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ECO-FOOTPRINT: QUANTIFYING ENTERIC METHANE EMISSIONS IN MEDITERRANEAN SMALL RUMINANTS

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Abstract: Greenhouse gas (GHG) emissions significantly impact climate change, with livestock contributing a substantial share. Livestock emissions, including methane (CH4), nitrous oxide (N2O), and carbon dioxide (CO2), constitute 14.5% of all human-induced GHG emissions. Small ruminants, such as sheep and goats, contribute approximately 6.7% to total livestock emissions. Accurate estimation of GHG emissions is crucial for inventory purposes and emission reduction strategies. Methane conversion rate (Ym) plays a pivotal role in quantifying enteric CH4 emissions, representing the proportion of the animal's gross energy intake converted to CH4 energy.

This study emphasizes the significance of Ym and its continuous revision to ensure reliable regional and national GHG emission inventories. The values of Ym ideally require direct measurements of CH4 emission, dietary intake, and digestibility. Accurate determination of Ym is vital for setting achievable targets to reduce enteric methane emissions. Understanding and improving Ym estimation procedures are essential steps toward mitigating the environmental impact of livestock-related GHG emissions.

Keywords: Greenhouse gases (GHG), Methane conversion rate (Ym), Livestock emissions, Enteric methane, Climate change mitigation

1. Introduction

Greenhouse gases (GHG) emissions have a marked impact on climate change. The observed warming from 1850–1900 to 1986–2005 was 0.61°C (5–95% confidence interval: 0.55 to 0.67°C), as reported by the Intergovernmental Panel on Climate Change (IPCC 2014). Total GHG emissions from livestock have been estimated to be 7.1 $GtCO_2$-eq/year taking 2005 as a reference year (Gerber et al. 2013), equivalent to 14.5% of all human-induced emissions. About 44% of the 7.1 $GtCO_2$-eq/year emitted by livestock (i.e., 3.1 $GtCO_2$-eq/year) come from CH_4; 29% (2 $GtCO_2$-eq/year) from N_2O, and 27% (2 $GtCO_2$-eq/year) from CO_2 (Gerber et al. 2013). Emissions of hydrofluorocarbons are globally marginal. Enteric CH_4 represents 30% of its global emission. Small ruminants' GHG emissions amount to 475 $MtCO_2$-eq/year, about 6.7% of livestock total emissions (Gerber et al. 2013). For inventory purposes IPCC Guidelines have been used to quantify GHG emissions. As far as enteric CH_4 is concerned, estimation procedures rely on several factors among which methane conversion rate (Y_m), introduced by the IPCC to indicate the proportion of the animal's gross energy intake (GEI) converted to enteric CH_4 energy (kJ/100 kJ GEI), is a critical variable. It is widely used for stating reliable regional or national GHG emission inventories and for setting attainable targets in reduction of enteric methane emissions (Niu et al. 2018). The Y_m, subjected to continuous revision and updating, represents a key variable whose values should be ideally obtained by direct measurements of CH_4 emission and the intake and digestibility of each diet (Hristov et al. 2018).

Southern Spain, specifically Andalucía, has a semiarid Mediterranean climate, with mild winters, extreme temperatures for the most part of the year and an annual pluviometry that may be as low as 300 mm, particularly in the eastern part of the region. Animal productivity in these semiarid lands is limited by both the amount and nature of the available vegetation (Robles 1990). An accurate specific assessment of animal production impact on GHG emissions in this region remains to be made. Due to the scarce research on energy balance and gas exchange measurements performed in ruminants in Spain, limited information is available on this subject and, consequently, the suitability of a specific Y_m value for regional inventory purposes may be linked to a high uncertainty. Concerning small ruminants, the Spanish Emissions Inventory (SEI) Working Committee has developed its own methodology to determine national emission factors linked to sheep production in Spain (Yáñez-Ruíz 2016). The polynomial regression equation of Cambra-López et al. (2008), based on data from Lassey et al. (1997), Judd et al. (1999), Leuning et al. (1999), Ulyatt et al. (2002a,b) and Pinares-Patiño et al. (2003), obtained in sheep grazing on New Zealand pastures, has been adopted to estimate Y_m from the digestibility of the diet. No single value from Spanish pastures or other diets were included in the database. The IPCC (2019) has proposed for sheep a mean Y_m value of 6.7 kJ/100 kJ GEI (SD ± 0.9), irrespective of feed quality, based on data collected by Swainson et al. (2018) from energy balance trials carried out between 2009 and 2015 on sheep fed New Zealand pastures. Feed intake was accurately measured with diets of wide variable quality and gas exchange was determined in open circuit respiration chambers. For goats, a mean value of 5.5 kJ/100 kJ GEI (SD ± 1.0) has been recently proposed by the IPCC (2019), based on the studies collected by Patra and Lalhriatpuii (2016) and from a technical report by Lassey (2012). This analysis involved a wide variety of feed samples and goat breeds. A generic estimation of CH_4 emissions from livestock may not be applicable to different areas of the world, so it might be important to define significant deviations from the global average.

For accurate CH_4 emission inventories, prediction models must be based on country/regional specific data of the animal population, species, and their physiological stage (IPCC, 2019). Therefore, it seems necessary to contrast the reliability of the application of conversion factors that, for the most part, refer to sub-tropical pastures (or diets with a high content of concentrates) to Spanish Mediterranean ecosystems, where semi-arid to arid lands prevail, and small ruminant herds are fed low concentrate diets and managed under extensive or semi-extensive productive conditions. Based on the analysis of 67 individual energy balance and emitted CH_4 measurements from 13 dietary treatments in experimental trials carried out in Spanish laboratories, we have recently proposed (Aguilera and Molina-Alcaide 2021) that an average Y_m value of 5.79 kJ/100 kJ GE intake (SD ± 0.43) be adopted for regional estimations of CH_4 emissions from sheep in semiarid to arid Spanish ecosystems. With the same purpose, for estimating CH_4 emitted by goats, several individual balance trials, involving 54 dietary treatments, have been included in the present study.

The aim of this work was (1) to contribute to generate information on Y_m estimates from pastures, forages and mixed diets usually consumed by sheep and goats in a Mediterranean ecosystem;(2) to calculate the total specific regional enteric CH_4 emission from the population of small ruminants using data of CH_4 emitted by autochthonous breeds of sheep and Murciano-Granadina goats and; (3) to evaluate the reliability of the application of specific Y_m values compared with those proposed by IPCC (IPCC, 2019) to calculate enteric CH_4 emission factors for inventory purposes within a semiarid ecosystem.

2. Materials and methods

The total regional enteric methane emission from sheep and goat has been calculated following the IPCC 2019 Tier 2 approach, as described in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, with some simplifications or modifications, as depicted below:

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-Total CH_4 emissions were obtained as:

CH_4 emissions (kg/year) = Number of animals × CH_4 emission factor (EF)

being EF calculated as:

EF (CH_4 kg/head/year) = GEI (MJ/year) × Y_m / 55.65 (MJ/kg CH_4),

where the methane conversion rate (Y_m) indicates the proportion of the animal's gross energy intake (GEI) converted to enteric CH_4 energy (kJ/100 kJ GEI) and the factor 55.65 (MJ/kg CH_4) is the energy content of methane.

Two methods have been followed to calculate EF for sheep and goat: a) Using the common Y_m values proposed by IPCC (2019) in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories for small ruminants (6.7±0.9 kJ/100 kJ GE intake, for sheep and 5.5±1.0 kJ/100 kJ GE intake, for goats), and b) Developing own specific Y_m values based on local studies. As far as method (b) is concerned, a database was compiled containing 13 treatment mean data from 5 published studies (involving 67 individual energy balance and CH_4 measurements) carried out on sheep (Table 1) and an average Y_m value was calculated from the mean data of the methane conversion rates reported [n=13 (diets); Table 1]. Additionally, a second database was compiled containing 54 treatment mean data from 20 peer-reviewed articles conducted in goats, involving 373 individual energy balance and CH_4 measurements (Table 2). An average Y_m value was calculated from the mean data of the methane conversion rates reported [n=54 (diets); Table 2]. All these experiments have in common that DM intake, energy intake and CH_4 emissions were individually and accurately measured, the latter using open-circuit respiration chambers or face masks.

Attention has been paid to the recommendations made by the SEI Working Group (Yáñez-Ruíz 2016) to achieve a high accuracy in the estimations of the enteric CH_4 emitted per year by the population of small ruminants in the geographic area under study. Accordingly, they have been based on the following three items: -Small ruminant population. Detailed and reliable account of small ruminants' population, namely sheep and goats, in the region of Andalucía, Southern Spain; breeds, type and level of production (milk, meat), and physiological state (growing phase, adult female/male, lactation, etc.). The statistical data provided by MAPAMA for the year 2019 (MAPAMA, 2021) were used (https://www.mapa.gob.es/es/estadistica/temas/publicaciones/anuario-de-estadistica/default.aspx; accessed October 2021).

Due to their high capacity for adaptation to semiarid lands and similar reproductive characteristics, Merina- and Segureña breeds of sheep (autochthonous breeds) are widely predominant in Southern Spain, particularly Segureña breed. Meat and fibre are the productive purposes of those breeds, although there is a tendency to milk production in the Merina breed encouraged by the high value achieved for Merina cheese. The total number of animals in this region is 2,182,845; being adult females, 1,674,526; adult males, 60,337 and growing lambs (male and females, up to 12 months of age), 447,981. The management system is extensive or semi-extensive, based on low-to-medium quality pastures, roughages, crop residues, mainly cereals straw, and other agricultural by-products, mainly olive cake (OC) from the olive oil industrial extraction. Taking the Segureña breed as a reference breed of sheep in Andalucía (ANCOS; www.ancos.org; accessed October 2021), adult body weight (BW) is assumed to be 50 kg for females and 70 kg for males, on average. First mating occurs at 8.5-10 months; lambing rate, 1.5/year. For pregnant ewes complementary feed is provided from 9 weeks before term. After lambing, concentrate is supplied to ewes according to the requirements for lactating a single lamb or twins, usually during a 6-week period. From the 4^{th} week of age, a pre-starter diet is offered to lambs. After weaning, lambs are reared on concentrates, and those not used for replacement are slaughtered at 3 months of age and about 24 kg BW. The average birth weight is 5.00 and 3.60 kg for single and twin lambs, respectively. The average growth rate is 215 g/day.

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Andalucía has the highest number of goats in Spain and is the largest producer of goat milk as well. Four goat breeds, all of them autochthonous, are produced in Andalucía: Florida-, Payoya-, Malagueñaand Murciano-Granadina breeds, the latter being by far the most widespread in Southern Spain (ACRIMUR; www.acrimur.es; accessed October 2021). All of them show a high capacity for adaptation to semiarid lands. The productive purpose is mainly for milk but also, for kid's meat. The total number of goats is 991,844; adult females, 755,455; adult males, 28,736; growing young animals (males and females, up to 12 months of age), 207,653.

The management system is highly variable, from semi-extensive to intensive farming. Low-tomedium quality pastures provide energy/nutrients for approx. 6-7 months/year. Although some differences in mature BW among breeds may exist, 50 kg BW, for the adult female, and 65 kg BW for the adult male may be representative for the standard adult goat. Seasonality of production is managed so that a stable and continuous production of milk throughout the year can be achieved. Deliveries are planned to occur by the end of autumn to benefit from the availability of pastures in spring. Sexual maturity is reached at 7 months of age and 70% of its mature BW. The average prolificacy is 2 animals; average birth weight, 2.11 kg (Sanz Sampelayo et al. 1990). Weaning takes place 2-3 days after delivery, and the young animals are grown with a milk replacer/pre-starter. Generally, the growing kids are slaughtered between 25-35 days of age and 7-9 kg BW.

-Regional specific factors. Detailed and reliable information on regional specific factors, as management systems (extensive, semi-intensive) and available feed resources (low-to-medium quality pastures; some roughages, crop residues, mainly cereals straw, greenhouse wastes and other agricultural by-products; barley grain and sunflower cake, as concentrate ingredients, and alfalfa hay or barley straw, as forage sources). When animals grazed on natural pastures, a direct observation and simulation method was used to determine the botanical composition of the feed consumed and to obtain representative samples of them (García et al. 1995; Molina-Alcaide et al. 1997). The amount of pasture daily consumed (I, g) was calculated from the daily faecal excretion (F, g) and the in vivo digestibility of the organic matter (OMD_{invivo}), expressed as a fraction of total OM, estimated from in vitro values ($OMD_{in\ vitro}$) of representative samples incubated in rumen fluid (Molina-Alcaide et al. 1997), using the relationship: $I = F / (1 - OMD_{invivo})$. The OMD_{invivo} was estimated from the following linear regression equation:

$$OMD_{invivo},\ \% = \underset{(\pm 0.69)}{15.9} + \underset{(\pm 0.027)}{0.758} \times OMD_{in\ vitro},\ \% \quad n = 29;\ r = 0.983;\ RSD = 3.50;\ P < 0.001$$

This linear regression was obtained in our laboratory (García 1992) using in vivo and in vitro digestibility data from 29 feeds of variable nature and composition: eight compound mixtures (OMD_{invivo}, 84.1-63%); five concentrates, mainly cereal grains and oilseed cakes (OMD_{invivo}, 92.2-85.4%); three hays (OMD_{invivo}, 76.2-51.8%); four grass or legume silages (OMD_{invivo}, 78.6-62.8%), and nine by-products of very diverse chemical composition: beet pulp, brewery residues, cereal straw and olive cake untreatedtreated with alkali (OMD_{invivo}, 88.9-26.9%).

To estimate the emission factors (kg CH_4/head/year) average energy densities of 10.5 to 11.7 MJ ME/kg DM and ME/GE ratios of 0.56 to 0.61 for mixed diets of practical use were assumed based on experimental data reported by Aguilera (2001). Those values are also within the range of those calculated for pastures grazed throughout the year in semi-arid lands (García et al. 1995).

-Specific energy requirements of native breeds. Whenever possible the energy requirements to achieve the observed levels of production were calculated based on own research. Taking the Segureña breed as a reference breed, the energy requirements for maintenance were calculated according to Aguilera et al. (1986) to be 374 kJ ME/kg $BW^{0.75}$; the energy cost of locomotion was assumed to be 2.85 J/kg BW/m, as determined by Farrell et al. (1972) in sheep walking on the ground level. It was also assumed that when animals are outdoors the average distance daily travelled was 7 km (Lachica et al.1997b and 1999); the energy cost of eating was 5.36 J/kg BW per g DM (Osuji et al. 1975). The energy requirements for gestation were calculated according to ARC (1980). The energy requirements for growth in lambs selected for replacement -from 3 to 12 months of age- were

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estimated according to FEDNA (2010). The energy requirements for wool production were calculated according to the IPCC (2019). A default value of 24 MJ/kg was taken for the net energy content of wool. The efficiency of ME for wool production (k_{wool}) was assumed to be 0.175, the mean value of 0.16 to 0.19 stated by Graham and Searle (1982). It was also assumed that under extensive farming the annual average production of wool achieves 0.60 of the maximum capacity (2.5 and 1.8 kg for males and females, respectively). The energy requirements for lactation were calculated according to FEDNA (2009), assuming an efficiency of ME for lactation (k_l) of Journal of Agriculture and Environmental Sciences, Vol. 10, No. 2, December 2021

0.62 and a milk energy content of 5.17 MJ NE/kg (Cruz Mira 1988). Average daily milk yield is 1.25 kg for ewes lactating a single lamb and 1.85 kg for those lactating twins, in a period of 45 days (Cruz Mira 1988).

The reference goat in Andalucía is the Murciano-Granadina breed and their energy requirements for maintenance are 401 kJ ME/kg $BW^{0.75}$ for the lactating goat (Aguilera et al. 1990); 443 kJ ME/kg $BW^{0.75}$ for the male goat (Prieto et al. 1990), and 421 kJ ME/kg $BW^{0.75}$ for the growing goat (Aguilera et al. 1991); the energy cost of locomotion was calculated as 3.35 J/kg BW/m (Lachica et al. 1997c), in goats walking on the ground level. It was assumed that the average distance daily travelled was 7 km (Lachica et al. 1997b and 1999). The energy cost of eating was estimated to be 7.95 J/kg BW per g DM, an average of values obtained for chopped alfalfa hay, vetch straw, olive leaves and twigs, and fresh-cut alfalfa (Lachica et al. 1997a). The energy requirements for gestation were calculated according to the ARC (1980). The energy requirements for young animals selected for replacement -from 3 to 12 months of age-, were estimated following FEDNA (2010). The energy requirements for lactation were calculated according to Aguilera et al. (1990); average daily milk yield was taken to be 530 kg in a standard period of 210 days, achieved under intensive management conditions and 3.59 MJ NE/kg milk was taken as well. It was assumed that the average milk yield of the grazing goat was 280 kg in a standard period of 210 days (Lachica et al. 1997b). **Table 1.** Chemical composition, digestibility, intake and enteric methane emission measured in Spanish autochthonous breeds of sheep*

Animals	DM, g/100 g	NDF, g/100	DMD, %	GED, %	DM intake,	CH_4, kJ/$BW^{0.75}$/d	Ym, (CH_4,	References

*DM, dry matter; NDF, neutral detergent fibre; DMD, Apparent digestibility of dry matter; GED, Apparent digestibility of gross energy; Ym, methane emission rate; BW, body weight; [1]Body weight, 40.2 ± 0.75 kg; Open-circuit respiration chambers; 4 dietary treatments; Four observations/dietary treatment; [2] Body weight, 57.5 ±1.9 kg; Open-circuit head box respiration system; 2 dietary treatments; Six observations/treatment; [3]Body weight, 44.3 ± 4.7 kg; Open-circuit respiration chambers; 2 dietary treatments; Six and nine observations/treatment; [4]Body weight, 58.8 ± 3.1 and 60.2 ± 3.2 kg of BW, respectively, for Guirra and Manchega sheep; Opencircuit head-hood respiration system; 2 dietary treatments; 1 dietary treatment/breed; Six observations/treatment; [5]Body weight, 58 ± 1.2 kg; Open-circuit head-hood respiration system; 3 dietary treatments; Four observations/treatment.

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Table 2. Chemical composition, digestibility, intake and enteric methane emission measured in Spanish autochthonous Murciano-granadina goats*

Animals	DM, g/100 g fresh matter	NDF, g/100 g DM	DMD, %	GED, %	DM intake, g/d	CH_4, kJ/$BW^{0.75}$/d	Ym, (CH_4, kJ/d)/(GEI, kJ/d)	References
Castrated male goats	88.7	40.7	62.4	61.1	556	58	0.068	Prieto et al. (1990)[1]

	90.2	41.9	63.9	62.2	608	63	0.069	
	88.3	50.7	48.5	47.5	608	42	0.046	
	90.6	50.7	50.7	47.8	766	47	0.044	
Lactating goats	87.9	35.7	69.6	68.0	1,165	89	0.057	Aguilera et al. (1990)[2]
	87.9	35.4	69.8	68.4	1,128	83	0.058	
	88.9	36.6	72.2	69.5	1,616	117	0.065	
	88.9	35.7	73.6	71.0	1,420	111	0.070	
	89.1	38.1	70.1	67.3	989	97	0.087	
	89.1	38.1	70.1	67.3	989	97	0.088	
Growing goats	NA	NA	72.6	72.7	373	48	0.053	Aguilera et al. (1991)[3]
	NA	NA	71.7	72.1	392	50	0.052	
Adult dry goats	90.7	45.6	65	65	820	40	0.042	López et al. (2010)[4]
	89.5	40.9	71	72	810	43	0.042	
	89.7	47.4	67	70	800	43	0.044	
	89.3	44.3	71	72	770	55	0.058	
Adult dry goats	NA	NA	68.3	67.7	715	39	0.040	López-Luján et al. (2010)[5]
	NA	NA	64.5	64.9	734	49	0.044	
	NA	NA	70.1	69.6	801	60	0.054	
	NA	NA	67.4	70.7	801	43	0.043	
Primiparous goats	87.2	55.4	68.3	67.7	715	30	0.030	López et al. (2011)[6]
	87.0	43.9	70.1	69.6	801	35	0.031	
Lactating goats	90.0	37.3	NA	NA	992	51	0.046	Abecia et al. (2012)[7]
Adult dry goats	92.2	47.6	67.8	70.5	639	55	0.064	Romero-Huelva and Molina-Alcaide (2012)[8]
	91.6	49.9	62.2	65.7	651	39	0.048	
	91.6	42.6	63.6	65.9	639	49	0.059	
	90.5	47.5	66.5	68.2	586	47	0.064	

Lactating goats	90.6	36.5	69	71	1,631	110	0.057	Romero-Huelva et al. (2012)[9]
	92.7	37.9	68	68	1,548	72	0.040	
	90.7	38.6	67	69	1,555	67	0.038	
	93.3	38.5	69	70	1,554	80	0.045	
Lactating goats	87.6	34.8	67.6	68.2	2,040	101	0.0444	López and Fernández (2013)[10]
	88.2	47.5	63.8	65.8	2,100	96	0.040	
Adult non-pregnant goats	NA	NA	NA	NA	612	NA	0.050	Martínez-Fernández et al. (2013)[11]
	NA	NA	NA	NA	394	NA	0.063	

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Dry goats	91.9	40.7	66	69	743	54	0.058	Martínez-Fernández et al. (2014b)[12]
Lactating goats	88.4	30.1	77.4	78.5	1,508	84	0.051	López et al. (2014)[13]
	88.4	30.1	77.6	79.4	1,528	118	0.073	
	90.2	59.0	71.3	73.6	1,570	118	0.0709	
Lactating goats	88.1	30.7	79.8	78.5	1,890	61	0.033	Ibáñez et al. (2015a)[14]
	88.5	35.7	74.2	73.3	1,630	92	0.058	
Lactating goats	87.5	40.6	68	69	2,030	95	0.042	Ibáñez et al. (2015b)[15]
	88.3	46.5	65	67	2,070	95	0.040	
Multiparous dairy goats	88.8	27.2	70.4	72.8	1,830	95	0.050	Criscioni and Fernández (2016)[16]
	89.1	22.8	73.9	77.1	1,610	73	0.041	
Lactating goats	95.6	38.2	77	76	1,537	123	0.081	Romero-Huelva et al. (2017)[17]
	95.3	36.4	79	78	1,512	86	0.063	
Lactating goats	92.6	33.0	77.3	76.8	1,288	49	0.057	Arco-Pérez et al. (2017)[18]
	80.1	52.6	74.7	76.2	1,166	57	0.040	
	86.8	52.4	78.0	78.3	994	56	0.039	
Lactating goats	91	31	61.1	65.1	1,700	63	0.037	Fernández et al. (2018)[19]

	90	21	68.6	72.4	1,500	47	0.032	
Lactating goats	89.4	22.9	NA	75.1	1,591	85	0.049	Marcos et al. (2019)[20]
	88.3	23.6	NA	73.5	1,637	67	0.039	
					Average Y_m	5.17 ± 1.38 kJ/100 kJ GE intake; n = 54 (diets)		

*DM, dry matter; NDF, neutral detergent fibre; DMD, Apparent digestibility of dry matter; GED, Apparent digestibility of gross energy; Ym, methane emission rate; BW, Body weight; [1]BW, 26.0 – 33.3 kg; Open-circuit respiration chambers; 4 dietary treatments; Eight observations/treatment; [2] BW, 34.3 – 40.7 kg; Opencircuit respiration chambers; 6 dietary treatments; Twelve observations/treatment; [3]BW, 13.1 – 21.9 kg; Open-circuit respiration chambers; 2 dietary treatments; Six observations/treatment; [4]Average BW, 38.41 ± 0.78 kg; Open-circuit mask respiration system; 4 dietary treatments; Three observations/treatment; [5]Open-circuit mask respiration system; 4 dietary treatments; Three observations/treatment; [6]Average BW, 33.08 ± 2.1 kg; Open-circuit mask respiration system; 2 dietary treatments; Three observations/ treatment; [7]Average BW, 43.0 ± 1.7 kg; Open-circuit respiration system; 1 dietary treatment; Nine observations; [8]Average BW, 32.1 ± 5.52 kg; Open-circuit respiration system; 4 dietary treatments; Four observations/treatment; [9]Average BW, 39.4 ± 5.39 kg; Open-circuit respiration system; 4 dietary treatments; Eight observations/treatment; [10]Average BW, 43.1 ± 2.5 kg; Open-circuit head box respiration system; 2 dietary treatments; Five observations/treatment; [11]Average BW, 33.0 ± 5.2 kg; Open-circuit respiration system; 2 dietary treatments; Four observations/treatment; [12]Average BW, 37.8 ± 5.73 kg; Open-circuit respiration system; 1 dietary treatment; Six observations/treatment; [13]Average BW, 41.7 ± 2.8 kg; Open-circuit mask respiration system; 3 dietary treatments; Four observations/treatment; [14]Average BW, 47.0 ± 2.5 kg; Open-circuit mask respiration system; 2 dietary treatments; Twelve observations/treatment; [15]Average BW, 43.0 ± 1.7 kg; Open-circuit head-hook respiration system; 2 dietary treatments; Ten observations/treatment; [16]Average BW, 46.1 ± 3.07 kg; Open-circuit mask respiration system; 2 dietary treatments; Ten observations/treatment; [17]Average BW, 44.5 ± 3.39 kg; Open-circuit respiration system; 2 dietary treatments; Four observations/treatment; [18]Average BW, 50.0 ± 6.6 kg; Open-circuit respiration system; 3 dietary treatments; Six observations/treatment; [19]Average BW, 44.1 ± 4.47 kg; Open-circuit head-box respiration system; 2 dietary treatments; Ten observations/treatment; [20]Average BW, 51.5 ± 1.83 kg; Open-circuit respiration system; 2 dietary treatments; Twelve observations/treatment.

3. Results

From the analysis of the information reported in Table 1, specifically from the mean Y_m value reported for each dietary treatment assayed, an average Y_m of 5.79 kJ/100 kJ GE intake [SD ± 0.43; n = 13 (diets)] was calculated and adopted for regional estimations of CH_4 emissions from sheep. The NDF fraction in the experimental diets was in the range of 34.2 to 56.5 g/100 g DM and the digestibility of GE (GED, %) ranged between 65.9 and 75.6. From published data reported in Table 2 an average Y_m value of 5.17 kJ/100 kJ GE intake [SD ± 1.38; n = 54 (diets)] was calculated and adopted for regional estimations of CH_4 emissions from goats. The NDF fraction in the experimental diets ranged widely between 21.0 and 55.4 g/100 g DM and GED between 47.5 and 79.4.

Total average ME requirements (MJ/head/day and MJ/head/year) for the different categories of sheep and goats and the corresponding estimates of the amount of enteric CH_4 individually produced (g/head/day; g/head/year) are shown in Table 3. As far as sheep production is concerned, total ME intake for maintenance, physical activity and production was calculated to be 12.0, 15.4 and 12.6 MJ/head/day, for the standard- adult ewe, adult male and growing lamb, respectively. Taking the Y_m value of 6.7 kJ/100 kJ GE intake proposed by IPCC 2019, emission factors of 9.4, 12.2 and 6.7 kg CH_4/head/year were obtained for the mature ewe, adult male and growing sheep,

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respectively (Table 3). When the alternative approach was followed, i.e., the assessment of a specific regional CH_4 to feed energy conversion rate (Y_m = 5.79 kJ/100 kJ GE intake), average CH_4 emission factors of 8.2, 10.5 and 5.8 kg CH_4/head/year were found, respectively (Table 3). With this approach, average methane emissions of 22.3 g CH_4/head/day (19.6 g CH_4/kg DM intake or 0.45 g CH_4/kg BW) were obtained for the standard adult ewe; 28.8 g CH_4/head/day (19.6 g CH_4/kg DM intake or 0.41 g CH_4/kg BW), for the standard adult male, and 21.6 g CH_4/head/day (20.0 g CH_4/kg DM intake or 0.90 g CH_4/kg BW), for the growing lamb.

Regarding goat production, total ME intakes for maintenance, physical activity and production of 14.116.8, 12.6 and 11.2 MJ/day were calculated for the standard- adult goat, adult male and growing young animals, respectively. The information provided by the studies cited in Table 2 indicates that these energy requirements were met from natural feed resources or feed mixtures containing 9.80 to 10.93 MJ ME/kg DM and ME/GE ratios of 0.54 to 0.60. The average GE content of these feeds was in the range of 18.21 - 18.31 MJ/kg DM.

When CH_4 production was estimated using the Y_m value of 5.5 kJ/100 kJ GE intake proposed by the IPCC (2019), the CH_4 emission factors estimated for the grazing goat were 8.8, 7.9 and 4.9 kg CH_4/head/year for mature female, adult male and growing young animal, respectively (Table 3). The emission factor attained 10.5 kg CH_4/head/year for female goats under a semi-intensive management system. It was due to the increased productivity promoted by the intensification of farming. The application of the average Y_m rate found from all Spanish balance trials (5.17 kJ CH_4/100 kJ GE intake) resulted in lower emission factors (8.3 - 9.9 and 7.4 kg CH_4/head/year, for the mature goat under grazing and semi-intensive management, respectively; 4.6 kg CH_4/head/year, for the growing young animal) compared with the application of IPCC recommended Y_m values. Using the local specific CH_4 conversion rate, average methane emissions of 22.7 g CH_4/head/day (16.9 g CH_4/kg DM intake or 0.35 g CH_4/kg BW) were obtained for the standard adult grazing goat; 27.0 g CH_4/head/day (16.9 g CH_4/kg DM intake or 0.42 g CH_4/kg BW), for the standard adult goat in a semi-intensive farming system; 20.3 g CH_4/head/day (18.1 g CH_4/kg DM intake or 0.33 g CH_4/kg BW), for the standard adult male, and 17.1 g CH_4/head/day (17.0 g CH_4/kg DM intake or 1.00 g CH_4/kg BW), for the growing young animal.

Taking 2019 as a reference year (MAPAMA, 2021), total enteric CH_4 emissions from the total population of small ruminants in Andalucía attain 19,552 + 8,089 = 27,641 metric tons/year (27.6 ktCH_4/year), when CH_4 emissions are estimated using the Y_m values proposed by IPCC (2019) and 16,896 + 7,603 = 24,499 metric tons/year (24.5 ktCH_4/year), when specific regional average Y_m values of 5.79 and 5.17 kJ CH_4/100 kJ GE intake are used for sheep and goats, respectively. These amounts of CH_4 emitted are equivalent to [27,641 × 28/(44/16)] = 281,436 metric tons CO_2-eq/year (281.4 ktCO_2-eq/year), for sheep ,and [24,499 × 28/(44/16)] = 249,444 metric tons CO_2-eq/year (249.4 ktCO_2-eq/year), for goats, where 28 is the global warming potential (GWP) of CH_4 respect to CO_2 and (44/16) is relative CO_2/CH_4 mol weight. In all, total small ruminants' enteric emissions attain 531 ktCO_2-eq/year in Southern Spain.

Table 3. Total ME requirements and enteric CH_4 production from the total population of autochthonous breeds of sheep and goat in Andalucía, Southern Spain.

	ME requirements		CH production		Total CH_4 emitted [approach (a)]	CH_4 production [approach (b)][1,2]		Total CH_4 emitted [approach (b)] [approach (a)][1,2]
	MJ/day	MJ/ year	g/day	kg/year	Metric tons/year[3]	g/day	kg/year	Metric tons/year[3]
Sheep								
Adult females	11.96	4,37	25.9	9.4	15,8	22.3	8.2	13,7

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Adult males	15.41	5,62	33.3	12.2	733	28.8	10.5	634
Growing animals	12.6	3,40*	25.0	6.7*	3,02	21.6	5.8*	2,61
Total, Metric tons /year					19,6			16,9
Adult females, grazing	14.1	5,14	24.1	8.8	5,66	22.7	8.3	5,32
Adult females, semiint.	16.8	6,12	28.7	10.5	1,19	27.0	9.9	1,12
Adult males	12.6	4,60	21.6	7.9	227	20.3	7.4	213
Growing animals	11.2	3,01*	18.2	4.9*	1,02	17.1	4.6*	958
Total, Metric tons /year					8,09			7,60
Total CH4 emitted from small ruminants, Metric tons /year					27,6			24,5

activity and production and feed's energy to CH_4 conversion rate (Hristov et al. 2018), the latest being a key factor in the estimation of enteric CH_4 emission.

There is a paucity of data on available feeds, production systems, DMI and CH_4 emission measurements in many regions of the Mediterranean basin, particularly of the coastal African countries, from which specific Y_m factors could be estimated. In the absence of such specific Y_m factors, the values reported in this study may be appropriate for application in regions with similar climate and edaphic conditions.

The nature and composition of the experimental diets analysed in the present study (Tables 1 and 2) ensure that dietary components are representative of those of practical use in Mediterranean lands. Additionally, the feeding levels studied are within or close to the range of values achieved under semi-extensive management systems. The IPCC 2019 Tier 2 approach estimates GEI through determination of net energy requirements for body functions, from which DMI is calculated assuming an estimated energy digestibility and efficiency of digestible energy utilization. In the present study GEI required to achieve the observed levels of production were based on data of digestibility and energy value determined in trials on sheep and goats simultaneously with enteric CH_4 emission measurements. Whenever possible, our own data on metabolizable energy requirements and corresponding energy efficiencies for maintenance, production and physical activities determined in sheep and goats (Aguilera et al. 1986, 1990 and 1991; Prieto et al. 1990; Lachica et al. 1997a,c) were used to calculate GEI required to achieve the observed levels of production within categories of sheep and goats. This approach contributes to diminish uncertainties in enteric CH_4 assessments. On the contrary, by assuming a common Y_m value, as proposed by IPCC (2019) [6.7% (SD ± 0.9) for adult sheep and of 5.5% (SD ± 1.0) for goats], irrespective to the quality of the feed available, the influence of some dietary factors on ruminal fermentation are ignored, increasing the uncertainty of estimations. The level of intake and, above all, the quality of the diet have a deep influence on the amount of CH_4 released [see Cambra-López et al. (2008) for a review]. Generally, the amount of enteric CH_4 emitted increases with the amount of feed consumed, although at a decreasing Y_m rate (Aguilera and Prieto 1991; Johnson and Johnson 1995). A negative relationship has been observed between the amount of CH_4 from the enteric fermentation and the digestibility of the diet (Johnson and Johnson 1995; Cambra-López et al. 2008). Therefore, the uncertainty of the estimations is expected to decrease whenever specific dietary factors are accounted for. After consideration of this evidence, the IPCC (2019) encourages the incorporation of regional specific information in local studies because they may aid to the evaluation of the uncertainties of the recommended factors for inventory purposes. Present estimations comply with these recommendations. Furthermore, it should be mentioned that data on energy intake to achieve the level of productivity observed in

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the geographic area of the study have been based on a specific knowledge, experimentally constructed, of the energy requirements of the native breeds, particularly respect to Murciano-granadina goat (Aguilera et al. 1990; Prieto et al. 1990; Aguilera et al. 1991; Lachica et al. 1997a; Lachica et al. 1997b; Lachica et al. 1999; Aguilera 2001). Another point of strength that may diminish the uncertainty in the estimation of the emission factors calculated in the present work is that enteric CH_4 production was obtained by assessment of the gas exchange of wethers or goats confined individually in a respiration chamber, considered to be the most robust approach (Johnson and Johnson 1995). Measurements of enteric CH_4 production made by an indirect calorimetric system based on a ventilated head-box designed for small ruminants (Fernández et al. 2012, 2015) complete the database used in the present study.

One of the two approaches adopted in the present study to estimate the amount of enteric CH_4 daily emitted per head of sheep or goat relies on the application of the common CH_4 conversion rates (Y_m) proposed by the IPCC (2019) for small ruminants (6.7±0.9 kJ/100 kJ GE intake, for sheep, and 5.5±1.0 kJ/100 kJ GE intake, for goats). Concerning sheep, the proposed value is based on the mean value of raw data compiled between 2009 and 2015 by Swainson et al. (2018) from experiments carried out in New Zealand in which a wide range of diet qualities were studied. These experiments involved accurate measurements of enteric CH_4 production in respiration chambers and of daily intake. The Y_m value proposed for goats is based on the analysis of 63 published studies from different countries and 18 goat breeds in which Y_m values or in vivo enteric CH_4 production and GE intake were reported, together with information on feed quality, digestibility, feed intake, breed, and animal type (IPCC, 2019). Most of these studies were taken from a database compiled from 42 papers which included 211 observations of enteric CH_4 emissions measured on 978 goats, collected by Patra and Lalhriatpuii (2016), and from a technical report of Lassey (2012).

For the adoption of a specific regional Y_m value, the low number of energy balance trials carried out in Spain on sheep -5 published studies (Table 1)- makes it difficult such a task and is a weakness point in present estimations. Nevertheless, an average Y_m value of 5.79 kJ/100 kJ GE intake [(SD ± 0.43; n=13 dietary treatments), involving 67 individual energy balance- and CH_4 emission measurements], has been calculated in the present study and adopted for specific regional estimations of CH_4 emissions from sheep in semiarid to arid ecosystems where meat is the main objective of the production system. As a result, estimations derived from the application of the specific regional Y_m approach resulted in significant lower CH_4 emissions (15.7%) than those calculated according to the Y_m value proposed by the IPCC (2019). Consequently, the mean Y_m value adopted by IPCC (2019) overestimates significantly CH_4 emission from rumen fermentation in the Spanish breeds of sheep in the arid lands of Southern Spain. To determine national emission factors linked to sheep production in Spain, the Spanish Emissions Inventory (SEI) Working Committee (Yáñez-Ruiz 2016) makes use of the polynomial regression equation of Cambra-López et al. (2008), based on data from Lassey et al. (1997), Judd et al. (1999), Leuning et al. (1999), Ulyatt et al. (2002a,b) and Pinares-Patiño et al. (2003), obtained in sheep grazing on New Zealand pastures, to estimate Y_m from the digestibility of the diet. From the experimental data reported in Table 1, an average GED of 68.9% can be calculated, resulting in a Y_m value of 6.43, that overestimates enteric CH_4 emissions from sheep in Andalucía by 11%. In summary, both the common Y_m value proposed by IPCC (2019) and that derived from the SEI approach overestimate specific regional enteric CH_4 emission from sheep.On the opposite, from the analysis of the data provided by the 54 Spanish trials from 20 published studies on CH_4 emission from goats, reported in Table 2, eighteen of them included in the IPCC study mentioned above (IPCC, 2019), an average Y_m value as low as 5.17 kJ CH_4/100 kJ GE intake was obtained. Nevertheless, underestimation of CH_4 emission from some Spanish trials cannot be discarded. Concerning this, in our trials with lactating goats (Aguilera et al. 1990) a conversion rate of 7.08 kJ CH_4 /100kJ GE intake, as an average value for goats in mid- and late lactation was obtained. The goats were fed individually, in two consecutive years, with diets based on mixtures of alfalfa hay and barley. These diets show an average energy density of 10.7 MJ ME/kg DM and ME/GE ratio of 0.58, somewhat higher than the values which can be calculated for pastures grazed throughout the year in semiarid

lands (García et al. 1995). In the study with castrated male goats (Prieto et al. 1990), in which the animals were fed alfalfa hay alone or added with barley grain, an average Y_m rate of 5.67 kJ CH_4/100kJ GEI was obtained.
The CH_4 emission factors calculated in the present work for mature sheep and growing lambs (8.2-10.5 and 5.8 kg CH_4/head/year, based on the specific regional Y_m rate adopted in the present study) are on average a 15.7% lower than the corresponding emission factors (9.4 -12.2 and 6.7 kg CH_4/head/year) calculated according the Y_m rate recommended by IPCC (2019). Also, present CH_4 emission factors for goats (8.3-9.9, 7.4 and 4.6 kg CH_4/head/year, in the adult female under grazing or semi-intensive farming system, mature male and growing animal, respectively), are somewhat lower (6.4%) than those derived from the application of the mean Y_m rate recommended by IPCC (2019) (8.8-10.5, 7.9 and 4.9 kg CH_4/head/year). Specific factors linked to the botanical and chemical composition, and quality of the available pastures or management systems may account for the observed differences. Also, animal genetic factors could explain, unless partially, variations in enteric CH_4 formation during the ruminal fermentation, as they may influence the composition of ruminal microflora [see Broucek (2018) for a review].
More studies are needed to derive robust emission factors for local/regional application. Present results underline that sheep and goats should be considered independently as CH_4 emitters, despite the evidence derived from direct comparisons when diets of moderately good to high quality are fed. In agreement with IPCC 2019 guidelines, research aiming at developing country-specific emission factors should be encouraged.

Acknowledgements
This research was financed in part by the Excellence Programme of Junta de Andalucía (Project P12-AGR-587).

References

Abecia, L., Toral, P.G., Martín-García, A.I., Martínez, G., Tomkins, N.W., Molina-Alcaide, E., & Newbold, C.J., (2012). Effect of bromochloromethane on methane emission, rumen fermentation pattern, milk yield, and fatty acid profile in lactating dairy goats. J. Dairy Sci. 95:2027-2036.

Aguilera, J.F. (2001). Aportaciones al conocimiento de la nutrición energética de pequeños rumiantes, con particular referencia al ganado caprino. Arch. Zootec. 50:565-596.

Aguilera, J.F., & Prieto, C. (1991). Methane production in goats given diets based on lucerne hay and barley. Arch. Anim. Nutr. 41:77-84.

Aguilera, J.F., Prieto, C., & Fonollá, J. (1990). Protein and energy metabolism of lactating Granadina goats. Br. J. Nutr. 63:165-175.

Aguilera, J.F., Molina, E., Prieto, C., & Boza, J. (1986). Estimación de las necesidades energéticas de mantenimiento en ganado ovino de raza Segureña. Arch. Zootec. 35:89-96.

Aguilera, J.F., Lara, L., Molina, E., & Prieto, C. (1991). Energy balance studies with growing Granadina goats during fasting and maintenance. Small Rumin. Res. 5:109-115.

Aguilera, J.F., & Molina-Alcaide, E. (2021). Enteric methane production in adult sheep of the Segureña breed fed diets containing alkali-treated olive cake. Small Rumin. Res. 194:106295.

Agricultural Research Council-ARC (1980). The nutrient requirements of ruminant livestock. Commonwealth Agricultural Bureaux, Slough.

Arco-Pérez, A., Ramos-Morales, E., Yáñez-Ruiz, D.R., Abecia, L., & Martín-García, A.I. (2017). Nutritive evaluation and milk quality of including of tomato or olive by-products silages with sunflower oil in the diet of dairy goats. Anim. Feed Sci. Technol. 232:57-70.

Asociación Española de Criadores de la cabra de raza Murciano-Granadina-ACRIMUR; www.acrimur.es; accessed October 2021).

Asociación Nacional de Criadores de Ovino Segureño-ANCOS; www.ancos.org; accessed October 2021).

Broucek, J. (2018). Methane abatement strategies based on genetics and dietary manipulation of ruminants: a review. Arch. Zootec. 67:448-458.

Cambra-López, M., García Rebollar, P., Estellés, F., & Torres, A. (2008). Estimación de las emisiones de los rumiantes en España: el factor de conversión de metano. Arch. Zootec. 57 (R):89-101.

Criscioni, P., López, M., Zena, V., & Carlos Fernández, C. (2015). Heat Production Partition in Sheep Fed above Maintenance from Indirect Calorimetry Data. Open J. Anim. Sci., 5:86-98.

Criscioni, P., & Fernández, C. (2016). Effect of rice bran as a replacement for oat grain in energy and nitrogen balance, methane emissions, and milk performance of Murciano-Granadina goats. J. Dairy Sci. 99:280290.

Cruz-Mira, M. (1988). Producción láctea en ovinos de raza Segureña. Periodo de amamantamiento. Comunicaciones agrarias, serie: Producción animal, no. 2.

Farrell, D.J., Leng, R.A., & Corbett, J.L. (1972). Undernutrition in grazing sheep. II. Calorimetric measurements on sheep taken from pasture. Aust. J. Agric. Res. 23:466-509.

Fundación Española para el Desarrollo de la Nutrición Animal-FEDNA (2009). In: Calsamiglia, S., Bach, A., de Blas, C., Fernández, C., & P. García-Rebollar (eds.). Recomendaciones nutricionales para rumiantes de leche. Normas FEDNA. Madrid, Spain. 89 pp.

Fundación Española para el Desarrollo de la Nutrición Animal-FEDNA (2010). In: Bach, A., Fernández, C., & M. Terre (eds.). Recomendaciones nutricionales para rumiantes de recría. Normas FEDNA. Madrid, Spain. 69 pp.

Fernández, C., Martí, J.V., Pérez-Baena, I., Palomares, J.L., Ibáñez, C., & Segarra, J.V. (2018). Effect of lemon leaves on energy and C–N balances, methane emission, and milk performance in Murciano-Granadina dairy goats. J. Anim. Sci. 96:1508-1518.

Fernández Martínez, C.J., López Luján, M.D.C., & Lachica, M. (2015). Low-cost mobile open circuit hood system for measuring gas exchange in small ruminants: from manual to automatic recording. J. Agri. Sci. 153:1302-1309.

García, M.A. (1992). Estudio de la ingestión voluntaria y de la fermentación ruminal de pastos naturales de zonas semiáridas en ganado ovino y caprino, Ph.D. Thesis, University of Granada, Spain, 196 pp.

García, M.A., Aguilera, J.F., & Molina-Alcaide, E. (1995). Voluntary intake and kinetics of degradation and passage of unsupplemented and supplemented pastures from semiarid lands in grazing goats and sheep. Livest. Prod. Sci. 44:245-255.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., & Tempio, G. (2013). Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome.

Graham, N. McC., & Searle, T.W. (1982). Energy and nitrogen utilization in body growth in young sheep from two breeds with differing capacities for wool growth. Aust. J. Agric. Res. 33:607-615.

Hristov, A.N., Kebreab, E., Niu, M., Oh, J., Arndt, C., Bannik, A., Bayat, A.R., Boland, T., Brito, A.F., Casper, D., Crompton, L.A., Dijkstra, J., Eugène, M.A., Garnsworthy, P.C., Haque, M.N., Hellwing, A.L.F., Huhtanen, P., Kreuzer, M., Kuhla, B., Lund, P., Madsen, J., Martin, C., Moate, P.J., Muetzel, S., Muñoz,

C., Peiren, N., Powell, J.M., Reynolds, C.K., Schwarm, A., Shingfield, K.J., Storlien, T.M., Weisbjerg, M.R., Yáñez-Ruiz, D.R., & Yu, Z. (2018). Symposium review: Uncertainties in enteric methane inventories, measurement techniques, and prediction models. J. Dairy Sci. 101:1-20.

Ibáñez, C., López, M.C., Criscioni, P., & Fernández, C. (2015a). Effect of replacing dietary corn with beet pulp on energy partitioning, substrate oxidation and methane production in lactating dairy goats. Anim. Prod. Sci. 55:56-63.

Ibáñez, C., Moya V.J., Arriaga H., López D.M., Merino P., & Fernández C. (2015b). Replacement of cereal with low starch fibrous by-products on nutrients utilization and methane emissions in dairy goats. Open J. Anim. Sci.5:198-209.

Intergovernmental Panel on Climate Change-IPCC (2019).2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4. Agriculture, Forestry and Other Land Use. Chapter 10. Emission from Livestock and Manure Management.

Johnson, K.A., & Johnson, D.E. (1995). Methane emission from cattle. J. Anim. Sci. 73:2483-2492.

Judd, M.J., Kellier, F.M., Ulyatt, M.J., Lassey, K.R., Tate, K.R., Shelton, D., Harvey, M.J., & Walker, C.F. (1999). Net methane emissions from grazing sheep. Glob. Change Biol.,5:647-657.

Lachica, L., Aguilera, J.F., & Prieto, C. (1997a). Energy expenditure related to the act of eating in Granadina goats given diets of different physical form. Br. J. Nutr. 77:417-426.

Lachica, M., Barroso, F.G., & Prieto, C. (1997b). Seasonal variation of locomotion and energy expenditure in goats under range grazing conditions. J. Range Manage. 50:234-238.

Lachica, L., Prieto, C., & Aguilera, J.F. (1997c). The energy costs of walking on the level and on negative and positive slopes in the Granadina goat (Capra hircus). Br. J. Nutr. 77:73-81.

Lachica, M., Somlo, R., Barroso, F.G., Boza, J., & Prieto, C. (1999). Goats locomotion energy expenditure under range grazing conditions: Seasonal variation. J. Range Manage. 52:431-435.

Lassey, K. (2012). Methane Emissions and Nitrogen Excretion Rates for New Zealand Goats. MAF Technical Paper No: 2012/13, Wellington, New Zealand: Ministry of Agriculture and Forestry.

Lassey, K.R., Ulyatt, M.J., Martin, R.J., Walker, C.F., & Shelton, I.D. (1997). Methane emission measured directly from grazing livestock in New Zealand. Atmos. Environ. 31:2905-2914.

Leuning, R., Baker, S.K., Jamie, I.M., Hsu, C.H., Klein, L., Denmead, O.T., & Griffith, D.W.T. (1999). Methane emission from free-ranging sheep: A comparison of two measurement methods. Atmos. Environ. 33:1357-1365.

López, M.C., Estellés, F., Moya, V.J., & Fernández, C. (2014). Use of dry citrus pulp or soybean hulls as a replacement for corn grain in energy and nitrogen partitioning, methane emissions, and milk performance in lactating Murciano-Granadina goats. J. Dairy Sci. 97:7821–7832.

López, M.C., & Fernández, C. (2013). Energy partitioning and substrate oxidation by Murciano-Granadina goats during mid lactation fed soy hulls and corn gluten feed blend as a replacement for corn grain. J. Dairy Sci., 96:4542–4552.

López, M.C., & Fernández, C. (2014). Energy partitioning and substrate oxidation by Guirra ewes fed soy hulls and corn gluten feed blend as a replacement for barley grain. Anim. Feed Sci. Technol. 189:11-18.

López, M.C., Ródenas, L., Piquer, O., Cerisuelo, A., Cervera, C., & Fernández, C. (2011). Determinación de producción de metano en caprinos alimentados con dietas con distintos cereales. Arch. Zootec. 60:943951.

López, M.C., Ródenas, L., Piquer, O., Martínez, E., Cerisuelo, A., Pascual, J.J., & Fernández, C. (2010). Effect of different physical form alfalfa on methane production in Murciano-Granadina dairy goats. J. Applied Anim. Res. 38:93-96.

López-Luján, M.D.C., Ródenas Martínez, L., Piquer Querol, O., Martinez-Paredes, E., Cervera Fras, M.C., & Fernández Martínez, C.J. (2010). Determination of the proportion of the ingested gross energy lost as exhaled methane by dairy goats consuming contrasting concentrate ingredients in mixed rations. Can. J. Anim. Sci. 90:585-590.

Marcos, C.N., Carro, M.D., Fernández Yepes, J.E., Haro, A., Romero-Huelva, M., & Molina-Alcaide, E. (2019). Effects of agroindustrial by-product supplementation on dairy goat milk characteristics, nutrient utilization, ruminal fermentation, and methane production. J. Dairy Sci. 103:1472-1483.

Martínez-Fernández, G., Abecia, L., Martín-García, A.I., Ramos-Morales, E., Hervás, G., Molina-Alcaide, E., & Yáñez-Ruiz, D.R. (2013). In vitro–in vivo study on the effects of plant compounds on rumen fermentation, microbial abundances and methane emissions in goats. Animal 7:1925-1934.

Martínez-Fernández, G., Abecia, L., Arco, A., Cantalapiedra-Hijar, G., Martín-García, A.I., Molina-Alcaide, E., Kindermann, M., Duval, S., & Yáñez-Ruiz, D.R. (2014a). Effects of ethyl-3-nitrooxy propionate and 3nitrooxypropanol on ruminal fermentation, microbial abundance, and methane emissions in sheep. J. Dairy Sci. 97:3790-3799.

Martínez-Fernández, G., Abecia, L., Ramos-Morales, E., Martin-García, A.I., Molina-Alcaide, E., & Yáñez-Ruiz, D.R. (2014b). Effects of propyl propane thiosulfinate on nutrient utilization, ruminal fermentation, microbial population and methane emissions in goats. Anim. Feed Sci. Technol. 191:16-25.

Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente-MAPAMA (2021). Anuario de Estadística de 2019; https://www.mapa.gob.es/es/estadistica/temas/publicaciones/anuario-de-estadistica/default.aspx; accessed October 2021.

Molina Alcaide, E., García, M.A., & Aguilera, J.F. (1997). The voluntary intake and rumen digestion by grazing goats and sheep of a low-quality pasture from a semi-arid land. Livest. Prod. Sci. 52:39-47.

Niu, M., Kebreab, E., Hristov, A.N., Oh, J., Arndt, C., Bannik, A., Bayat, A.R., Brito, A.F., Boland, T., Casper, D., Crompton, L.A., Dijkstra, J., Eugène, M.A., Garnsworthy, P.C., Haque, M.N., Hellwing, A.L.F., Huhtanen, P., Kreuzer, M., Kuhla, B., Lund, P., Madsen, J., Martin, C., McClelland, S.C., McGee, M., Moate, P.J., Muetzel, S., Muñoz, C., O'Kiely, P., Peiren, N., Reynolds, C.K., Schwarm, A., Shingfield, K.J., Storlien, T.M., Weisbjerg, M.R., Yáñez-Ruiz, D.R., & Yu, Z. (2018). Prediction of enteric methane production, yield, and intensity in dairy cattle using an intercontinental database. Glob. Change Bio. 2018:1-22.

Osuji, P.O., Gordon, J.G., & Webster, A.J.F. (1975). Energy exchanges associated with eating and rumination of sheep given grass diets of different physical form. Br. J. Nutr. 34:59-71.

Patra, A.K., & Lalhriatpuii, M. (2016). Development of statistical models for prediction of enteric methane emission from goats using nutrient composition and intake variables. Agric. Ecosyst. Environ. 215:8999.

Pinares-Patiño, C.S., Ulyatt, M.J., Lassey, K.R., Barry, T.N., & Holmes, C.W. (2003). Persistence of differences between sheep in methane emission under generous grazing conditions. J. Agr. Sci.140:227-233.

Prieto, C., Aguilera, J.F., Lara, L., & Fonollá, J. (1990). Protein and energy requirements for maintenance of indigenous Granadina goats. Br. J. Nutr. 63:155-163.

Robles, A.B. (1990). Evaluación de la oferta forrajera y capacidad sustentadora de un agrosistema semiárido del Sureste Ibérico. Ph.D. Thesis. University of Granada, Spain.

Romero-Huelva, M., Ramirez-Fenosa, M.A., Planelles-Gonzalez, R., Garcia-Casado, P., & Molina-Alcaide, E. (2017). Can by-products replace conventional ingredients in concentrate of dairy goat diet? J. Dairy Sci. 100:4500–4512.

Romero-Huelva, M., & Molina-Alcaide, E. (2012). Nutrient utilization, ruminal fermentation, microbial nitrogen flow, microbial abundances, and methane emissions in goats fed diets including tomato and cucumber waste fruits. J. Anim. Sci. 91:914-923.

Romero-Huelva, M., Ramos-Morales, E., & Molina-Alcaide, E. (2012). Nutrient utilization, ruminal fermentation, microbial abundances, and milk yield and composition in dairy goats fed diets including tomato and cucumber waste fruits. J. Dairy Sci. 95:6015–6026.

Sanz Sampelayo, M.R., Ruiz, I., Gil, F., & Boza, J. (1990). Body composition of goat kids during sucking. Voluntary feed intake. Br. J. Nutr. 64:611-617.

Swainson, N., Muetzel, S., & Clark, H. (2018). Updated predictions of enteric methane emissions from sheep suitable for use in the New Zealand national greenhouse gas inventory. Anim. Prod. Sci. 58:973–979.

Ulyatt, M.J., Lassey, K.R., Shelton, I.D., & Walker, C.F. (2002a). Methane emission from dairy cows and wether sheep fed subtropical grass dominant pastures in mid-summer in New Zealand. New Zeal. J. Agr. Res.45:227-234.

Ulyatt, M.J., Lassey, K.R., Shelton, I.D., & Walker, C.F. (2002b). Seasonal variation in methane emission from dairy cows and breeding ewes grazing ryegrass/white clover pasture in New Zealand.New Zeal. J. Agr. Res.,45:217-226.

Yáñez-Ruiz, D. R. (2016). Bases zootécnicas para el cálculo del balance alimentario de nitrógeno y de fósforo. Ministerio de Agricultura y Pesca, Alimentación y Medio ambiente-MAPAMA. Spain. 234 pp.