00315	0.44544
	Scenario 5**	5.86	8,780.93	24.14	0.00315	0.44544
Dairy herd	Conventional	0.63	32,112.64	138.03	0.00918	0.80322
	Scenario 1	0.71	28,684.55	123.29	0.00918	0.80322
	Scenario 2	0.77	26,323.23	113.14	0.00918	0.80322
	Scenario 3	0.68	29,806.35	128.11	0.00918	0.80322
	Scenario 4	0.75	27,007.19	116.08	0.00918	0.80322
	Scenario 5	0.82	24,700.90	106.17	0.00918	0.80322

*The characteristics of each scenario can be found in table 1.
**Scenarios that include the SSP do not affect the maize plot component, as there is no interaction between the two components.

The dairy herd produced 144,904.25 kg of manure during six months, for scenario 2 (table 3), this amount of manure generated an emission of 4,644 kg of CO_2, 396.52 kg of CH_4 and 6.92 kg of N_2O, being 15,118 kg CO_2eq. Scenarios 4 and 5 (table 3) consider the use of compost and biol, the amount of manure used for composting was 90,984 kg, which produced 2,916.51 kg of CO_2, 248.97 kg of CH_4 and 4.35 kg of N_2O, which is expressed as 9,492.5 kg of CO_2eq. In relation to these data, Gastelen *et al*. (2023), mention that emissions from enteric fermentation and cattle manure corresponded to 46.5 % of the total carbon footprint associated with milk production, in the present work in the dairy herd subsystem this proportion was 51.1 % with conventional management.

Methane and carbon dioxide generation in the biodigester

In scenario 1 (table 3), the use of 144,904.25 kg of manure for biodigestion was considered, estimating a production of 6.377 m^3 of biogas in six months, the composition of the biogas was 60.3 % CH_4 and 38.6 % CO_2, generating 2,350.76 kg of CH_4 and 4,071.39 kg of CO_2, which is equivalent to 53,437 kg of CO_2eq, when the biogas is combusted it is transformed into 10,535.98 kg of CO_2.

The composition of the biogas is in agreement with Suarez-Chernov *et al*. (2019), who present results of methane between 50-70 % and carbon dioxide between 25-50 % for biogas produced from cattle manure. In scenarios 4 and 5 (table 3), the amount of manure used for the biodigester was 53,920 kg, the estimate of biogas produced was 2,372.95 m^3, therefore, the GHG generation was 874.73 kg CH_4 and 1. 514 kg of CO_2, which is equivalent to 19,884.46 kg CO_2eq, with the combustion of the biogas being transformed into 3,920.52 kg CO_2, generating a mitigation of 15,963.93 kg CO_2. Venegas-Venegas *et al*. (2023) reported that biogas, with a composition of 60 % CH_4 and 40 % CO_2, contains 22.81 MJ of energy per m^3, so the biodigester used in this livestock system has the potential to substitute 54,128.13 MJ of energy, which is equivalent to mitigating 11,438.63 kg of CO_2eq.

Carbon storage in the silvopastoral system

In the intensive SSP with *Leucaena leucocephala*, a population of 860 juvenile trees with DBH greater than 2.5 cm and 37,460 juvenile trees with DBH less than 2.5 cm per hectare was estimated. The amount of carbon stored in two years since its establishment was 3,205 kg, equivalent to 11,764 kg of CO_2; for GHG mitigation,

Table 3. GHG emissions in manure treated by composting and biodigestion.

Manure treatment	Scenario	Manure (kg)	CO_2 (kg)	CH_4 (kg)	N_2O (kg)	CO_2eq SCB (kg)	CO_2eq CB (kg)
Biodigestion	Scenario 1	144,904.25	4,071.39	2,350.76	0	53,437	10,535.98
	Scenario 4 and 5	53,920	1,514	874.73	0	19,884.46	3,920.52
Compost	Scenario 2	144,904.25	4,644	396.52	6.92	15,118	NC
	Scenario 4 and 5	90,984	2,916.51	248.97	4.35	9,492.5	NC

NC = No combustion. SBC = No biogas combustion. BC = Combustion of biogas.

the amount stored in six months, 2,941 kg of CO_2, was considered. López-Hernández *et al*. (2023) reported carbon storage values in livestock systems in Chiapas, Mexico, between 0.5 and 15.5 Mg C.ha^{-1}, depending on the age of the SSP.

GHG generation and mitigation in the maize plot, livestock system and dairy herd subsystem with agroecological technologies

Greenhouse gas generation decreased in the livestock system with the incorporation of agroecological technologies, specifically in the maize plot and dairy herd subsystem components, as shown in table 4.

On the maize plot, with the incorporation of the biol in scenario 1, GHGs were reduced from 27,756.64 kg CO_2eq to 10,933.32 kg CO_2eq and using compost in scenario 2 gave the best result with 4,141.62 kg CO_2eq. Scenarios 4 and 5 emitted 5,629.52 kg CO_2eq. As the SSP (scenario 3) has no interaction with the maize plot component, it does not affect the GHG emission.

Scenario 5 of the dairy herd subsystem generated the lowest GHG emissions, where the components corn silage, sorghum sudan, and sorghum fortuna contributed 3,395, 2,025.27 and 4,426 kg CO_2eq, respectively. The green fodder cutting activity produced 379 kg CO_2eq, stubble grinding generated 1,629 kg CO_2eq, balanced feed contributed 14,240 kg CO_2eq and hauling silage and green fodder to the feed bunkers generated 677 and 178 kg CO_2eq, respectively. Electric power for milking emitted 1,144 kg CO_2eq, enteric fermentation contributed more GHGs with 35,653 kg CO_2eq, which is equivalent to 1,546.9 kg CH_4, manure produced and stored generated 9,492 kg CO_2eq; and the biodigester with the combustion gas generated 3,921 kg CO_2eq. These results show that the use of agroecological technologies decreases GHG emissions in this livestock system. The use of compost and biol in the maize plot decreased GHG emissions by 79.71 % for this agricultural component by substituting industrial energy with ecological energy by recycling nutrients (Cevallos *et al*., 2019). By combining the use of these fertilisers in the agricultural plots with the intensive silvopastoral system, 21,630.33 kg CO_2eq of the dairy herd subsystem were mitigated, representing 23.22 % of the total GHG emissions.

Taking the following indicators as a reference, with the use of three agroecological technologies, dairy herd emissions decreased from 2.01 kg CO_2eq.kg^{-1} milk equivalent to 1.83 kg CO_2eq.kg^{-1} energy-corrected milk (ECM) to 1.51 kg CO_2eq.kg^{-1} milk equivalent to 1.40 kg CO_2eq.kg^{-1} ECM. These results are higher than those reported by Ridha (2013), where he estimated GHG emissions from several dairy herds in three regions of Spain, with the lowest value being 0.59 kg CO_2eq.kg^{-1} ECM and the highest value being 1.09 kg CO_2eq.kg^{-1} ECM.

Despite the improvement in GHG emissions from the dairy herd subsystem, in order to contribute significantly to GHG mitigation, it is recommended to: 1) Increase the productive efficiency of the animals; 2) Increase the area of the intensive silvopastoral system; 3) Decrease diesel consumption; 4) Incorporate tropical forage varieties that decrease the production of enteric methane; and 5) Estimate the carbon sequestration of the forest area.

Conclusions

The use of agroecological technologies in the livestock system increased energy efficiency and decreased greenhouse gas emissions as a result of the substitution of fossil inputs and carbon sequestration. The results of this research suggest the use of agroecological technologies such as composting, silvopastoral system and biodigesters in livestock units in Chiapas, to contribute to efficient energy management and, therefore, mitigate GHG.

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Table 4. GHG emissions of the maize plot component and the dairy herd subsystem with agroecological scenarios.

Component	Scenario*	CO_2 (kg)	CH_4 (kg)	N_2O (kg)	CO_2eq (kg)	CO_2eq (kg.ha^{-1})	CO_2eq (kg.kg^{-1} MS)
Maize plot	Conventional	11,656.68	27.24	50.09	27,756.64	3,965.23	0.6896
	Scenario 1	6,169.82	11.15	14.61	10,933.32	1,561.90	0.2716
	Scenario 2	3,029.83	4.32	3.29	4,141.62	591.66	0.1029
	Scenario 3**	11,656.68	27.24	50.09	27,756.64	3,965.23	0.6896
	Scenario 4	3,840.90	5.86	5.37	5,629.52	804.22	0.1399
	Scenario 5**	3,840.90	5.86	5.37	5,629.52	804.22	0.1399
Dairy herd	Conventional	27,893.89	1,993.37	75.48	93,153.96	15,097.89	17.55
	Scenario 1	30,476.41	1,587.15	47.16	78,427.54	12,711.11	14.78
	Scenario 2	22,691.94	1,979.55	47.26	78,914.21	12,789.99	14.87
	Scenario 3	22,675.65	1,988.62	71.40	86,571.20	14,030.99	16.31
	Scenario 4	25,373.12	1,832.93	45.94	78,106.39	12,659.06	14.72
	Scenario 5	20,154.88	1,828.17	41.86	71,523.63	11,592.16	13.48

*The characteristics of each scenario can be found in table 1.
**Scenarios that include the SSP do not affect the maize plot component, as there is no interaction between the two components.

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