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Energy Conservation in a Livestock Building Combined with a Renewable Energy Heating System towards CO_2 Emission Reduction: The Case Study of a Sheep Barn in North Greece

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Abstract: Cold stress in sheep is usually overlooked, even though the animals' welfare and productivity are affected by low temperatures. The aim of this research was to find out if and to what extent the temperature inside a sheep barn could be maintained within the range of the thermoneutral zone during winter, primarily to increase feed conversion and to reduce GHG emissions. For this reason, an automation system was installed at a sheep barn in northern Greece, and heat losses from the building were calculated. The biogas potential of the sheep barn waste was examined in the laboratory via the BMP method. The results showed that the installation of an automation system together with a hypothetical biogas heating system could maintain the barn's temperature in the range of a sheep's thermoneutral zone during winter for the 94% of the scenarios examined if the total energy of the biogas was utilized, while heating energy that was instantly and continuously used succeeded in 48% of the investigated cases. The surplus of energy produced by biogas could potentially raise the water temperature that animals drink up to 2.9 °C. The absence of cold stress decreases the dry matter intake and the CH_4 produced by ruminal fermentation. Moreover, lower GHG emissions are achieved as waste is treated through anaerobic digestion, which would likely be released into the environment if left untreated.

Keywords: greenhouse gas emissions; climate control; anaerobic digestion; biogas; cold stress; sheep barn

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1. Introduction

Livestock and climate change are strongly associated. Livestock is contributing to the increase of greenhouse gas (GHG) emissions with the direct (waste) or indirect production (feed production and feed waste) of gases such as methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) [1]. According to the literature, more than 30 billion livestock contribute annually 14–16% of the total global GHG emissions [2]. Livestock production has intensified throughout the years and is expected to increase in order to meet the increasing population demands [3]. As a result, GHG emissions are also expected to rise. On the other hand, climate change affects livestock as the parameters that define the optimum growth conditions of animals, such as temperature and relative humidity, are subjected to an ongoing change in many regions globally. In addition, many sudden variations and extreme weather phenomena are more frequently observed [4]. This predicament affects the productivity of animals (milk and meat production, reproduction), as well as other factors that are connected with livestock production such as crops, land, feed quality, etc. [5].

All animals have a thermoneutral zone (TNZ), which is a range of ambient temperatures where normal metabolism offers enough heat to keep an optimum constant temperature. The temperature boundaries of the TNZ are the upper critical temperature (UCT) and the lower critical temperature (LCT). Much research has been conducted regarding the heat stress problem. However, cold stress also affects the animals' welfare. At temperatures lower than LCT, animals need to increase their metabolism to maintain normal body temperature; at higher temperatures than UCT, the animal's body temperature increases above normal because of inadequate evaporative heat loss. Animals consume feed to sustain their body temperature inside the boundaries of the TNZ [6]. Thus, the feed intake is converted to body heat instead of milk weight gain and other productivity factors. Temperatures beyond these limits increase the animal GHG emissions as the efficiency of feed conversion is decreased and their respiration is increased. Apart from the inefficient conversion of feed, when animals are below the LCT they consume larger amounts of feed [6] in order to retain their body temperature at the proper level and not to increase productivity. The control of the environmental conditions inside a livestock building is performed with the installation of automation and climate control systems [7–12]. These systems consume energy, and they are contributing to the increase in GHG emissions as they are mainly powered by electricity or fossil fuels. This multidimensional issue, enhanced by climate change, concerns all livestock, both in colder and warmer periods, according to the region and type of livestock.

Small ruminants contribute to a percentage between 7–10% of the total GHG emissions from livestock production [13]. Sheep are responsible for near half of these emissions [14,15]. As in other livestock types, ruminal fermentation and feed production are the main sources of GHG emissions from sheep [15]. Greece has a significant number of sheep farms; sheep are usually housed in simple constructions without the support of equipment for climate regulation. Most sheep barns in Greece are operating without an artificial ventilation system. The ventilation is performed via the natural movement of air through the side openings and ridge windows. The most common practice for the producers is to keep the windows open all year long. This practice tackles the heat stress problem during warmer periods. During colder periods, though, the temperature inside the sheep barn is lower than the lower critical temperature of the animals' TNZ. As a result, the animals consume more feed to retain their body temperature within their TNZ, and they face a change in their metabolic reactions [6,16], which leads to an increase in feed intake during the winter months [17–19] without leading to a weight increase [20]. As reported in the literature, an increase in feed intake leads to an increase in GHG emissions [21–23]. Actually, the relationship between dry matter intake (DMI) and GHGs emissions is directly proportional, and it was reported previously in several research works [22,24,25]. So, an efficient and environmentally friendly method that aims to retain proper conditions inside a sheep barn all year long, in combination with a reduction of sheep waste and GHG emissions, is of great importance.

Drinking water temperatures, especially in the winter months, are also an important aspect that affects animal performance. According to the literature, water should be kept in a specific temperature range (2–20 °C) in order to enhance the productivity of sheep [26–28]. It is strongly related to the animal's digestion performance, and under cold environmental conditions, heating of the drinking water may be necessary. Especially, when it is usually stored in open tanks inside non-heated storage rooms or outside the barn.

Up until now, sheep barns in Greece have operated during the winter without considering any of the above-mentioned issues (cold stress, water temperature and feed conversion rates), resulting in low productivity rates while causing an environmental burden. The aggregation of heat produced by each animal's biological functions could potentially contribute to mitigating the effect of low temperatures in the external environment on the internal climate of the sheep barn. In the case of sheep, the heat produced depends on the body weight and species [29,30]. This heat could be used to increase the temperature inside the barn during colder periods. On the other hand, waste from sheep could also be a source of heat if it was converted to biogas through anaerobic digestion and used as fuel for a heating system.

Anaerobic digestion is the microbiological process of decomposing organic matter in the absence of oxygen. Biogas is the main product of anaerobic digestion, and it primarily consists of CH_4 and CO_2. It can be used directly in specified internal combustion engines to generate electricity and heat, but it can also be used only for heat generation. It has been reported that utilization of biogas through a boiler reached an energy efficiency of 83% for heat generation [31]. The combination of retaining the heat generated by animal bodies inside the barn and utilizing the sheep waste through anaerobic digestion for biogas heat generation may be the solution for reducing GHG emissions and increasing productivity of livestock during the winter. This sustainable solution for the regulation of the microclimate conditions inside a sheep barn has never been examined extensively.

The aim of this research was to find out if and to what extent the temperature inside a sheep barn could be maintained within the range of TNZ during winter, primarily to increase feed conversion and reduce GHG emissions. Thus, a hypothesis was made that the energy needs of a sheep barn in northern Greece will be covered from the animals' body heat and the biogas produced from the utilization of the sheep waste. For this reason, an automation system was installed, and the biogas potential of the sheep waste was examined in the laboratory. Specifically, an automated system for opening and closing the window openings of the sheep barn was installed and programmed to operate based on the sheep TNZ. This system also monitored the air quality inside the barn in terms of relative humidity, CH_4, ammonia and CO_2 levels. Sheep barns' waste biogas potential was examined to calculate the heat that could be generated by directly burning the biogas and to estimate the GHG emissions of the sheep waste if it was not subjected to anaerobic digestion. The outcome of this research is important as it proposes an agricultural practice that could lead to the sustainable operation of simple structures, such as sheep barns. This practice is accompanied by low energy consumption, can be applied locally, has a relatively low cost and is simple to use. In addition, it is in line with the targets set by the EU for the mitigation of GHG emissions by all economic sectors, including agriculture [32].

2. Materials and Methods

2.1. Experimental Sheep Barn

The sheep barn was near Galatista town of the Chalkidiki regional unit in northern Greece. The exact location coordinates were 40°26′21.6″ N/23°16′16.4″E, and the elevation was 496 m [30]. An outside view of the sheep barn and a schematic view of the building, as well as the building materials and structure dimensions, are presented in Figure 1. The materials of which the building was constructed and their geometrical characteristics as well as the thermal transmittance (U value) are presented in Table 1.

For the scope of the experiment, specific parts of the barn were modified, and new equipment was installed. Hand operation for the side windows was removed, and electric motors were installed for automated operation. Also, the mechanical part of the automated electrical roof window was repaired, and a programmable logic controller (PLC) with a touch screen was installed with appropriate sensors (see Section 2.2—Automation system, data logging and sensors) for monitoring the air quality inside the sheep barn. Installation works and equipment are highlighted in photos provided as Supplementary Material (Section S5).

The Assaf sheep was the housed animal of the barn. The number of housed sheep varied from 150–250, depending on the birth replacement animal rates. The animals were growing lambs (yearlings), and their weight was about 30 kg. During the experimental period, the number of animals was 180. The type of housing is freestall.

The modifications to the barn and the installation of the automatic control system aim to enhance the microclimatic conditions inside the barn, which strongly relate to animal welfare. With the proposed operation rationale, the ventilation of the barn is improved, as it was performed only in cases where the gas concentrations or relative humidity were not at acceptable levels. In this automatic system operation, the temperature parameter was also included, which is also a crucial factor for animal welfare. Thus, ventilation was also performed, considering the optimum temperature for the sheep and reducing the heat losses, when possible, during the winter. All the parameters listed above (gas concentration, relative humidity and temperature) are microclimatic parameters that need to be maintained at an appropriate level for animal welfare. Through the implementation of the automation system, this is achieved with low energy consumption and operation costs.

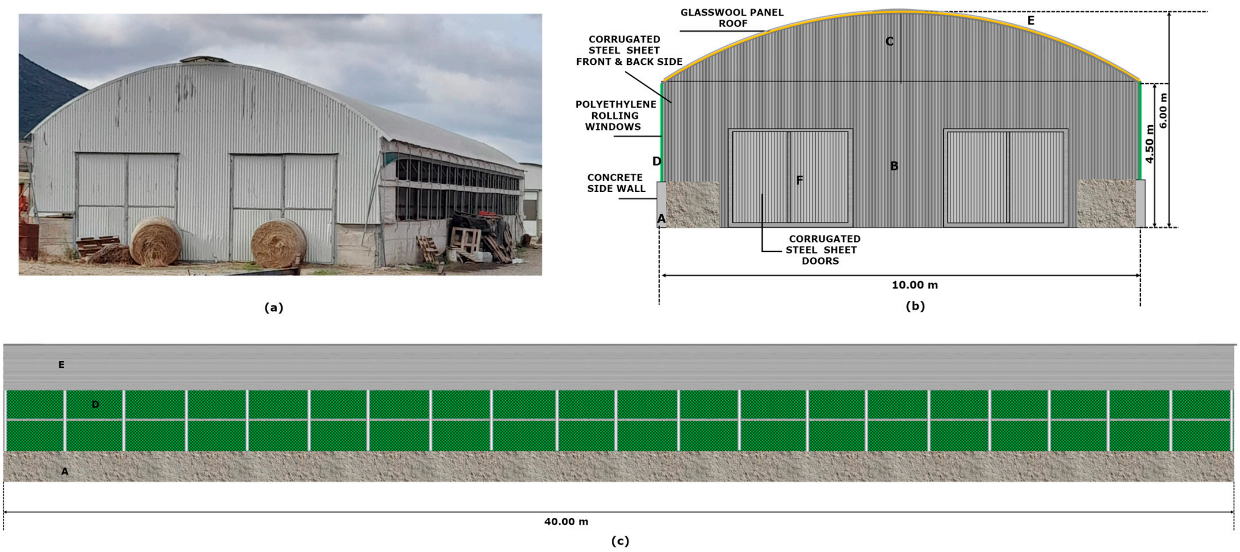


Figure 1. (**a**) Outsidze view of the sheep barn near Galatista town; schematic views with dimensions of (**b**) the front and (**c**) the side of the building.

Table 1. Sheep barn material properties, geometrical characteristics and the U value [33–38].

Symbol	Description	Material	Dimensions	U Value ($W{\cdot}m^{-2}{\cdot}K^{-1}$)	Heat Exchange Surface (m^2)
A	Side front and back side part	Concrete	Height: 1.50 m Thickness: 0.15 m Length: Lengthwise the right and left side (40 m) / 1 m in front and back side on the left and right (Figure 1)	3.89	126
B	Front and back side rectangular part	Corrugated metal sheet (steel)	Thickness: 0.01 m Rest dimensions (Figure 1)	7.26	84
C	Front and back side pediment:	Corrugated metal sheet (steel)	Thickness: 0.01 m Rest dimensions (Figure 1)	7.26	23.5
D	Side double rolling windows	PVC sheets	Height 3.00 m Thickness: 0.01 m Length: 40.00 m	4.99	240
E	Roof	Curved insulation panel (glass wool)	Thickness: 0.1 m Rest dimensions (Figure 1)	0.43	438
F	Doors	Corrugated metal sheet (steel)	Height 3.00 m Width: 3.00 m	Included in front and back sides	Included in front and back sides

2.2. Automation System, Data Logging and Sensors

An automatic operation and monitoring system was installed in the sheep barn. The system consisted of a PLC unit, electrical installations (board, cables and window motors) and sensors. Three combined temperature and relative humidity sensors (Autonics, THD-DD1-C, Mundelein-IL-USA) were used for monitoring the internal and the external environments of the sheep barn. Two of them were positioned in the sheep barn at a height of about 1.5 m from the ground, while the second was positioned close to the roof window at about 5.0 m from the ground. The third one was installed on the roof of the sheep barn to monitor the ambient outdoor temperature and relative humidity. Air quality inside the barn was monitored with a CH_4 sensor (Bacharach MGS 550 gas detector, Pittsburgh, PA, USA), a CO_2 sensor (Bacharach MGS 450 gas detector, Pittsburgh, PA, USA) and an NH_3 sensor (Bacharach MGS 450 gas detector, Pittsburgh, PA, USA), which were positioned at a height as close as possible to the sheep's height. All the above-mentioned parameters were measured and stored every 15 min by the PLC unit. All the sensors in the PLC unit were new, and they were already factory calibrated. The experimental measurements occurred from 23 January to 27 January of 2022 from 6:00 am to 16:00 pm every day. The specific period was chosen because the conditions were favorable for the scope of the experiment.

2.3. Operation of the Sheep Barn Automation System

The system was programmed to open and close the windows based on specific ranges of parameters that are presented in Table 2. The rationale behind this operation design was to keep the temperature inside the TNZ without endangering the air quality of the internal environment. The range of the upper and lower limits of the parameters were reported in previous research [6,39–41].

Table 2. Parameters range for opening and closing of windows.

Parameter	Lower Value (Windows Close)	Higher Value (Windows Open)	Priority
Average temperature (2 sensors)	8 °C	12 °C	3
Average relative humidity (2 sensors)	65%	70%	2
NH_3	5 ppm	20 ppm	1
CH_4	-	-	5
CO_2	700 ppm	2500 ppm	4

2.4. Biogas Potential

Biogas potential tests of sheep manure, wheat straw and different mixtures of them were performed in the laboratory. In total, nine substrates were examined, and they are presented in Table 3.

Table 3. Substrates for biogas potential and their attributed acronyms.

Substrates	Acronyms
Wheat Straw	WS
Sheep manure—fresh	BL—0d
Sheep manure—15 days	BL—15d
Sheep manure—30 days	BL—30d
75% SM: 25% WS—fresh	75:25 0d
75% SM: 25% WS—15 days	75:25 15d
75% SM: 25% WS—30 days	75:25 30d
60% SM: 40% WS—fresh	60:40 0d
90% SM: 10% WS—fresh	90:10 0d

The manure produced per sheep (SM) was estimated bibliographically at 0.04 $kg \cdot kg_{sheep}^{-1}$ [42], 50% of which is considered feces and 50% urine [43], while the quantity of wheat straw (WS) used in the sheep barn as bedding material was provided by the owner and was 0.2 $kg_{WS} \cdot sheep^{-1} \cdot day^{-1}$. The barn's average sheep weight was about 30 kg, which results in an estimated manure generation of 0.6 $kg \cdot sheep^{-1} \cdot d^{-1}$. From the selected mixtures for biogas potential, the mixture of 75% SM with 25% WS (*w/w*) was the ratio closest to the real conditions inside the experimental sheep barn.

Sheep manure and bedding (wheat) straw were collected at certain time periods (fresh, 15 days old and 30 days). Prior to anaerobic digestion, manure samples were homogenized, and wheat straw was cut into a length of approximately 2.5 cm. The inoculum used was obtained from previous anaerobic digestion experiments and pre-incubated at 37 ± 0.5 °C until no significant methane production was observed [44]. Blank biogas potential tests with only inoculum were performed to monitor residual biogas production. All the biogas potential tests were performed in triplicate.

Glass bottles of 0.3 L were used as batch reactors for anaerobic digestion. The batch reactors were filled with the different mixtures of substrate and inoculum, with a feed to inoculum ratio (F/I) of 1 in terms of volatile solids (VS). The final operating volume was adjusted to 0.17 L by adding deionized water, and the headspace of each batch reactor was purged with nitrogen gas (99.99% purity) for approximately 2 min to ensure anaerobic conditions before being sealed and placed into an automated thermal chamber that retained the temperature at 37 ± 0.5 °C. Once per day, the batch reactors were manually mixed vigorously. Biogas production was converted to standard temperature and pressure conditions (0 °C and 1 atm). Procedures and analysis were performed according to a proposed protocol for batch essays that has been previously established [44].

2.5. Calculations

2.5.1. Energy Conservation

Energy conservation is achieved based on the hypothesis that to retain the air temperature inside the barn and the drinking water temperature within an acceptable range, an artificial heating system should be used. Thus, with the proposed combined operation, the heat is produced by the sheep's metabolism and by a heating system that burns biogas, which is produced by the anaerobic digestion of sheep waste. Therefore, the use of artificial heating systems (commonly powered with conventional fuels) for tackling cold stress in sheep is mitigated.

The barn is handled as a closed system, so based on the 1st law of thermodynamics, if a certain temperature value needs to be retained inside the structure, a balance between the heat losses and heat gains should be achieved (Equation (1)). It should be noted that in this case the loss from ventilation is considered negligible since the windows are closed.

$$\dot{Q}_{an} + \dot{Q}_{bg} = \dot{Q}_{ch} + \dot{Q}_{inf} \quad (1)$$

$\dot{Q}_{an}$: Total heat produced by animals in the sheep barn (W)

$\dot{Q}_{bg}$: Potential heat produced by a heating system utilizing biogas (W)

$\dot{Q}_{ch}$: Heat losses by combined heat transfer mechanism (W)

$\dot{Q}_{inf}$: Heat losses by infiltration (W)

The value of $\dot{Q}_{an}$ is calculated by the number of animals and the heat produced by each animal individually. According to literature, sheep produce about 2.6 $W{\cdot}kg_{bodyweight}{}^{-1}$ [29].

The $\dot{Q}_{bg}$ will be calculated by using a typical heating system performance rate equation, based on the hypothesis that part of the energy of the produced biogas will be transformed into effective heat (Equation (2)).

$$\eta_{th} = \frac{\dot{Q}_{bg}}{\dot{Q}_{bgp}} \quad (2)$$

Biogas exploitation for the production of energy has been studied previously and it was found that it can attribute from 5.0 $kWh{\cdot}m^{-3}$ up to 7.5 $kWh{\cdot}m^{-3}$ [45]. An average value of 6.25 $kWh{\cdot}m^{-3}$ was used for the energy calculations regarding biogas utilization.

η_{th}: Performance rate of the heating system

$\dot{Q}_{bg}$: Potential heat produced by a heating system utilizing biogas (W)

$\dot{Q}_{bgp}$: Input energy of the system from the produced biogas (W)

The heat losses by combined heat transfer phenomena are calculated by Equation (3) [33].

$$\dot{Q}_{ch} = U{\cdot}A{\cdot}(\Delta T) \quad (3)$$

U: U value ($W{\cdot}m^2{\cdot}K^{-1}$)

A: Heat exchange surface (m^2)

ΔT: Temperature difference between the prevailing temperature inside the barn and the ambient outdoor temperature (°C)

The U value depends on the constructive element's thermal properties and thickness, and it was calculated or referred to according to the literature [37,39]. The heat exchange surface depends on the dimensions and shape of each constructive element. ΔT is usually taken as the temperature difference between the temperature that is required to prevail inside the structure (optimum growth within the thermoneutral zone or lower acceptable, etc.) and the average lower temperature of the region. In the current experiment, the values of the ambient outdoor temperature will be provided by the monitoring system (PLC). The temperature inside the barn was set at 10 °C based on the literature for optimum performance of sheep [6,41].

The heat losses by infiltration are calculated by Equation (4) [46].

$$\dot{Q}_{inf} = \rho \cdot c_p \cdot n \cdot \frac{V}{3600} \cdot (\Delta T) \tag{4}$$

ρ: Air density ($kg \cdot m^{-3}$)
c_p: Water specific heat ($kJ \cdot kg^{-1} \cdot K^{-1}$)
n: Air exchanges (h^{-1})
V: Air volume of the structure (m^3)
ΔT: Temperature difference between the prevailing temperature inside the barn and the ambient outdoor temperature (°C)

Based on the bibliography, the values for air density, air specific heat and air exchanges (considering the barn as an old building) were 1 $kg \cdot m^{-3}$, 1 $kJ \cdot kg^{-1} \cdot K^{-1}$ [47], and 1 h^{-1} [46], respectively. The volume of the structure was calculated to be equal to 2742 m^3, while the ΔT was calculated by Equation (3).

All the above-mentioned energy flow parameters can be converted to energy values if multiplied with time to work, with energy values expressed in kWh.

Keeping the temperature of the drinking water at proper levels also requires the consumption of energy. Heat produced from biogas will be examined to see if it could contribute to retaining the water at a proper temperature. For this reason, the 1st law of thermodynamics was used as presented in Equation (5) [47].

$$Q_w = m \cdot c_p \cdot (\Delta T_{water}) \cdot 0.00027 \tag{5}$$

Q_w: Heat required for water heating (kWh)
m: Total water mass (kg)
c_p: Water specific heat ($kJ \cdot kg^{-1} \cdot K^{-1}$)
ΔT_{water}: Water temperature difference (K)

The water mass required for a sheep weight between 27–50 kg is about 3.8–5.7 $L \cdot d^{-1}$ [48]. The average value of 4.75 $L \cdot d^{-1}$ was used. The water specific heat is 4.2 $kJ \cdot kg^{-1} \cdot K^{-1}$ [47]. The lower temperature of drinking water was chosen at 2 °C, while the highest will be calculated based on the production of biogas by anaerobic digestion.

2.5.2. Reduction of GHG Emissions

An approximate estimation was performed about the GHG emissions and their reduction in the case of utilizing organic carbon due to anaerobic processes to produce biogas for tested substrates. To calculate the $g_{VS} \cdot sheep^{-1} \cdot d^{-1}$, if stored fresh and used at 15 days and 30 days' time periods, the fresh quantity of 0.6 $kg \cdot sheep^{-1} \cdot d^{-1}$ was multiplied by the weight loss that occurred at those periods based on the total solids (TS) measurements of the samples.

The volume of biogas potential and GHG emissions were calculated, in $L_{Biogas\text{-}GHGs} \cdot sheep^{-1} \cdot d^{-1}$, using the Equation (6).

$$Volume_{Biogas-GHGs} = (V_{CH_4} + V_{CO_2}) \cdot \frac{600 \cdot (100 - WL_{t=n})}{MW_{vs=1} \cdot 100} \tag{6}$$

where:
V_{CH_4}: total methane production volume of sample (L)
V_{CO_2}: total carbon dioxide production volume of sample (L)
$WL_{t=n}$: percentage of weight loss of manure (%), where t = n refers to the collection time period of the manure sample (n = 0 days, 15 days, 30 days)

$MW_{vs=1}$: Weight of manure to obtain 1 g_{VS} for that substrate (g)

The daily production volumes of CH_4 and CO_2 (mL) were calculated using Equation (7) [44].

$$\text{Volume}_{\text{dailyGas}} = \frac{C_n - C_{n-1}}{100} \cdot V_{hs} \quad (7)$$

where:

C_n: daily gas concentration measurement (%)

C_{n-1}: previous-day gas concentration measurement (%)

V_{hs}: batch reactor headspace volume (mL)

2.6. Analytical Methods

Total solids (TS) and volatile solids (VS) of the sheep manure, wheat straw and inoculum were determined according to Standard Methods [49]. Headspace samples from the reactors were taken for biogas composition analysis (for the first 11 days daily and every few days after). They were collected with a gas-tight syringe and immediately injected in a gas chromatograph, as described by Kalamaras et al. (2020) [50]. The GC was calibrated by using a certified gas of known composition (60% methane- 40% carbon dioxide) and helium gas was used as a carrier gas. The measured values were adjusted to the volumes at standard temperature (0 °C) and pressure (1 atm). The termination of the experiment occurred when methane production was <1% of the accumulated volume of methane for three consecutive days, as established by Holliger et al. (2016) [51].

At the end of the experiment, samples were extracted from each batch reactor to prepare them for VFA analysis. Samples were centrifuged twice for 10 min at 12,000 rpm, and pH was measured. Analysis was performed (1 µL injection sample volume) in a gas chromatograph, and helium was used as a carrier gas, as described in previous research studies [52,53].

2.7. Statistical Analysis

Statistical data analysis was performed with the software IBM SPSS Statistics, version 28. Analysis included descriptive statistics and mean values, standard errors and standard deviations were calculated. Comparisons of the means were performed using one-way analysis of variance, and they were evaluated using the least-significant-difference (Tukey) test. Readings were considered significant when the p value was < 0.05.

2.8. Ethical Statement

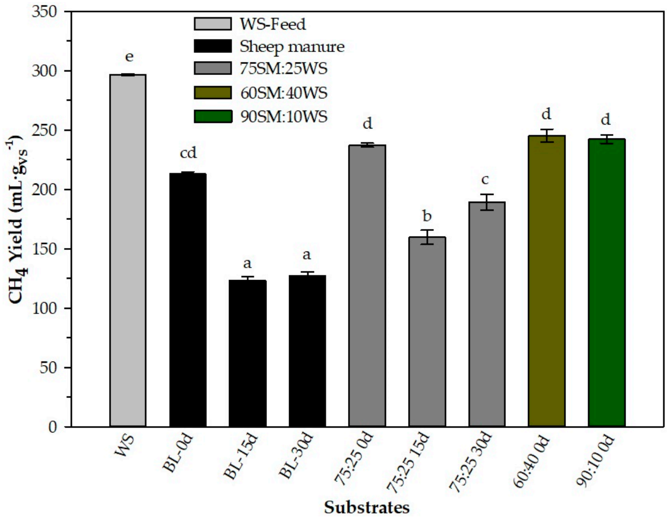
In the present study, no handling, and no harm was caused, in any case, or disruption to the behavior and well-being of the animals. Samples were collected from the livestock building's floor only after the farmer provided his consent. The study was carried out following Directives 2010/63/EU [54] and 86/609/EEC [55] regarding the protection of animals used for experimental and other scientific purposes, and activities were performed in compliance with the regulations.

3. Results

3.1. Biogas Potential of Sheep Barn Waste

Sheep manure collected at certain time periods (0 days, 15 days and 30 days), wheat straw and mixtures of them were used as substrates for anaerobic digestion and were compared regarding methane production. The results of the total methane yield and the cumulative methane production as a function of time for all substrates are presented in Figure 2.

Methane production started immediately in all the reactors. The wheat straw was used both as feed and bedding material in the study's experimental sheep barn. Its high nutritional value is clearly reflected in the results below, as it had the highest methane production. This explains the fact that all three substrates with only sheep manure had less production than their corresponding substrate, which contained 25% (weight) of wheat straw. The highest methane production of manure-based substrates was observed with fresh manure. Methane production was lower in all substrates where fresh manure was not used (15 days and 30 days manure), regardless of the addition of wheat straw. The 75:25 30d had a higher yield than the 75:25 15d. In all batch reactors, at least 80% of their total CH_4 volume was achieved by the 27th day and at least 90% by the 35th. The 75% SM: 25% WS ratio represented the real condition in the study's barn case. However, different ratios (*w/w*) of fresh sheep manure (0 days) and wheat straw (60% SM: 40% WS and 90% SM: 10% WS) were also tested to evaluate their CH_4 potential. In terms of CH_4, they did not show any significant statistical difference with the sheep barn's ratio (75% SM: 25% WS), regarding yield and production rate (Figure 2). Therefore, it can be concluded that altering the weight ratio by a step of 15% of sheep manure to wheat straw did not significantly affect the CH_4 production. The above results indicate the higher efficiency of anaerobic co-digestion regarding the CH_4 production of sheep manure and bedding straw, as well as the importance of the freshness of the manure collected.



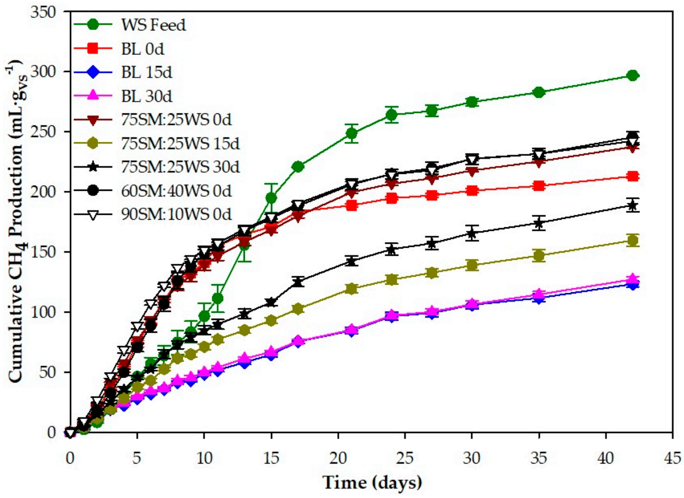
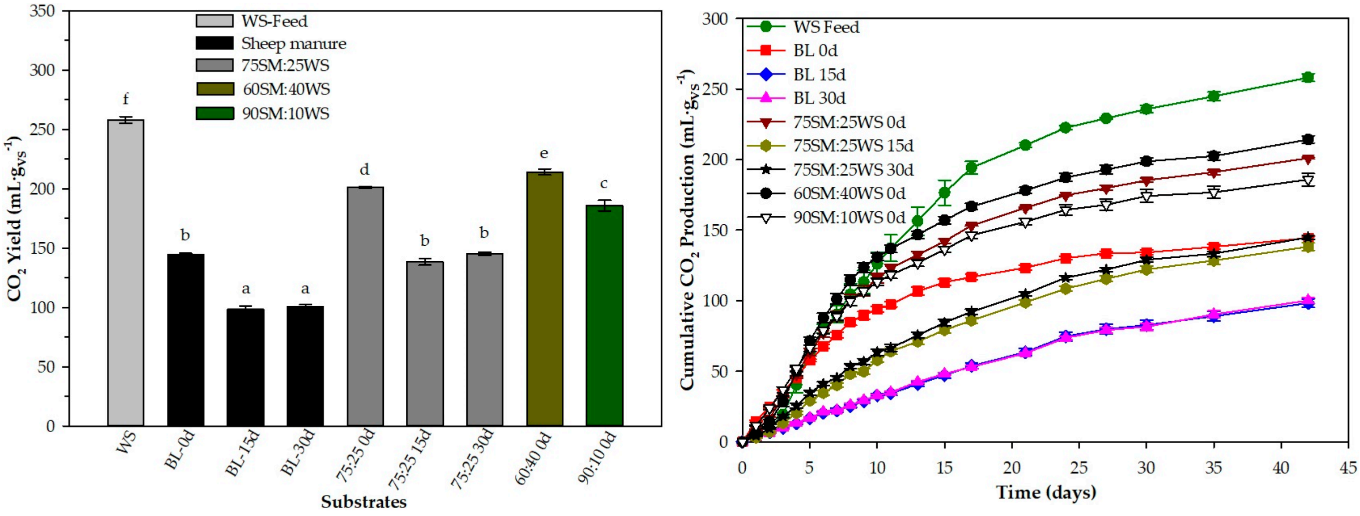


Figure 2. Methane yields (**a**) and cumulative methane productions (**b**) from the anaerobic mono- and co-digestion of each substrate. Different letters above the bars signify distinct statistical groups ($p < 0.05$) between the different tests. The bars designate the standard deviation.

CO_2 production was also measured during anaerobic mono- and co-digestion of all substrates to evaluate the organic carbon in waste that will transform over time into CO_2 emissions due to waste biological activity inside the sheep barn. The results of the CO_2 yield and cumulative production for all substrates are presented in Figure 3.

The CO_2 produced by anaerobic digestion followed, mostly shows the same trend as CH_4 productions mentioned previously. The highest CO_2 yield was produced from the wheat straw (WS-Feed) and had a significant statistical difference with the rest of the samples. In accordance with this, all three mixed substrates had a higher production in comparison with the mono-digestion of manure. Between the mixed substrates, the ratio of 60:40 0d had the highest CO_2 production. Thus, it can be concluded that by increasing the addition of wheat straw to the mixture, the CO_2 production increases accordingly. The lowest production rate and total volume were observed from BL—15d and BL—30d, which indicates that time was an important factor regarding CO_2 yield.

Total VFA concentrations were less than 0.06 $g \cdot L^{-1}$ in all the tested substrates (see Supplementary Section S2). Therefore, there was no inhibition on the biogas production, and a stable anerobic digestion process was performed. The total volume of CH_4 and CO_2 produced at the end of the experiments for all substrates is summarized below in Table 4.



(**a**) (**b**)

Figure 3. Carbon dioxide yields (**a**) and cumulative carbon dioxide productions (**b**) from the anaerobic mono- and co-digestion of each substrate. Different letters above the bars signify distinct statistical groups ($p < 0.05$) between the different tests. The bars designate the standard deviation.

Table 4. Total volume of methane and carbon dioxide production from the tested substrates.

Substrates	Total CH_4 Production, $mL \cdot g_{VS}{}^{-1}$	Total CO_2 Production, $mL \cdot g_{VS}{}^{-1}$
Wheat Straw	296.71 ± 0.86 *	258.14 ± 2.72
Sheep manure—fresh	212.95 ± 1.89	144.45 ± 0.97
Sheep manure—15 days	123.25 ± 3.11	98.25 ± 2.96
Sheep manure—30 days	127.12 ± 3.00	100.13 ± 2.02
75% SM: 25% WS—fresh	237.42 ± 1.76	201.07 ± 0.69
75% SM: 25% WS—15 days	159.65 ± 6.02	138.31 ± 2.75
75% SM: 25% WS—30 days	189.05 ± 6.84	144.90 ± 1.38
60% SM: 40% WS—fresh	245.39 ± 5.41	214.15 ± 2.58
90% SM: 10% WS—fresh	242.32 ± 3.57	185.83 ± 4.43

* Standard deviation.

3.2. GHGs Emissions Based on Anaerobic Digestion

A rough estimation of the GHG emissions was performed based on the anaerobic digestion tests. The sum of CH_4 and CO_2 production for each tested substrate represents the organic carbon that could have been released due to biological activities. Specifically, composting processes are intensified due to aerobic conditions, and CO_2 is released by aerobic microorganisms; CH_4 could also be produced when anaerobic conditions occur. The total volume of CO_2 emissions per g of VS inside the sheep barn could be equal to the sum of CO_2 and CH_4 volumes per g of VS added in the batch experiments, as each mole of CH_4 produced anaerobically could correspond to 1 mole of CO_2 produced aerobically. The GHG estimation was performed by multiplying the amount of manure (g_{VS}) produced per sheep per day with the biogas potential (Equation (6)). The GHG emissions expressed as biogas potential based on the substrates used for anaerobic digestion are presented in Table 5.

The substrate with a ratio of 60SM:40WS obtained the highest biogas potential. Nevertheless, it should be highlighted that this ratio does not represent a realistic scenario due to being impractical and economically unviable, and it was tested in terms of investigating a possible higher methane production from the sheep barn wastes. This fact applies also to the 100% wheat straw ratio, which is not presented in Table 5.

Table 5. Estimation of GHG emissions expressed as biogas potential based on the availability of organic carbon during anaerobic digestion of substrates.

Substrates	Period (d)	Biogas-GHGs (mL·g_{VS}^{-1})	Available g_{VS}·$Sheep^{-1}$·d^{-1} for Each Substrate	$L_{Biogas\text{-}GHGs}$ ·$Sheep^{-1}$·d^{-1}
Sheep manure	0	357.40 ± 2.20 *	128.21	45.82 ± 0.28
	15	221.50 ± 5.49	54.57	12.09 ± 0.30
	30	227.25 ± 4.45	52.18	11.86 ± 0.23
Sheep manure 75% + Wheat straw 25%	0	438.49 ± 1.24	300	131.55 ± 0.37
	15	297.97 ± 7.62	74.72	22.26 ± 0.57
	30	333.95 ± 6.84	72.27	24.13 ± 0.49
Sheep manure 90% + Wheat straw 10%	0	428.15 ± 6.57	185.76	79.53 ± 1.22
Sheep manure 60% + Wheat straw 40%	0	459.54 ± 6.60	472.44	217.11 ± 3.12

* Standard deviation.

3.3. Sheep Barn Energy Analysis

All the substrates presented in Table 5 were used, except for the ratio of 60% SM: 40% WS, mainly for economic viability reasons. The potential heat gained by burning the biogas for energy analysis was named $\dot{Q}_{bgX}$ (where X is the numerical order of the first seven substrates in Table 5. The automation system operated for 10 h daily without technical problems. The time durations for which the windows remained closed for each day are presented in Table 6. Temperature and relative humidity graphs of the climate inside and outside the sheep barn as well as gas measurements during the experimental period are presented in detail in the Supplementary Materials (Sections S3 and S4) .

Table 6. Time duration of closed windows during the operation of the automation system.

Day	23 January	24 January	25 January	26 January	27 January
Time (min) duration of closed windows	240	345	300	180	90
Percentage of time (%) with closed windows during operation	40%	57.5%	50%	30%	15%

The potential biogas production and the relevant energy exchanges in the barn were calculated by Equations (1)–(4) and (6), and they are presented in Table 7. Energy exchanges in the sheep barn for all of the scenarios are presented in detail in the Supplementary Materials (Section S1). Heat losses from the sheep barn and body heat generated from sheep were valued for the energy analysis only when the windows were closed during the operation period of 10 h. Two different settings for energy analysis were examined. The first setting considered all the heating energy produced from biogas by the anaerobic digestion of the substrates. So, additional equipment, such as heat or biogas storage, was utilized for the exploitation of heat energy when it was required to raise the temperature inside the barn and when the windows were closed. In the second setting, the storage equipment was not present, and the biogas was used continuously by the heating system. Biogas heat energy in this setting was calculated based on the volume of biogas produced via anaerobic digestion of substrates generated inside the barn and only when the windows were closed during the 10 h of the automated system operation. The exact hourly heat exchange for each category is illustrated in the Supplementary Materials.

Table 7. Sheep barn energy analysis for the two settings when the windows were closed during the operation of the automated system.

Day	23 January	24 January	25 January	26 January	27 January
Total energy amounts with a biogas or a heat storage (kWh)					
Heat losses ($\dot{Q}_{ch} + \dot{Q}_{inf}$)	160.4	149.5	229.3	124.5	28.8
Total body heat from sheep ($\dot{Q}_{an}$)	59.7	77.2	63.2	31.6	21.1

Table 7. *Cont.*

Day		23 January	24 January	25 January	26 January	27 January
Qbiogas ($\dot{Q}_{bg}$)	$\dot{Q}_{bg1}$	* (+) 417.5	(+) 417.5	(+) 417.5	(+) 417.5	(+) 417.5
	$\dot{Q}_{bg2}$	(+) 110.2	(+) 110.2	** (–) 110.2	(+) 110.2	(+) 110.2
	$\dot{Q}_{bg3}$	(+) 108.1	(+) 108.1	(–) 108.1	(+) 108.1	(+) 108.1
	$\dot{Q}_{bg4}$	(+) 1198.7	(+) 1198.7	(+) 1198.7	(+) 1198.7	(+) 1198.7
	$\dot{Q}_{bg5}$	(+) 202.8	(+) 202.8	(+) 202.8	(+) 202.8	(+) 202.8
	$\dot{Q}_{bg6}$	(+) 211.9	(+) 211.9	(+) 211.9	(+) 211.9	(+) 211.9
	$\dot{Q}_{bg7}$	(+) 724.7	(+) 724.7	(+) 724.7	(+) 724.7	(+) 724.7
Total energy amounts with continuous heating from biogas (kWh)						
Heat losses ($\dot{Q}_{ch} + \dot{Q}_{inf}$)		160.4	149.5	229.3	124.5	28.47
Total body heat from sheep ($\dot{Q}_{an}$)		59.7	77.2	63.2	31.6	21.1
Qbiogas ($\dot{Q}_{bg}$)	$\dot{Q}_{bg1}$	(–) 56.2	(+) 80.7	(–) 70.2	(–) 42.1	(+) 21.1
	$\dot{Q}_{bg2}$	(–) 44.1	(–) 63.4	(–) 55.1	(–) 33.1	(+) 16.5
	$\dot{Q}_{bg3}$	(–) 43.2	(–) 62.2	(–) 54.1	(–) 32.4	(+) 16.2
	$\dot{Q}_{bg4}$	(+) 479.5	(+) 689.3	(+) 599.4	(+) 359.6	(+) 179.8
	$\dot{Q}_{bg5}$	(–) 81.1	(–) 116.6	(–) 101.4	(–) 60.8	(+) 30.4
	$\dot{Q}_{bg6}$	(–) 84.8	(+) 121.8	(–) 106.0	(–) 63.6	(+) 31.8
	$\dot{Q}_{bg7}$	(+) 289.9	(+) 416.7	(+) 362.4	(+) 217.4	(+) 108.7

*: (+) when heat gain ($\dot{Q}_{an} + \dot{Q}_{bg}X$) is higher than heat losses, **: (–) when heat gain ($\dot{Q}_{an} + \dot{Q}_{bg}X$) is lower than heat losses.

3.4. Potential Energy for Heating of the Drinking Water

As shown in Table 7, in many cases, the $\dot{Q}_{bg}$ potential was greater than required to cover the sheep barn heating needs. This surplus of heating energy could be used to increase the temperature of the water according to Equation (5). In the case of using the heat surplus to raise the temperature of the water, the biogas heating system should have a hot water distribution system (not a hot air distribution system) to have the capability to direct this heat to the drinking water tank each time it is not operating to cover the heating needs of the building. In Table 8, the remaining heat for each day with the $\dot{Q}_{bg}$ scenario as well as the water temperature potential rise are presented.

Table 8. Residual heating energy used for the heating of the drinking water after being used for sheep barn heating and the corresponding rise in the drinking water temperature.

Day	23 January	24 January	25 January	26 January	27 January
Q_{w1} (kWh)	202.0	324.3	258.4	328.1	409.7
ΔT_{water1} (°C)	0.6	0.9	0.7	0.9	1.1
Q_{w2} (kWh)	0.0	32.4	0.0	0.0	102.4
ΔT_{water2} (°C)	0.0	0.1	0.0	0.0	0.3
Q_{w3} (kWh)	0.0	30.4	0.0	0.0	100.3
ΔT_{water3} (°C)	0.0	0.1	0.0	0.0	0.3
Q_{w4} (kWh)	768.4	1066.5	1039.6	1109.3	1190.9
ΔT_{water4} (°C)	2.1	3.0	2.9	3.1	3.3
Q_{w5} (kWh)	46.3	120.3	0.0	0.0	195.0
ΔT_{water5} (°C))	0.1	0.3	0.0	0.0	0.5
Q_{w6} (kWh)	52.9	129.0	0.0	0.0	204.1
ΔT_{water6} (°C)	0.1	0.4	0.0	0.0	0.6
Q_{w7} (kWh)	424.7	616.2	565.6	635.3	716.9
ΔT_{water7} (°C)	1.2	1.7	1.6	1.8	2.0

4. Discussion

Renewable energy heating systems in livestock buildings represent an efficient and environmentally friendly technology that contributes to the implementation of carbon neutral farming practices. The proposed operation for the experimental sheep barn in this work has a low initial investment and operating cost and promotes an efficient waste management approach. Previous studies have examined biogas production from animal waste and its utilization for generating electricity and heat [56–58], but not specifically for covering the heating needs of a sheep barn while achieving optimum welfare conditions for the animals.

The total methane production of all substrates varied from 296.71 $mL \cdot g^{-1}{}_{VS}$ to 123.25 $mL \cdot g^{-1}{}_{VS}$. The results showed that as the time from generation to collection of waste increased, biogas production decreased. An interesting finding was that samples collected after 30 days obtained a slightly higher production than samples collected after 15 days. A possible explanation is that lignocellulosic substances were possibly degraded by aerobic microorganisms and became more accessible for biogas production during anaerobic digestion. Moreover, the addition of nitrogen can significantly increase the degradation rate of lignin. The application of even 0.12% nitrogen could increase the degradability of lignin up to 29.8%, as studied by Vázquez et al. [59]. Thus, the presence of sheep urine inside the barn, which contains N [60], could probably have had an impact on the lignocellulosic substances. The 75 SM: 25 WS ratio that was already used by the farmer in the experimental sheep barn was lower in terms of methane production by 2.02% and 3.25% compared with the ratios of 90SM:10WS and 60SM:40WS, respectively. These ratios were investigated to obtain higher methane productions in comparison with the current practice. However, the higher methane production obtained by these substrates was not enough in comparison with the ratio already used in the sheep barn. Therefore, the best of the examined ratios for producing methane for heating purposes in the sheep barn was the farmer's current practice (75 SM: 25 WS). Similar wheat straw methane yields were reported in previous studies [61]. Regarding fresh sheep manure mono-digestion, the 212.95 $mL \cdot g_{VS}{}^{-1}$ obtained by anaerobic digestion was also comparable with previous research [62].

An estimation of the biogas potential per sheep per day was performed based on the conducted anaerobic digestion and co-digestion tests. In all cases, substrates that contained fresh sheep manure had a significantly higher biogas potential than their equivalents, containing 15 days and 30 days old samples. The current sheep barn's ratio (75 SM: 25 WS) could provide the highest potential of up to 131.55 $L_{biogas} \cdot sheep^{-1} \cdot d^{-1}$. Time seemed to have a significant effect on the reduction of biogas potential. Specifically, for the sheep manure mono-digestion, at least 73.61% of the biogas was lost when fresh manure was not used, whereas for the mixed 75 SM: 25 WS tests, at least 81.66% was observed. It could be indicated that these reductions would possibly result in lost emissions if the substrates were obtained at those later time periods. By performing the anaerobic digestion process, organic carbon can be utilized that otherwise could have been emissions, which results in GHG savings.

The installation of the automation system in combination with heat from biogas had a positive effect on the microclimate of the structure. In particular, the heat gained from the sheep contributed to a rise in the temperature inside the structure, providing an environment within the TNZ range. When the windows were closed, the trapped heat produced by the sheep was sometimes enough to fully cover the structure's heat losses. When this was not possible, heat losses ($\dot{Q}_{ch} + \dot{Q}_{inf}$) were covered in a percentage between 27–60%, 30–56%, 25–52%, 25–30% and 55–58% during 23, 24, 25, 26 and 27 January, respectively. In the morning hours, when the ambient environment temperature was sometimes below zero, the energy covered was the lower threshold of the ranges mentioned above for each day. The higher threshold occurred during hours when the ambient environment temperature was close to 10 °C.

The examined setting of the hypothetical biogas heating system that was equipped also with a biogas or heat storage system covered all of the heat losses from the sheep barn (Table 7, $\dot{Q}_{bg1}$) when fresh manure and ratios of manure and wheat straw were used. However, manure that was left in the sheep barn for the examined two periods covered most of the heating needs of the barn, except for one day. At the second setting, where the biogas heating system did not have storage equipment, only the weight ratios (%) of 75:25 and 90:10 of fresh sheep manure and wheat straw succeeded in covering the heat loss from the sheep barn.

The percentage of the losses covered by the hypothetical biogas heating system is strongly dependent on the heat distribution system. In the first setting, in 94% of the examined cases (Table 7), the heat losses were covered by the combined heat gain from the sheep's body metabolism and from the biogas heating unit. This could be done by storing the energy in a biogas or a heat-insulated buffer tank and using it only when the temperature of the barn is lower than the LCT of sheep. In the option of a heated buffer tank, the heating medium, possibly water, will help to dissipate the heat through a distribution system. Therefore, this setting has a more complex installation and a higher initial investment cost than the second setting, where no energy storage is present. In the second setting, the produced biogas was continuously burned, and the heat gain was distributed inside the barn by an air heater, and it was not possible to store the heating energy. For the second setting, the heat energy losses were fully covered at a percentage of 48%, but the investment and operation costs of this system are lower. Up until now, low temperatures in sheep barns were not systematically addressed in most cases, both in research and in real-world conditions. Some passive methods are mentioned in the literature [63,64] for preventing wind speed (natural or artificial shelter belts), which leads to low temperatures inside the barn. The main problem with non-controlled ventilation systems in sheep barns is that windows or doors remain open most of the time to avoid inadequate ventilation (high relative humidity or NH_3 concentrations). It has been found that this approach leads to an indoor temperature that is a little higher than the ambient outdoor temperature (1–2 °C) [64]. This temperature is outside of the thermoneutral zone of the sheep, with all the negative consequences that have already been mentioned. Thus, the proposed system provides an overall management of the microclimatic conditions in the barn without affecting any aspect of the animals' welfare or health compared to traditional or common practices. Some suggestions for maintaining the proper temperature for newborn sheep are also mentioned, such as the use of heating lamps [65], but this system is accompanied by energy consumption and requires careful installation to avoid possible accidents.

The heating of the drinking water could be provided by the biogas heating system (1st setting with biogas or heat storage). Installation of an insulated drinking water storage tank is crucial to delivering the surplus of energy (Table 7) and achieving the corresponding drinking water temperature. From a technical point of view, heat surplus will be driven to the water storage tank and can be easily implemented as an extension of the aforementioned heating system. The temperature rise was significant in the co-digestion of fresh manure and wheat straw mixtures of 75:25 (Q_{w4}, Table 8) and 90:10 (Q_{w7}, Table 8), where the temperature could rise, on average, for all the examined days by 2.9 °C and 1.7 °C, respectively. In the rest of the cases, the temperature rise was not significant. It should also be noticed that the use of surplus energy for water heating may contrast with the use of energy to cover heating needs inside the building at a later time, as described above. It must be decided by the producer which option is more beneficial for the sheep and where to utilize this energy amount for heating the building or for drinking water. In practice the artificial heating of water [65,66] or continuous replacement are suggested [65]. These practices result in increased energy consumption and labor costs compared to the proposed system, which utilizes a renewable energy source.

The temperature inside the barn was higher in comparison with the environment outside the sheep barn, so the sheep's dry matter intake (DMI) was reduced. This is portrayed by the Equation (8), as DMI depends on the temperature of the environment [6].

$$DMI = 111.3 - 0.52 \cdot Ti \quad (8)$$

The DMI reduction is higher when the temperature difference between indoor and ambient environment temperatures is wider. The decrease in DMI also reduces the feed intake by the sheep, which probably results in lower waste generation and, consequently, lower GHG emissions. Moreover, it leads to a further reduction of CH_4 emissions, which originate by ruminal fermentation. The reduction of CH_4 emissions ($kg_{ch4} \cdot sheep^{-1}\ d^{-1}$) based on the DMI ($kg_{feed} \cdot sheep^{-1} \cdot d^{-1}$) decrease is estimated by Equation (9) [19].

$$(CH_{4w}) = 5.6488 \cdot (DMI_w) + 0.6518 \quad (9)$$

The reduction of methane from ruminal fermentation is an added environmental benefit of the proposed operation rationale, but it could also lead to energy conservation since less energy is consumed for feed production and transportation to the sheep barn.

The extent of the internal temperature of the sheep barn that can be achieved, aiming to achieve increased feed conversion and GHG emissions reduction.

5. Conclusions

The sustainability and benefits of an automation system in a sheep barn combined with a hypothetical biogas heating system utilizing the barn's waste were examined in this work. The results indicated that this method has a positive effect on the microclimate of the livestock building and the animals' welfare by maintaining the temperature within the range of the thermoneutral zone. The proposed solution covered the heat losses of the sheep barn in 94% of the examined cases in the first setting where energy storage was used. Thus, the aim of this study was achieved, and the initial hypothesis was confirmed. When the sheep barn heat losses were fully covered by the biogas heating system, surplus heat could also be used to increase the temperature of the drinking water from 1.7 °C to 2.9 °C. The outcome of this research highlights an agricultural practice for livestock buildings that is sustainable and reduces GHG emissions. Further research may be conducted to evaluate the addition of a solar system to increase the capability and capacity of the proposed practice.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16031087/s1, Section S1: Illustration of dynamic heat exchanges in the sheep barn, Section S2: Volatile Fatty Acids graphic illustration, Section S3: Temperature and relative humidity graphs, Section S4: Internal air quality of the sheep barn, Section S5: Repairs and installation of equipment for the automation system for opening and closing side and the roof windows, as also the location of sensors for monitoring the internal air quality of the sheep barn, Section S6: U—Value calculation.

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Abbreviations

GHGs	Greenhouse gases	c_p	Water specific heat ($kJ \cdot kg^{-1} \cdot K^{-1}$)
BMP	Biomethane potential	n	Air exchanges (h^{-1})
TNZ	Thermoneutral zone	V	Air volume of the structure (m^3)
UCT	Upper Critical Temperature	Q_w	Heat required for water heating (kWh)
LCT	Lower Critical Temperature	m	Total water mass (kg)
PLC	Programmable logic controller	ΔT_{water}	Water temperature difference (K)
SM	Sheep manure	$Volume_{Biogas-GHGs}$	Volume of biogas potential—GHGs emissions
WS	Wheat straw	V_{CH_4}	Total methane production volume of sample (L)
w/w	Weight to weight	V_{CO_2}	Total carbon dioxide production volume of sample (L)
$\dot{Q}_{an}$	Total heat produced by animals in the sheep barn (W)	$WL_{t=n}$	Percentage of weight loss of manure (%), where t = n refers to the collection time period of the manure
$\dot{Q}_{bg}$	Potential heat produced by a heating system utilizing biogas (W)	$MW_{vs=1}$	Weight of manure to obtain 1 g_{VS} for that substrate (g)
$\dot{Q}_{ch}$	Heat losses by combined heat transfer mechanism (W)	$Volume_{dailyGas}$	The daily production volume of measured gas (mL)
$\dot{Q}_{inf}$	Heat losses by infiltration (W)	C_n	Daily gas concentration measurement (%)
	Performance rate of the heating system	C_{n-1}	Previous day gas concentration measurement (%)
$\dot{Q}_{bgp}$	Input energy of the system by the produced biogas (W)	V_{hs}	Batch reactor headspace volume (mL)
U	U value ($W \cdot m^2 \cdot K^{-1}$)	VS	Volatile solids
A	Heat exchange surface (m^2)	TS	Total solids
ΔT	Temperature difference of the prevailing temperature in the barn and the ambient outdoor temperature (°C)	GC	Gas chromatography
ρ	Air density ($kg \cdot m^{-3}$)	VFA	Volatile fatty acids

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