dairy

MDPI

Article

Use of Thermography on Dairy Goats Under Elevated Ambient Temperature and Udder Inflammation

Joel Bueso-Ródenas [1,*], Gema Romero [2], Alfonso Navarro [2], Elena Pérez [2], Pilar Gascó [2] and José Ramón Díaz [2]

[1] Department of Animal Production and Public Health, Faculty of Veterinary Medicine and Experimental Sciences, Catholic University of Valencia San Vicente Mártir, 46001 Valencia, Spain
[2] Departamento Tecnología Agroalimentaria, Universidad Miguel Hernández (UMH), Ctra. de Beniel km 3.2, 03312 Orihuela, Spain; gemaromero@umh.es (G.R.); alfonso.navarros@umh.es (A.N.); eperez@umh.es (E.P.); gasco_margon@gva.es (P.G.); jr.diaz@umh.es (J.R.D.)
* Correspondence: joel.bueso@ucv.es

Abstract

Infrared thermography has been proposed as a non-invasive tool for mastitis detection in dairy ruminants; however, the extent of environmental confounding and diagnostic performance in small ruminants remain poorly characterized. This study evaluated udder thermography in dairy goats through correlation analysis under winter and summer conditions, and an experimental intramammary inflammation challenge using *Staphylococcus aureus* lipoteichoic acid, with receiver operating characteristic analysis using somatic cell count >1500 $\times$ 10^3 cells/mL as the reference standard. Strong positive correlations between ambient temperature and udder surface temperatures intensified substantially from winter to summer, while surface temperatures showed weak or absent correlations with rectal temperature. Experimental inflammation induced a 12-fold increase in somatic cell count (305 vs. 3658 $\times$ 10^3 cells/mL, $p < 0.001$); however, thermographic responses remained minimal and spatially inconsistent, with area under the curve values approximating 0.5 and weak correlations between thermographic measurements and somatic cell count. Environmental temperature variation and physiological thermoregulatory adjustments substantially exceeded the minimal thermal signal generated by intramammary inflammation, limiting diagnostic utility. Infrared thermography showed poor diagnostic utility for detecting experimentally induced intramammary inflammation in dairy goats under the tested conditions.

Keywords: Murciano-Granadina goats; mastitis; thermography; somatic cell count; heat stress

Check for updates

Academic Editor: Mariangela Caroprese

Received: 31 January 2026
Revised: 25 March 2026
Accepted: 25 March 2026
Published: 26 March 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

Infrared thermography (IRT) enables non-invasive temperature monitoring through the detection of infrared radiation emitted from body surfaces [1,2]. Applications in ruminants include stress assessment, metabolic evaluation, lameness detection, and disease diagnosis [3–7]. Surface temperature reflects the balance between metabolic heat production, thermoregulatory vasomotor control, and environmental heat exchange [8,9]. Environmental factors including ambient temperature, humidity, air velocity, and solar radiation directly affect thermal gradients between an animal and its environment, modulating heat loss and potentially confounding disease detection [10–12]. Recently, Ibanez et al. [13] evaluated non-contact devices for body temperature measurement. These applications demonstrate IRT potential, though each requires specific validation.

Udder thermography for mastitis detection has shown variable results in cattle. Multiple studies have reported inconsistent sensitivity and specificity values, with environmental temperature fluctuations identified as a major confounding factor [14–18]. Hovinen et al. [19] demonstrated that experimental Escherichia coli endotoxin challenge elevated udder temperature, but clinical signs were observed before thermal changes. Polat et al. [20] reported sensitivity of 73% and specificity of 85% for subclinical mastitis detection using California Mastitis Test score correlation.

In small ruminants, thermographic mastitis research remains limited. Marnet et al. [21] found no regression or trend between log SCC and IRT measurements in 551 Alpine goats, concluding that IRT failed to detect mastitis in goats and could not be used for prophylactic purposes. Recently, Bueso-Rodenas et al. [22] reported lower udder temperatures in glands with higher SCC in Manchega sheep under monthly monitoring, suggesting that more frequent sampling may improve IRT sensitivity, although monthly intervals precluded determining the precise onset of mastitis. Castro-Costa et al. [23] examined 83 lactating dairy ewes (Manchega n = 48, Lacaune n = 35) and found no differences in udder skin temperature between healthy and infected udder halves, regardless of whether infection was subclinical or clinical, concluding that IRT was unable to discriminate between healthy and infected udders; breed differences were also observed, with Manchega ewes displaying lower temperatures, likely attributable to their hairier udders. Recent comprehensive reviews have critically examined IRT applications for mastitis assessment in dairy ruminants [24], highlighting both technological advancements and persistent operational challenges, particularly the lack of standardized procedures and optimal camera settings that currently limit widespread adoption of the technique for diagnostic purposes. Limited research exists evaluating IRT in dairy goats under controlled inflammatory conditions with systematic quantification of environmental effects. Moreover, experimental induction of mammary inflammation in dairy goats using species-specific pathogens, particularly staphylococci, has not been reported.

It was hypothesized that ambient temperature is a major source of variation in thermographic measurements and systemic temperature indicators in dairy goats, and that experimentally induced intramammary inflammation would produce detectable thermographic changes in the affected gland, enabling discrimination from non-inflamed glands. Thus, this study evaluated udder thermography in dairy goats through two investigations: (1) correlation analysis between ambient temperature, systemic temperatures, and udder thermography under winter (i) and summer conditions (ii); (2) an experimental intramammary inflammation using Lipoteichoic acid from *Staphylococcus aureus* with receiver operating characteristic analysis using somatic cell count (SCC >1500 $\times$ 10^3 cells/mL) as reference standard.

2. Materials and Methods

The Institutional Animal Care and Use Committee (IACUC) of Miguel Hernández University of Elche approved the referenced Animal Use (UMH.DTA.JDS.001.09).

2.1. Installations, Animal Handling and Experimental Design

The study was conducted at the Teaching Farm of the Polytechnic School of Orihuela, Miguel Hernández University (Orihuela, Spain). Routine farm management included once-daily milking of goats. Milking was performed in a 1 $\times$ 12 Casse-type milking parlour, which was also used for the thermographic assessments and milk sample collection. Animals were housed in free-stall facilities with indoor pens adjacent to the milking parlour. For the duration of the experimental period, access to outdoor sun-exposed areas was restricted to control thermographic confounding from solar radiant load. Water and cereal

straw were provided ad libitum. A concentrate based on cereal grains and oilseeds was supplied in controlled amounts according to species and stage of lactation

Three experimental trials were conducted: (i) analysis of global correlation patterns between thermographic temperatures, rectal temperature, and udder health parameters under winter conditions; (ii) the same analysis under summer conditions; and (iii) an experimental intramammary inflammation challenge in dairy goats to evaluate the performance of infrared thermography for detecting experimentally induced intramammary inflammation.

Animals involved in the three studies were selected from the herd based on good health status, absence of asymmetric elevation in SCC between glands, and negative bacteriological cultures at the start of each study (see Section 2.3). For the winter correlation study and inflammation challenge, all animals were Murciano-Granadina dairy goats in mid-lactation (approximately 3 months post-partum), with a mean parity of 3.6 $\pm$ 1.6 (range: 1–6), baseline SCC of 22–614 $\times$ 10^3 cells/mL, and mean daily milk production of 1178 $\pm$ 238 mL. For the summer correlation study, animals were in late lactation (approximately 8 months post-partum), with a mean parity of 3.2 $\pm$ 1.0 (range: 2–5), baseline SCC of 93–965 $\times$ 10^3 cells/mL, and mean daily milk production of 753 $\pm$ 262 mL.

For the correlation studies, a regular time-based sampling protocol was applied over two six-day periods, with observations recorded at 4 h intervals. Samplings included Infrared Thermographic Measurements (see Section 2.2) and Milk Sample Collection (see Section 2.3).

The inflammation challenge was developed with 10 animals just after the end of the first correlation study. The acute inflammatory response was monitored at regular intervals over 72 h post-inoculation. Observations were recorded at 0 (pre-inoculation baseline), and at 4 h intervals (17 timepoints total), capturing the acute phase of the experimentally induced inflammation. Experimental intramammary challenges were performed using bacterial toxins to induce acute inflammation. Goats (n = 5) received Lipoteichoic acid from *Staphylococcus aureus* (0.2 µg per mammary gland diluted in 10 mL sterile saline), obtained from Sigma-Aldrich (St. Louis, MO, USA) and reconstituted in sterile physiological saline immediately before use. The remaining five goats served as non-inoculated controls and were monitored throughout the experimental period to account for potential environmental or management-related variation in thermographic and milk parameters independent of the inflammatory challenge. Inoculations were performed via the teat canal using aseptic technique with sterile disposable cannulas, immediately after morning milking on the first day. One mammary gland was randomly selected for inoculation, while the contralateral gland served as a paired internal control.

2.2. Infrared Thermographic Measurements

Infrared thermographic images were captured using an FLIR ThermaCAM SC 660 camera (FLIR Systems, Inc., Wilsonville, OR, USA) with a thermal sensitivity (NETD) of <0.045 °C at 30 °C, a measurement accuracy of $\pm$2% or $\pm$2 °C (whichever is greater), and a spatial resolution of 640 $\times$ 480 pixels. The camera operated in the 7.5–13 µm spectral range. Emissivity was set to 0.98, appropriate for mammalian skin surfaces.

Thermographic images of the udder were obtained in the milking parlour immediately after animal restraint and before milking. The camera was positioned on a tripod at a standardized distance of 0.8 m from the udder, capturing caudal views of both mammary glands. Images were acquired under controlled lighting conditions to avoid reflective artifacts. Ambient temperature and relative humidity in the milking parlour were recorded concurrently with each thermographic session.

The udder was segmented into five circular regions of interest (AR01–AR05), arranged diagonally from the teat toward the upper portion of the gland (Figure 1). For each region,

both maximum and mean infrared temperatures were extracted. Each circle comprised approximately 3674 pixels, corresponding to roughly 12% of the total image area and approximately 75% of the selected glandular surface. Temperature values were extracted using FLIR ThermaCAM Researcher Professional software version 2.10 (FLIR Systems, Inc., Wilsonville, OR, USA) and reported as maximum (Max) and average (Avg) for each region. Additional surface temperatures were recorded at standardized anatomical landmarks: lacrimal temperature (TLac, maximum temperature of the medial canthus region) and perianal temperature (TPer, maximum temperature of the hairless perianal skin).

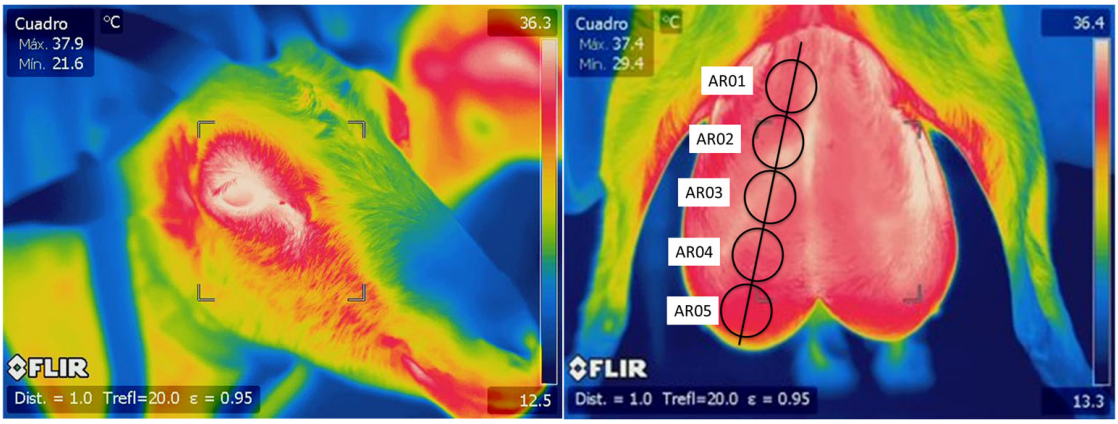


Figure 1. Thermographic images from the lacrimal area, mammary glands (AR01; AR02; AR03; AR04; AR05) and perianal area.

Core body temperature was assessed as rectal temperature (TRec), measured using a digital clinical thermometer (accuracy ±0.1 °C) inserted approximately 5 cm into the rectum and held until a stable reading was obtained.

2.3. Milk Sample Collection and Laboratory Analysis

Milk samples were collected aseptically from each mammary gland immediately following thermographic image acquisition at each timepoint. Prior to sampling, teats were cleaned with 70% ethanol and dried with sterile gauze. The first three streams of foremilk were discarded, and approximately 50 mL was collected into sterile tubes. Somatic cell count (SCC, $\times 10^3$ cells/mL) was determined using a DeLaval cell counter (DeLaval International AB, Tumba, Sweden) calibrated for caprine milk according to manufacturer specifications. Samples were analyzed within 4 h of collection. Electrical conductivity (EC; mS/cm) was measured in duplicate using a conductivity meter (Crison Instruments GLP32, Alella, Spain) calibrated at 25 °C, and the mean value was recorded. Bacteriological cultures were performed at the beginning and end of the experimental periods following the procedures described by Bueso-Ródenas et al. [22,25], and were also used to confirm the absence of pre-existing intramammary infection both before and throughout the experimental challenge period.

2.4. Environmental Monitoring

Ambient temperature and relative humidity were continuously monitored using a Testo 174H USB datalogger (Testo SE & Co., Lenzkirch, Germany) recording at 15 min intervals. The datalogger was positioned in the milking parlour at approximately 1.5 m height, shaded from direct solar radiation, with a temperature accuracy of ±0.5 °C. During the winter correlation study (i) and the inflammation challenge (iii), mean temperature in the milking parlour was 14.5 ± 1.6 °C (range: 10.0–18.0 °C) and mean relative humidity was 65.7 ± 10.8%, yielding a mean THI of 14.5 ± 1.4 (range: 10.5–17.8). During the summer

correlation study (ii), ambient temperature in the milking parlour ranged from 21.8 to 37.3 °C (mean: 29.8 ± 3.3 °C) with a mean relative humidity of 66.1 ± 13.3%, yielding a mean THI of 28.1 ± 2.4 (range: 21.5–33.0). Solar radiant load was not quantified; however, access to outdoor sun-exposed areas was denied during all experimental periods to prevent confounding effects on surface temperature measurements.

2.5. Statistical Analysis

Data were analyzed using SAS software version 9.4 (SAS Institute Inc., Cary, NC, USA). Normality of residuals was assessed using the Shapiro–Wilk test. Somatic cell count data were $\log_{10}$-transformed prior to analysis to achieve normality; for the presentation of means, back-transformation was applied.

Pearson correlation coefficients were calculated between thermographic variables (AR01–AR05, TLac, TPer and TRec), ambient temperature, and udder health parameters using PROC CORR, with separate matrices generated for winter and summer conditions. The effect of time of day on thermographic variables was assessed using the Kruskal–Wallis H test across sampling timepoints, and its association with rectal temperature was evaluated using Spearman's rank correlation to distinguish circadian from ambient temperature-driven variation.

Thermal responses to the experimental intramammary challenge were evaluated accounting for the repeated-measures structure of the data, with multiple observations per animal and gland across timepoints. Pre-inoculation baseline was defined as the mean value across all pre-challenge timepoints per animal. Between-group comparisons were conducted using the Mann–Whitney U test (PROC NPAR1WAY, WILCOXON option) and the Kruskal–Wallis H test as an omnibus test (PROC NPAR1WAY). To account for the non-independence of repeated observations within animals, a linear mixed model was fitted using PROC MIXED with animal as a random effect (random intercept), $\log_{10}$-transformed SCC as the outcome variable, and ΔTemperature as a fixed effect.

Receiver operating characteristic (ROC) curve analysis was performed using ΔTemperature as the predictor variable and SCC-based classification of experimentally induced intramammary inflammation as the outcome variable. Glands were classified as inflamed using SCC >1500 × 10^3 cells/mL, consistent with the threshold used to define unspecific intramammary inflammation in Murciano-Granadina dairy goats under identical farm and management conditions [25]. Two analytical approaches were compared: temporal (ΔT = post-inoculation AR02Max minus mean pre-inoculation AR02Max within the same gland) and anatomical (ΔT = challenged gland AR02Max minus contralateral gland AR02Max at the same timepoint). To address the clustered nature of post-challenge observations arising from multiple timepoints nested within only five challenged animals, 95% confidence intervals for AUC were estimated using cluster bootstrap resampling with the animal as the resampling unit. Discriminative performance was interpreted as excellent (≥0.9), good (0.80–0.89), acceptable (0.70–0.79), poor (0.60–0.69), or very poor/chance (<0.6). The optimal temperature threshold was identified using Youden's index (sensitivity + specificity − 1).

Diagnostic performance metrics including sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), accuracy, and false negative rate were calculated using PROC FREQ. The association between ΔTemperature and $\log_{10}$-transformed SCC was assessed using Spearman's rank correlation at the observation level and Pearson's correlation coefficient derived from the mixed model fixed-effect estimates, both using PROC CORR. Statistical significance was set at $p < 0.05$. All statistical analyses were performed using SAS software version 9.4 (SAS Institute Inc., Cary, NC, USA).

3. Results

3.1. Global Correlation Patterns Between Thermographic and Physiological Variables

Under winter conditions (Table 1), Pearson correlation analysis revealed predominantly positive associations between ambient temperature (Tamb), systemic temperatures, and udder thermographic variables. Tamb was moderately correlated with rectal temperature (TRec), lacrimal temperature (TLac), and perianal temperature (TPer), with correlation coefficients ranging from r = 0.35 to 0.59. Tamb also showed moderate correlations with both maximum and average udder surface temperatures across all anatomical regions (AR01–AR05; r = 0.39–0.61). TRec showed its strongest correlation with TPer. Time of day had a significant effect on udder surface temperatures under winter conditions (Kruskal–Wallis H = 42.89, $p < 0.001$), with minimum values recorded at 06:00 h (35.59 °C) and maximum values at 16:00 h (37.48 °C); however, time of day showed no significant correlation with rectal temperature (Spearman r = 0.135, $p = 0.111$).

Strong internal correlations were observed among udder thermographic variables. Within each anatomical region, maximum and average temperatures were very highly correlated (e.g., AR01Max–AR01Avg, r = 0.96; AR02Max–AR02Avg, r = 0.97), and high correlations were also detected between adjacent udder regions, particularly between intermediate and ventral areas (e.g., AR03Max–AR04Max, r = 0.93; AR04Max–AR05Max, r = 0.91).

Correlations with Tamb and systemic temperatures tended to increase from the most dorsal region (AR01) toward the more ventral regions (AR04–AR05), although differences among regions were moderate. Among systemic indicators, TPer showed the strongest and most consistent correlations with udder thermographic variables across all regions (r = 0.56–0.62 for ARMax and ARAvg). Correlations involving TRec were lower but remained positive and moderate (r = 0.38–0.46), while TLac showed weaker associations with udder surface temperatures (r = 0.23–0.45).

During the summer period (Table 2), correlation coefficients were consistently higher than those observed in winter. Tamb showed strong positive correlations with all udder thermographic variables across all anatomical regions (AR01–AR05; r = 0.66–0.73), as well as with TLac (r = 0.74) and TPer (r = 0.65), while the correlation with TRec was moderate (r = 0.48). TRec again showed its strongest correlation with TPer, with a markedly stronger association than in winter (r = 0.75). Maximum and average temperatures remained highly correlated within each udder region ($r \geq 0.95$), and correlations between different regions were consistently high, frequently exceeding r = 0.90 including between dorsal (AR01–AR02) and ventral areas (AR04–AR05). TLac displayed the highest correlations with udder surface temperatures across all regions (r = 0.90–0.97), followed by TPer (r = 0.75–0.83), while TRec showed moderate to strong correlations (r = 0.65–0.70), higher than those recorded in winter. Under the more extreme heat conditions of the summer period, goats experienced greater difficulty maintaining stable internal body temperatures. In a post hoc analysis, when ambient temperature reached its highest observed values (34–37 °C), mean rectal temperature was notably elevated (approximately 39.5 °C), with transient instances of individual goats exceeding 40 °C. Time of day also had a significant effect on udder surface temperatures under summer conditions (Kruskal–Wallis H = 207.46, $p < 0.001$), with minimum values at 06:00 h (38.35 °C) and maximum values at 18:00 h (39.46 °C), and a significant but weak correlation between time of day and rectal temperature was observed (Spearman r = 0.192, $p < 0.001$).

Table 1. Pearson correlation matrix between measured parameters in dairy goats (ambient temperature between 10 and 18 °C). The intensity of the color depends on the value of the correlation, being fainter close to zero. TRec: rectal temperature; TPer: perianal temperature; TLac: lacrimal temperature; AR: anatomical region; Max: maximum temperature; Avg: average temperature.

	Tamb	TRec	TLac	TPer	AR01Max	AR02Max	AR03Max	AR04Max	AR05Max	AR01Avg	AR02Avg	AR03Avg	AR04Avg	AR05Avg
Tamb	1.00	0.35	0.59	0.53	0.43	0.39	0.50	0.55	0.58	0.47	0.40	0.52	0.61	0.61
TRec	0.35	1.00	0.21	0.60	0.39	0.39	0.44	0.44	0.46	0.38	0.40	0.39	0.38	0.46
TLac	0.59	0.21	1.00	0.33	0.29	0.23	0.35	0.39	0.43	0.29	0.25	0.36	0.44	0.45
TPer	0.53	0.60	0.33	1.00	0.58	0.58	0.62	0.61	0.59	0.58	0.56	0.60	0.57	0.56
AR01Max	0.43	0.39	0.29	0.58	1.00	0.65	0.69	0.67	0.65	0.96	0.67	0.68	0.64	0.60
AR02Max	0.39	0.39	0.23	0.58	0.65	1.00	0.89	0.72	0.60	0.68	0.97	0.87	0.67	0.49
AR03Max	0.50	0.44	0.35	0.62	0.69	0.89	1.00	0.93	0.80	0.70	0.87	0.96	0.87	0.72
AR04Max	0.55	0.44	0.39	0.61	0.67	0.72	0.93	1.00	0.91	0.67	0.71	0.90	0.93	0.84
AR05Max	0.58	0.46	0.43	0.59	0.65	0.60	0.80	0.91	1.00	0.64	0.61	0.78	0.87	0.91
AR01Avg	0.47	0.38	0.29	0.58	0.96	0.68	0.70	0.67	0.64	1.00	0.69	0.70	0.65	0.61
AR02Avg	0.40	0.40	0.25	0.56	0.67	0.97	0.87	0.71	0.61	0.69	1.00	0.87	0.67	0.51
AR03Avg	0.52	0.39	0.36	0.60	0.68	0.87	0.96	0.90	0.78	0.70	0.87	1.00	0.89	0.71
AR04Avg	0.61	0.38	0.44	0.57	0.64	0.67	0.87	0.93	0.87	0.65	0.67	0.89	1.00	0.89
AR05Avg	0.61	0.46	0.45	0.56	0.60	0.49	0.72	0.84	0.91	0.61	0.51	0.71	0.89	1.00

Table 2. Pearson correlation matrix between measured parameters in dairy goats (ambient temperature between 27 and 34 °C). The intensity of the color depends on the value of the correlation, being fainter close to zero. TRec: rectal temperature; TPer: perianal temperature; TLac: lacrimal temperature; AR: anatomical region; Max: maximum temperature; Avg: average temperature.

	Tamb	TRec	TLac	TPer	AR01Max	AR02Max	AR03Max	AR04Max	AR05Max	AR01Avg	AR02Avg	AR03Avg	AR04Avg	AR05Avg
Tamb	1.00	0.48	0.74	0.65	0.66	0.68	0.71	0.72	0.72	0.68	0.70	0.73	0.73	0.72
TRec	0.48	1.00	0.69	0.75	0.67	0.67	0.68	0.70	0.70	0.65	0.66	0.67	0.67	0.67
TLac	0.74	0.69	1.00	0.82	0.90	0.93	0.96	0.97	0.94	0.90	0.93	0.95	0.96	0.92
TPer	0.65	0.75	0.82	1.00	0.75	0.78	0.82	0.83	0.81	0.74	0.79	0.80	0.81	0.77
AR01Max	0.66	0.67	0.90	0.75	1.00	0.95	0.90	0.88	0.86	0.97	0.95	0.91	0.89	0.86
AR02Max	0.68	0.67	0.93	0.78	0.95	1.00	0.95	0.91	0.87	0.92	0.98	0.95	0.90	0.85
AR03Max	0.71	0.68	0.96	0.82	0.90	0.95	1.00	0.97	0.92	0.88	0.94	0.97	0.94	0.87
AR04Max	0.72	0.70	0.97	0.83	0.88	0.91	0.97	1.00	0.96	0.86	0.91	0.94	0.96	0.91
AR05Max	0.72	0.70	0.94	0.81	0.86	0.87	0.92	0.96	1.00	0.85	0.87	0.90	0.93	0.93
AR01Avg	0.68	0.65	0.90	0.74	0.97	0.95	0.88	0.86	0.85	1.00	0.95	0.90	0.89	0.86
AR02Avg	0.70	0.66	0.93	0.79	0.95	0.98	0.94	0.91	0.87	0.95	1.00	0.96	0.91	0.86
AR03Avg	0.73	0.67	0.95	0.80	0.91	0.95	0.97	0.94	0.90	0.90	0.96	1.00	0.95	0.88
AR04Avg	0.73	0.67	0.96	0.81	0.89	0.90	0.94	0.96	0.93	0.89	0.91	0.95	1.00	0.93
AR05Avg	0.72	0.67	0.92	0.77	0.86	0.85	0.87	0.91	0.93	0.86	0.86	0.88	0.93	1.00

https://doi.org/10.3390/dairy7020027

3.2. Effect of Experimental Intramammary Inoculation on Udder Health Indicators and Thermographic Responses

Following intramammary inoculation, SCC in the inoculated glands increased markedly from pre- to post-inoculation (304.74 ± 38.42 vs. 3658.38 ± 371.28 $\times 10^3$ cells/mL; $p < 0.001$), and was also significantly higher than in the contralateral glands (298.19 ± 19.07 $\times 10^3$ cells/mL; $p < 0.001$). EC increased significantly between pre- and post-inoculation in inoculated glands ($p = 0.028$), with no significant lateral difference observed ($p = 0.134$) (Table 3).

Table 3. Changes in somatic cell count, electrical conductivity, systemic temperatures, and udder surface thermographic variables following experimental intramammary inflammation induced by Staphylococcus aureus lipoteichoic acid in dairy goats.

Variable	Inoculated Glands Pre-Inoculation	Inoculated Glands Post Inoculation	Contralateral Glands Post Inoculation	*p* Pre vs. Post	*p* Inoc vs. Cont
SCC ($\times 10^3$)	304.74 ± 38.42	3658.38 ± 371.28	298.19 ± 19.07	<0.001	<0.001
EC (mS/cm)	5.30 ± 0.07	5.50 ± 0.04	5.45 ± 0.03	0.028	0.134
TRec (°C)	38.68 ± 0.13	38.41 ± 0.05	38.41 ± 0.05	0.006	1.000
TLac (°C)	38.49 ± 0.05	38.50 ± 0.04	38.49 ± 0.04	0.901	0.838
TPer (°C)	38.47 ± 0.15	38.81 ± 0.11	38.81 ± 0.11	0.030	1.000
AR01Max (°C)	36.71 ± 0.15	36.95 ± 0.09	36.84 ± 0.12	0.149	0.790
AR02Max (°C)	36.86 ± 0.16	37.24 ± 0.09	36.75 ± 0.10	0.008	<0.001
AR03Max (°C)	37.10 ± 0.14	37.51 ± 0.09	37.11 ± 0.09	0.009	0.002
AR04Max (°C)	37.11 ± 0.16	37.42 ± 0.09	37.31 ± 0.08	0.136	0.626
AR05Max (°C)	36.90 ± 0.18	37.10 ± 0.10	37.23 ± 0.09	0.436	0.217
AR01Avg (°C)	35.63 ± 0.16	35.82 ± 0.10	35.55 ± 0.12	0.177	0.076
AR02Avg (°C)	35.75 ± 0.16	36.02 ± 0.11	35.66 ± 0.11	0.075	0.028
AR03Avg (°C)	35.95 ± 0.16	36.24 ± 0.11	36.07 ± 0.10	0.125	0.439
AR04Avg (°C)	35.93 ± 0.18	36.13 ± 0.11	35.96 ± 0.10	0.396	0.550
AR05Avg (°C)	35.61 ± 0.23	35.73 ± 0.13	35.81 ± 0.10	0.689	0.584

SCC: somatic cell count; EC: electrical conductivity; TRec: rectal temperature; TLac: lacrimal temperature; TPer: perianal temperature; AR: anatomical region; Max: maximum temperature; Avg: average temperature; inoc: inoculated gland; cont: contralateral gland.

TRec showed a significant decrease following inoculation ($p = 0.006$), TPer showed a significant increase ($p = 0.030$), and no significant change was detected in TLac ($p = 0.901$) (Table 3).

Regarding udder surface thermography, significant increases in maximum temperature were observed in specific anatomical regions of the inoculated glands. AR02Max increased significantly from pre- to post-inoculation (36.86 ± 0.16 vs. 37.24 ± 0.09 °C; $p = 0.008$) and was higher than the contralateral gland after inoculation ($p < 0.001$). A similar pattern was observed for AR03Max, which increased after inoculation (37.10 ± 0.14 vs. 37.51 ± 0.09 °C; $p = 0.009$) and differed from the contralateral gland ($p = 0.002$). No significant pre- vs. post-inoculation differences were detected for AR01Max, AR04Max, or AR05Max, nor were differences observed between inoculated and contralateral glands for these regions (Table 3).

For average udder temperatures, no statistically significant differences were observed between pre- and post-inoculation measurements in any anatomical region (AR01Avg–AR05Avg; $p > 0.05$). Comparisons between inoculated and contralateral glands revealed a significant difference for AR02Avg ($p = 0.028$), while all other regions showed no significant lateral differences (Table 3).

The temporal representation of individual SCC and AR02Max values provided additional resolution of the inflammatory response. Based on individual SCC trajectories, the intramammary challenge was successful in four out of five goats, which exhibited a

pronounced increase in SCC following inoculation. In these animals, SCC values increased rapidly after challenge, reaching peak levels within the first 24–48 h post-inoculation and remaining elevated during the acute phase, although the magnitude and timing of the response varied among individuals. One animal showed only a limited and delayed SCC response, with values remaining close to baseline throughout the observation period (Figure 2).

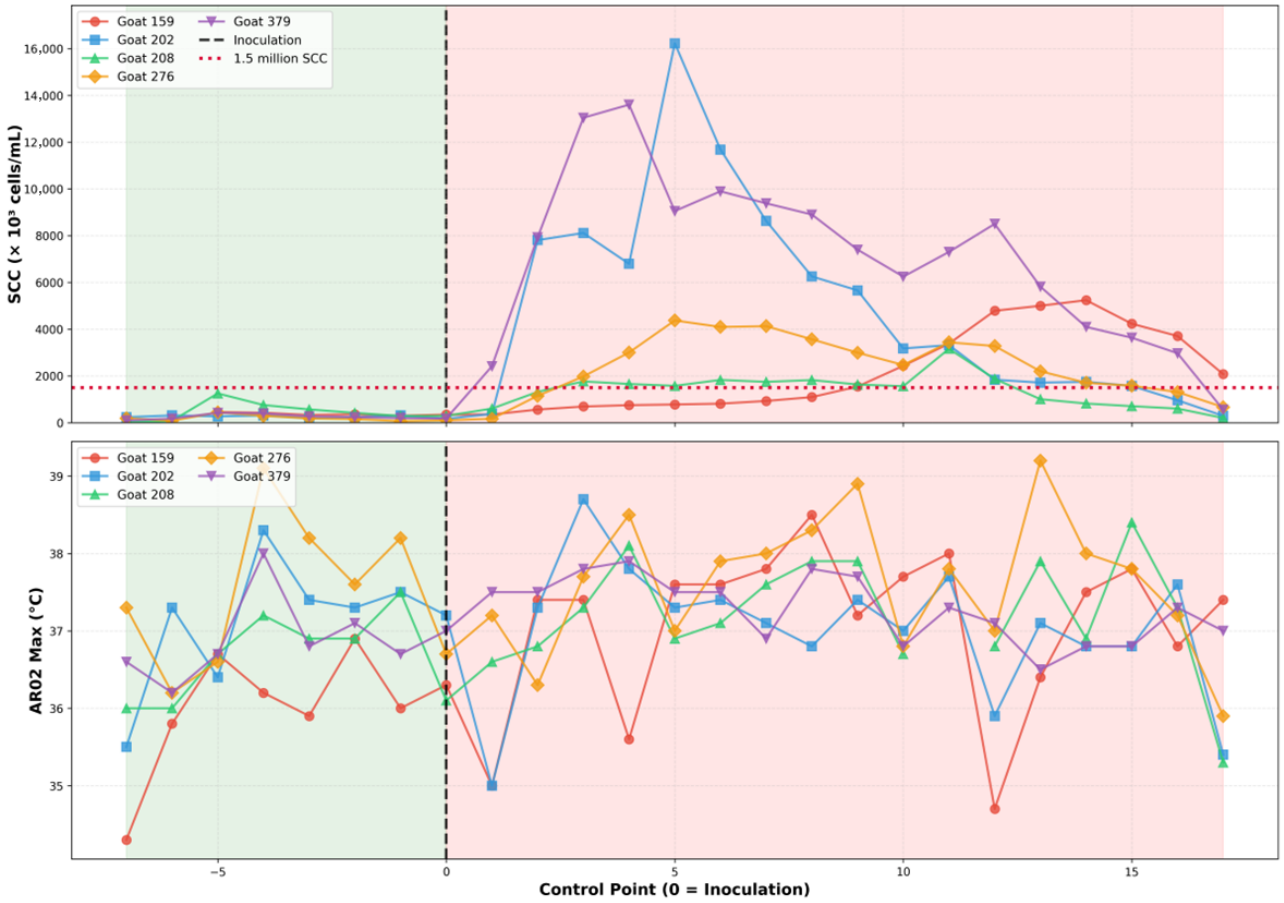


Figure 2. Individual trajectories of somatic cell count (SCC) and AR02 maximum udder surface temperature (AR02Max) relative to the time of intramammary inoculation (control point 0) in dairy goats.

At the individual level, increases in AR02Max were observed primarily in animals showing a clear SCC response, although the temporal pattern of AR02Max changes was heterogeneous. In some goats, AR02Max increased concurrently with the early rise in SCC, whereas in others, AR02Max changes were more transient or temporally displaced relative to SCC elevation. In the animal with minimal SCC response, AR02Max values remained relatively stable over time (Figure 2).

3.3. Diagnostic Performance of the Thermography

Receiver operating characteristic (ROC) analysis was performed to evaluate the diagnostic capacity of infrared thermography for detecting intramammary inflammation. AR02Max was selected as the test variable based on its significant temporal and anatomical differences observed. The reference standard was SCC >1500 × 10^3 cells/mL. Analysis included 84 post-inoculation observations from challenged glands: 61 observations exceeded the SCC threshold (inflammation present) and 23 remained below the threshold (inflammation absent). Two analytical approaches were compared: temporal (comparing post-inoculation temperature to pre-inoculation baseline within the same gland) and

anatomical (comparing challenged gland temperature to contralateral gland temperature at the same time point).

Table 4 presents the correlation between temperature changes and SCC magnitude. The temporal approach (ΔT = AR02Max post-inoculation minus AR02Max pre-inoculation) showed an observation-level Spearman correlation ρ = 0.133 (p = 0.228) and a within-animal correlation r = 0.401 ($p < 0.001$). The anatomical approach (ΔT = AR02Max challenged gland minus AR02Max contralateral gland) showed an observation-level Spearman correlation ρ = −0.003 (p = 0.977) and a within-animal correlation r = −0.200 (p = 0.068).

Table 4. Diagnostic performance of infrared thermography for detecting experimentally induced intramammary inflammation in dairy goats using temporal and spatial temperature-based approaches.

Metric	Temporal (Post-Pre)	Spatial (Inoc-Contra)
Method	ΔT within gland	ΔT between glands
Spearman ρ (observation-level)	0.133	−0.003
p-value (observation-level)	0.228	0.977
Within-animal r	0.401	−0.200
Within-animal p	<0.001	0.068
AUC	0.569	0.566
95% CI (cluster bootstrap)	0.434–0.869	0.408–0.693
Optimal threshold (°C)	−0.30	0.45
Sensitivity	90.2%	55.7%
Specificity	39.1%	65.2%
Accuracy	76.2%	58.3%
PPV	79.7%	81.0%
NPV	60.0%	35.7%
False Negative Rate	9.8%	44.3%
N observations	84	84
N animals	5	5
N inflamed glands (SCC >1500 × 10^3 cells/mL)	61	61

AUC: area under the curve; PPV: positive predictive value; NPV: negative predictive value; NS: not significant; ΔT: temperature difference; inoc: inoculated gland; contra: contralateral gland.

AUC was 0.569 for the temporal approach and 0.566 for the anatomical approach. The 95% confidence intervals, estimated using cluster bootstrap resampling with animal as the resampling unit (2000 iterations), were 0.434–0.869 for the temporal approach and 0.408–0.693 for the anatomical approach.

The temporal approach used an optimal threshold of −0.30 °C (temperature decrease). At this threshold, sensitivity was 90.2%, specificity was 39.1%, and overall accuracy was 76.2%. Positive predictive value was 79.7%, negative predictive value was 60.0%, and false negative rate was 9.8%. The anatomical approach used an optimal threshold of +0.45 °C (temperature increase in challenged gland relative to contralateral gland). At this threshold, sensitivity was 55.7%, specificity was 65.2%, and overall accuracy was 58.3%. Positive predictive value was 81.0%, negative predictive value was 35.7%, and false negative rate was 44.3%.

4. Discussion

The present study has some inherent limitations, including the relatively small number of animals in the inflammation challenge and the use of an experimental, rather than naturally occurring, inflammatory model. These factors should be considered when interpreting the results. Despite these limitations, the study successfully achieved its experimental objectives: correlation patterns between ambient temperature and thermographic variables differed substantially between winter and summer conditions, confirming the strong influence

of environmental temperature on udder surface measurements, and the experimental intramammary inflammation model induced a robust and consistent inflammatory response.

This study demonstrates strong correlations between ambient temperature and udder surface temperatures in dairy goats, consistent with previous findings in Manchega sheep where ambient temperature exhibited high positive correlations ($r = 0.72–0.80$, $p < 0.01$) with thermographic measurements across all udder regions [22]. These correlations reflect fundamental thermoregulatory mechanisms whereby peripheral vasodilation facilitates heat dissipation during warm conditions [8,26,27]. Environmental thermal load substantially influences thermographic readings [10,14,15]. The magnitude of environmental influence on surface temperature has been documented across multiple species, with ambient factors explaining up to 48% of thermographic variance in cattle [10,28] and similar patterns in small ruminants [12,13,29–31]. This environmental sensitivity represents a fundamental challenge for using thermography as a diagnostic tool in field conditions where ambient temperatures fluctuate substantially.

The intensification of correlations between ambient temperature and thermographic measurements during summer heat challenge reflects compromised thermoregulatory capacity under sustained thermal stress. Heat stress in dairy ruminants enhances peripheral blood flow to maximize heat loss [27,32–34], thereby increasing thermal coupling between environment and body surface. Small ruminants demonstrate remarkable resilience to environmental temperature variation [32–34], yet the present findings indicate that correlation coefficients increased substantially from winter to summer conditions, suggesting goats experienced greater difficulty maintaining thermal homeostasis during acute heat episodes. Major advances in understanding environmental effects on dairy cattle [35] have established that heat stress alters cardiovascular function, metabolic rate, and peripheral circulation [11,33], with similar mechanisms operative in small ruminants [32,33]. The strengthened environmental–thermographic associations during heat stress reduce the diagnostic signal-to-noise ratio for detecting localized inflammatory processes, as physiological thermoregulatory responses mask pathological thermal signals.

Regarding the utility of surface temperatures for predicting rectal temperature, the present findings demonstrate weak or absent correlations between these parameters, consistent with previous reports in multiple ruminant species [22,26]. This dissociation reflects the effectiveness of thermoregulatory vasomotor control: core temperature is tightly regulated within narrow physiological limits [8,9], whereas peripheral temperatures fluctuate widely in response to environmental conditions and local circulatory adjustments [10,12]. Consequently, surface thermography cannot reliably predict systemic temperature status, and these modalities provide fundamentally different thermal information. Recent validation studies comparing non-contact infrared devices with rectal measurements in sheep [13] have confirmed substantial discrepancies, particularly under variable ambient conditions. The circadian variation in body temperature [8] further complicates interpretation, as peripheral and core temperatures demonstrate different temporal patterns. Notably, the present findings demonstrate that the association between time of day and rectal temperature was negligible under winter conditions, suggesting that the diurnal variation observed in thermographic measurements was driven primarily by ambient temperature fluctuation rather than an independent circadian physiological effect. Under elevated ambient temperature conditions, a circadian component in rectal temperature variation cannot be excluded, further compounding the difficulty of interpreting thermographic readings as indicators of intramammary inflammation. These findings underscore that thermographic and rectal temperatures reflect distinct physiological processes and should not be considered interchangeable metrics.

The experimental intramammary inflammation model successfully induced a robust inflammatory response, as evidenced by the substantial increase in somatic cell count from baseline values of 305 × 10^3 cells/mL to 3658 × 10^3 cells/mL ($p < 0.001$), representing a 12-fold elevation comparable to acute mastitis scenarios [22,36–42]. The use of lipoteichoic acid from Staphylococcus aureus as an inflammatory stimulus elicits innate immune responses characterized by neutrophil recruitment [43,44], cytokine production [44], and local tissue reactions [23,40]. The controlled experimental approach eliminated confounding factors inherent to naturally occurring mastitis, including variable infection duration, pathogen virulence, and individual immune response heterogeneity [41–43]. Despite this standardized and quantified inflammatory stimulus, the thermographic response remained minimal, with udder surface temperatures increasing only marginally in specific regions. This dissociation between marked intramammary cellular inflammation and modest thermographic changes highlights fundamental limitations in using surface temperature to detect internal glandular processes, particularly when considering the depth of mammary tissue [22,31,45] and the insulating properties of udder structures. From a physiological perspective, this variability arises from the interplay of three main factors: the attenuation of heat transfer from deep glandular tissue through overlying fat and skin layers, the competing influence of peripheral thermoregulatory vasomotor responses that redistribute blood flow independently of local inflammation, and the limited magnitude of acute innate immune-mediated vasodilation relative to the large thermographic variance induced by ambient temperature fluctuations.

Although modest temperature elevations were detected in specific udder regions following inflammatory challenge, these changes remained highly localized and inconsistent across anatomical zones. The observation that only certain thermographic variables showed significant increases while others remained unchanged indicates substantial spatial heterogeneity in thermal response, likely reflecting variations in tissue depth, blood flow distribution, and thermal conductivity across the udder [22,31,45]. Machine milking effects on teat tissue [31,46,47] demonstrate that localized circulatory changes can produce measurable thermal responses, yet these mechanical effects may exceed pathological signals from inflammation. Critically, systemic temperature parameters (rectal, lacrimal, perianal) showed no response to the intramammary inflammatory challenge, confirming that the induced mastitis remained localized without systemic manifestations. This pattern contrasts with the systemic responses observed in natural clinical mastitis cases [22,42] where fever and behavioral changes accompany local udder inflammation. The localized thermal pattern observed in this study is consistent with findings in Manchega sheep [22], where glands with positive microbiological cultures showed significant temperature differences in only one of ten thermographic variables. Recent work in crossbred goats [48] has demonstrated that seasonal variations significantly affect thermographic mastitis detection, with thermogram analysis revealing significant temperature differences between healthy and mastitis-affected quarters across different seasons, and higher ambient temperatures during summer further complicating the interpretation of thermal patterns. The complexity of the inflammation–temperature relationship appears influenced by infection chronicity, pathogen type, tissue integrity, circulatory status [24,47–50], and environmental conditions [48].

Despite the successful induction of quantifiable mammary inflammation and the use of high-precision thermographic equipment, the present results strongly suggest that infrared thermography cannot serve as a reliable early detection tool under the conditions evaluated. Diagnostic performance was specifically evaluated using ΔTemperature derived from AR02Max, which was identified as the most responsive thermographic variable based on both temporal and anatomical analyses. Receiver operating characteristic analysis

yielded area under the curve values approximating 0.5 (chance level), with poor correlation coefficients between thermographic measurements and somatic cell count. Despite the apparently high sensitivity observed at the selected threshold, the AUC values close to 0.5 indicate that this performance is driven by threshold selection rather than true discriminative capacity. These findings align with recent reports across multiple species: Marnet et al. [21] in Alpine goats (n = 551) found no regression between log SCC and IRT ($r = -0.001$, $p = 0.992$); Castro-Costa et al. [24] were unable to discriminate between healthy and infected udders in dairy ewes despite camera accuracy of ± 0.15 °C; and multiple bovine studies [14–18,20,49] have reported inconsistent diagnostic performance with high false-positive rates. The fundamental limitation stems from the minimal thermal signal produced by even marked intramammary inflammation (12-fold SCC increase producing only modest temperature changes), which is substantially exceeded by environmental temperature variation and physiological thermoregulatory fluctuations. This paradox has been documented in Manchega sheep [22], where glands with high SCC (>400,000 cells/mL) exhibited lower temperatures than healthy glands, suggesting that chronic inflammation may reduce local blood flow and temperature rather than increasing it. The inverse relationship between inflammation severity and thermographic readings has also been observed in mastitis detection studies in sheep [45] and goats [21,48], where chronic infections with tissue damage may impair local circulation and reduce thermal signals, and seasonal environmental variations further complicate detection [48]. Although IRT has shown utility for early mastitis detection in crossbred goats throughout the year with significant temperature rises in mastitis-affected quarters [48], the present controlled experimental conditions reveal that even substantial inflammatory responses produce thermographic changes that are masked by environmental and physiological variation. This complex and sometimes inverse relationship between inflammation and thermographic readings precludes the development of reliable diagnostic thresholds for intramammary inflammation detection under the tested conditions.

The present investigation provides evidence that thermography showed limited diagnostic utility for detecting experimentally induced intramammary inflammation under the conditions evaluated. Multiple individual-level analytical strategies, environmental control, experimental standardization, and high-precision equipment all failed to achieve diagnostically useful sensitivity or specificity. The core problem is the minimal thermal signal from intramammary inflammation relative to the large thermographic variance induced by ambient temperature [10–12], thermoregulatory adjustments [8,26,27,32], circadian rhythms [8], seasonal variations [48], and individual variation [9,49]. This limitation could be inherent to the physics of infrared emission from deep tissues through overlying structures with variable insulating properties. Despite recent technological advancements and comprehensive reviews of IRT applications [24], fundamental physiological constraints persist. Future research should focus on alternative non-invasive modalities for mastitis detection in small ruminants, potentially including electrical conductivity monitoring, acoustic analysis, or integration of multiple sensor technologies [51–53]. However, somatic cell count quantification [39,53] and microbiological culture [41–43] remain the gold standards for mastitis diagnosis, offering specificity and sensitivity unattainable through surface temperature measurements. The present findings strongly support the conclusion that thermography, while valuable for assessing heat stress [32–35], animal welfare [50], and milking machine effects [31,46,47], has limited diagnostic utility for mastitis detection under the specific conditions evaluated in this study.

5. Conclusions

Correlation analysis demonstrated strong positive associations between ambient temperature and udder surface temperatures, with coefficients intensifying substantially from winter to summer conditions, confirming environmental thermal load as a critical confounding factor. Surface temperatures showed weak or absent correlations with rectal temperature across all conditions, indicating these measurements reflect fundamentally different physiological processes. Despite a robust 12-fold increase in somatic cell count following experimental intramammary inflammation with Staphylococcus aureus lipoteichoic acid (from 305×10^3 to 3658×10^3 cells/mL, $p < 0.001$), thermographic responses remained minimal and spatially inconsistent, with ROC analysis yielding AUC values approximating chance level. The dominance of environmental and physiological thermoregulatory variation over the thermal signal generated by intramammary inflammation precluded reliable diagnostic discrimination. Thermography showed poor diagnostic utility for detecting experimentally induced intramammary inflammation in dairy goats under the tested conditions, with somatic cell count quantification and microbiological culture remaining the gold standards for diagnosis.

Author Contributions: Conceptualization, J.R.D., J.B.-R. and G.R.; methodology, J.B.-R., A.N. and E.P.; software, A.N. and P.G.; validation, J.R.D., J.B.-R. and G.R.; formal analysis, E.P., A.N. and P.G.; investigation, J.B.-R. and J.R.D.; resources, J.R.D.; data curation J.B.-R.; writing—original draft preparation, J.B.-R.; writing—review and editing, J.B.-R. and J.R.D.; visualization, J.R.D. and J.B.-R.; supervision, J.R.D. and J.B.-R.; project administration, J.R.D.; funding acquisition, J.R.D. and G.R. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by research Projects AGL2006-06909 [Ministerio de Educación y Ciencia of Spain, Madrid, and Fondo Europeo de Desarrollo Regional (FEDER), European Union], and AGL2009-10695 (Ministerio de Ciencia e Innovación of Spain, Madrid).

Institutional Review Board Statement: The Institutional Animal Care and Use Committee (IACUC) of Miguel Hernández University of Elche approved the referenced Animal Use (UMH.DTA.JDS.001.09, date of approval: 15 July 2009).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Mitchell, M.A. Thermal imaging in physiology: Theoretical and practical considerations. In *Thermography: Current Status and Advances in Livestock Animals and in Veterinary Medicine*; Luzi, F., Mitchell, M.A., Nanni Costa, L., Redaelli, V., Eds.; Fondazione Iniziative Zooprofilattiche e Zootecniche: Brescia, Italy, 2013; pp. 47–65.
2. Luzi, F.; Mitchell, M.; Nanni Costa, L.; Redaelli, V. *Thermography: Current Status and Advances in Livestock Animals and in Veterinary Medicine*; Fondazione Iniziative Zooprofilattiche e Zootecniche: Brescia, Italy, 2013.
3. Teixeira, D.L.; Boyle, L.A.; Enriquez-Hidalgo, D. Skin Temperature of Slaughter Pigs with Tail Lesions. *Front. Vet. Sci.* **2020**, *7*, 198. [CrossRef] [PubMed]
4. Martins, J.N.; Silva, S.R. Use of Infrared Thermography to Assess Body Temperature as a Physiological Stress Indicator in Horses during Ridden and Lunging Sessions. *Animals* **2022**, *12*, 3255. [CrossRef] [PubMed]
5. Gelasakis, A.I.; Kalogianni, A.I.; Moschovas, M.; Tsimpouri, E.; Pnevmatikos, T.; Bossis, I.; Arsenos, G.; Simitzis, P. Evaluation of Infrared Thermography for the Detection of Footrot and White Line Disease Lesions in Dairy Sheep. *Vet. Sci.* **2021**, *8*, 219. [CrossRef] [PubMed]
6. Coe, A.; Blackie, N. Comparison of Low- and High-Cost Infrared Thermal Imaging Devices for the Detection of Lameness in Dairy Cattle. *Vet. Sci.* **2022**, *9*, 414. [CrossRef]
7. Castells, E.; Lacasta, D.; Climent, M.; Perez, M.; Sanroman, F.; Jimenez, C.; Ferrer, L.M. Diagnostic Imaging Techniques of the Respiratory Tract of Sheep. *Small Rumin. Res.* **2019**, *180*, 112–126. [CrossRef]
8. Refinetti, R. The circadian rhythm of body temperature. *Front. Biosci.* **2010**, *15*, 564–594. [CrossRef]

9. Silanikove, N. Effects of heat stress on the welfare of extensively managed domestic ruminants. *Livest. Prod. Sci.* **2000**, *67*, 1–18. [CrossRef]
10. Church, J.S.; Hegadoren, P.R.; Paetkau, M.J.; Miller, C.C.; Regev-Shoshani, G.; Schaefer, A.L.; Schwartzkopf-Genswein, K.S. Influence of environmental factors on infrared eye temperature measurements in cattle. *Res. Vet. Sci.* **2014**, *96*, 220–226. [CrossRef]
11. Kadzere, C.T.; Murphy, M.R.; Silanikove, N.; Maltz, E. Heat stress in lactating dairy cows: A review. *Livest. Prod. Sci.* **2002**, *77*, 59–91. [CrossRef]
12. McManus, C.; Tanure, C.B.; Peripolli, V.; Seixas, L.; Fischer, V.; Gabbi, A.M.; Menegassi, S.R.O.; Stumpf, M.T.; Kolling, G.J.; Dias, E.; et al. Infrared thermography in animal production: An overview. *Comput. Electron. Agric.* **2016**, *123*, 10–16. [CrossRef]
13. Ibanez, C.; Moreno-Manrique, M.; Villagra, A.; Bueso-Rodenas, J.; Minguez, C. Evaluation of non-contact device to measure body temperature in sheep. *Animals* **2024**, *14*, 98. [CrossRef] [PubMed]
14. Berry, R.J.; Kennedy, A.D.; Scott, S.L.; Kyle, B.L.; Schaefer, A.L. Daily variation in the udder surface temperature of dairy cows measured by infrared thermography: Potential for mastitis detection. *Can. J. Anim. Sci.* **2003**, *83*, 687–693. [CrossRef]
15. Colak, A.; Polat, B.; Okumus, Z.; Kaya, M.; Yanmaz, L.E.; Hayirli, A. Short communication: Early detection of mastitis using infrared thermography in dairy cows. *J. Dairy Sci.* **2008**, *91*, 4244–4248. [CrossRef] [PubMed]
16. Metzner, M.; Sauter-Louis, C.; Seemueller, A.; Petzl, W.; Zerbe, H. Infrared thermography of the udder surface of dairy cattle: Characteristics, methods, and correlation with rectal temperature. *Vet. J.* **2014**, *199*, 57–62. [CrossRef]
17. Byrne, D.T.; Berry, D.P.; Esmonde, H.; McGovern, F.; Creighton, P.; McHugh, N. Associations between infrared thermography and somatic cell count in dairy cows. *J. Dairy Sci.* **2016**, *99*, 4250–4257.
18. Zaninelli, M.; Redaelli, V.; Luzi, F.; Bronzo, V.; Mitchell, M.; Dell'Orto, V.; Bontempo, V.; Cattaneo, D.; Savoini, G. First evaluation of infrared thermography as a tool for the monitoring of udder health status in farms of dairy cows. *Sensors* **2018**, *18*, 862. [CrossRef]
19. Hovinen, M.; Siivonen, J.; Taponen, S.; Hanninen, L.; Pastell, M.; Aisla, A.M.; Pyorala, S. Detection of clinical mastitis with the help of a thermal camera. *J. Dairy Sci.* **2008**, *91*, 4592–4598. [CrossRef]
20. Polat, B.; Colak, A.; Cengiz, M.; Yanmaz, L.E.; Oral, H.; Bastan, A.; Kaya, S.; Hayirli, A. Sensitivity and specificity of infrared thermography in detection of subclinical mastitis in dairy cows. *J. Dairy Sci.* **2010**, *93*, 3525–3532. [CrossRef]
21. Marnet, P.G.; Velasquez, A.B.; Dzidic, A. Infrared thermography of teat in French dairy Alpine goats: A promising tool to study animal-machine interaction during milking but not to detect mastitis. *Animals* **2024**, *14*, 882. [CrossRef]
22. Bueso-Ródenas, J.; Moreno-Manrique, M.; Gascó, P.; Arias, R.; Romero, G.; Díaz, J.R. Evaluation of Body and Udder Temperatures and Mammary Gland Health Status Throughout Lactation in Manchega Dairy Sheep. *Animals* **2025**, *15*, 773. [CrossRef]
23. Castro-Costa, A.; Caja, G.; Salama, A.A.K.; Rovai, M.; Flores, C.; Aguilo, J. Thermographic variation of the udder of dairy ewes in early lactation and following an *Escherichia coli* endotoxin intramammary challenge in late lactation. *J. Dairy Sci.* **2014**, *97*, 1377–1387. [CrossRef] [PubMed]
24. Korelidou, V.; Simitzis, P.; Massouras, T.; Gelasakis, A.I. Infrared thermography as a diagnostic tool for the assessment of mastitis in dairy ruminants. *Animals* **2024**, *14*, 2691. [CrossRef] [PubMed]
25. Bueso-Ródenas, J.; Romero, G.; Roca, A.; Díaz, J.R. Effect of One Automatic Cluster Remover (ACR) Setting on Milking Efficiency on Murciano-Granadina Goats. *Livest. Sci.* **2014**, *161*, 193–200. [CrossRef]
26. Brown-Brandl, T.M.; Eigenberg, R.A.; Nienaber, J.A. Heat stress risk factors of feedlot heifers. *Livest. Sci.* **2006**, *105*, 57–68. [CrossRef]
27. Polsky, L.; von Keyserlingk, M.A.G. Invited review: Effects of heat stress on dairy cattle welfare. *J. Dairy Sci.* **2017**, *100*, 8645–8665. [CrossRef]
28. West, J.W. Effects of heat-stress on production in dairy cattle. *J. Dairy Sci.* **2003**, *86*, 2131–2144. [CrossRef]
29. Marai, I.F.M.; El-Darawany, A.A.; Fadiel, A.; Abdel-Hafez, M.A.M. Physiological traits as affected by heat stress in sheep—A review. *Small Rumin. Res.* **2007**, *71*, 1–12. [CrossRef]
30. Alejandro, M.; Romero, G.; Sabater, J.M.; Diaz, J.R. Infrared thermography as a tool to determine teat tissue changes caused by machine milking in Murciano-Granadina goats. *Livest. Sci.* **2014**, *160*, 178–185. [CrossRef]
31. Murgia, L.; Stelletta, C.; Caria, M.; Gianesella, M.; Gatto, M.; Pazzona, A.; Morgante, M. Using infrared thermography to monitor the effect of different milking vacuum levels on teat tissue in dairy ewes. *Ital. J. Anim. Sci.* **2008**, *7*, 125–133.
32. Joy, A.; Dunshea, F.R.; Leury, B.J.; Clarke, I.J.; DiGiacomo, K.; Chauhan, S.S. Resilience of small ruminants to climate change and increased environmental temperature: A review. *Animals* **2020**, *10*, 867. [CrossRef]
33. Bernabucci, U.; Lacetera, N.; Baumgard, L.H.; Rhoads, R.P.; Ronchi, B.; Nardone, A. Metabolic and hormonal acclimation to heat stress in domesticated ruminants. *Animal* **2010**, *4*, 1167–1183. [CrossRef] [PubMed]
34. Gaughan, J.B.; Mader, T.L.; Holt, S.M.; Lisle, A. A new heat load index for feedlot cattle. *J. Anim. Sci.* **2008**, *86*, 226–234. [CrossRef] [PubMed]
35. Collier, R.J.; Dahl, G.E.; VanBaale, M.J. Major advances associated with environmental effects on dairy cattle. *J. Dairy Sci.* **2006**, *89*, 1244–1253. [CrossRef] [PubMed]

36. Lehtolainen, T.; Suominen, S.; Kutila, T.; Pyorala, S. Effect of intramammary *Escherichia coli* endotoxin in early- vs. late-lactating dairy cows. *J. Dairy Sci.* **2003**, *86*, 2327–2333. [CrossRef]
37. Bannerman, D.D.; Paape, M.J.; Lee, J.-W.; Zhao, X.; Hope, J.C.; Rainard, P. *Escherichia coli* and *Staphylococcus aureus* elicit differential innate immune responses following intramammary infection. *Clin. Vaccine Immunol.* **2004**, *11*, 463–472. [CrossRef]
38. Rainard, P.; Riollet, C. Innate immunity of the bovine mammary gland. *Vet. Res.* **2006**, *37*, 369–400. [CrossRef]
39. Paape, M.J.; Capuco, A.V.; Contreras, A.; Marco, J.C. Milk somatic cells and lactation in small ruminants. *J. Dairy Sci.* **2001**, *84*, E237–E244. [CrossRef]
40. Wellnitz, O.; Bruckmaier, R.M. The innate immune response of the bovine mammary gland to bacterial infection. *Vet. J.* **2012**, *192*, 148–152. [CrossRef]
41. Bergonier, D.; de Cremoux, R.; Rupp, R.; Lagriffoul, G.; Berthelot, X. Mastitis of dairy small ruminants. *Vet. Res.* **2003**, *34*, 689–716. [CrossRef]
42. Contreras, A.; Sierra, D.; Sanchez, A.; Corrales, J.C.; Marco, J.C.; Paape, M.J.; Gonzalo, C. Mastitis in small ruminants. *Small Rumin. Res.* **2007**, *68*, 145–153. [CrossRef]
43. Gelasakis, A.I.; Mavrogianni, V.S.; Petridis, I.G.; Vasileiou, N.G.C.; Fthenakis, G.C. Mastitis in sheep—The last 10 years and the future of research. *Vet. Microbiol.* **2015**, *181*, 136–146. [CrossRef] [PubMed]
44. Leitner, G.; Chaffer, M.; Zamir, S.; Mor, T.; Glickman, A.; Winkler, M.; Weisblit, L.; Saran, A. Udder disease etiology, milk somatic cell counts and NAGase activity in Israeli Assaf sheep throughout lactation. *Small Rumin. Res.* **2001**, *39*, 107–112. [CrossRef] [PubMed]
45. Martins, R.F.S.; Paim, T.P.; Cardoso, C.A.; Dallago, B.S.L.; de Melo, C.B.; Louvandini, H.; McManus, C. Mastitis detection in sheep by infrared thermography. *Res. Vet. Sci.* **2013**, *94*, 722–724. [CrossRef] [PubMed]
46. Kunc, P.; Knizkova, I.; Prikryl, M.; Maloun, J. Infrared thermography as a tool to study the milking process: A review. *Agric. Trop. Subtrop.* **2007**, *40*, 29–32.
47. Tangorra, F.M.; Redaelli, V.; Luzi, F.; Zaninelli, M. The use of infrared thermography for the monitoring of udder teat stress caused by milking machines. *Animals* **2019**, *9*, 384. [CrossRef]
48. Gayathri, S.L.; Bhakat, M.; Mohanty, T.K. Seasonal assessment of mastitis in crossbred goats: A thermographic approach. *J. Therm. Biol.* **2024**, *124*, 103947. [CrossRef]
49. Pampariene, I.; Veikutis, V.; Oberauskas, V.; Zymantiene, J.; Zelvyte, R.; Stankevicius, A.; Marciulionyte, D.; Palevicius, P. Thermography based inflammation monitoring of udder state in dairy cows: Sensitivity and diagnostic priorities comparing with routine California mastitis test. *J. Vib. Eng. Technol.* **2016**, *18*, 511–521.
50. Stewart, M.; Webster, J.R.; Schaefer, A.L.; Cook, N.J.; Scott, S.L. Infrared thermography as a non-invasive tool to study animal welfare. *Anim. Welf.* **2005**, *14*, 319–325. [CrossRef]
51. Mabrook, M.F.; Petty, M.C. Effect of composition on the electrical conductance of milk. *J. Food Eng.* **2003**, *60*, 321–325. [CrossRef]
52. Norberg, E.; Hogeveen, H.; Korsgaard, I.R.; Friggens, N.C.; Lovendahl, P.; Sloth, K.H.M.N. Electrical conductivity of milk: Ability to predict mastitis status. *J. Dairy Sci.* **2004**, *87*, 1099–1107. [CrossRef]
53. McDougall, S.; Murdough, P.; Pankey, W.; Delaney, C.; Barlow, J.; Scruton, D. Relationships among somatic cell count, California mastitis test, impedance and bacteriological status of milk in goats and sheep in early lactation. *Small Rumin. Res.* **2001**, *40*, 245–254. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.