




Exploring the role of animal welfare in cow performance and farm profitability in Italian dairy herds

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ARTICLE INFO

Keywords:

ClassyFarm
Milk composition
Milk quality
Milk price
Holstein
Simmental
Daily profit

ABSTRACT

Good welfare supports dairy herd health, enhances milk production and quality, and offers financial incentives for farmers committed to animal welfare. In Italy, the ClassyFarm system assesses dairy herd welfare through the evaluation of farm biosecurity, management, structures, and animal-based measures. Dairy farms with loose housing systems (LHS) and tied housing systems (THS) are evaluated using distinct ClassyFarm checklists, and an algorithm generates an overall welfare score ranging from 0% (poor welfare) to 100% (excellent welfare). Analysing 434 farms of Holstein and Simmental cows in north-eastern Italy, we explored whether housing systems (LHS and THS) and breed composition (single- vs. multi-breed herds) influence welfare scores as assessed by ClassyFarm. Additionally, we investigated whether milk quality and production differ in cows exposed to different welfare levels, considering 4 subsets: Holstein in LHS, Holstein in THS, Simmental in LHS, and Simmental in THS. Holstein single-breed herds achieved higher management ($82.10 \pm 1.78\%$) and biosecurity scores ($58.50 \pm 2.44\%$). Simmental single-breed herds scored highest in animal-based measures ($87.90 \pm 1.61\%$), while multi-breed herds generally obtained lower scores than single-breed farms. Herds with higher management and biosecurity scores were associated with greater milk yield, milk quality, and economic returns, indicating that farmers who prioritize high welfare standards for their dairy herds may improve overall farm profitability. Our findings confirm the direct importance of investing resources in dairy cows' welfare.

1. Introduction

Dairy cow welfare has attracted public attention for many years (Buller et al., 2018), but due to evolving knowledge and legislation, there is still a long way to go before establishing a single, harmonized protocol for its measurement (Mellor et al., 2020).

Specific European legislation sets uniform minimum standards for calves (Council Directive 2008/119/EC; EFSA, 2023a), while general regulations outlined in Council Directive 98/58/EC (concerning the protection of farmed animals) are applied to dairy cattle (Council Directive 98/58/EC). As a result, there are significant differences among European countries regarding housing, care, and management, which can potentially impair cows' welfare status (Sandøe et al., 2023). In 2020, the European Commission planned to revise animal welfare legislation in the framework of the Farm to Fork strategy to align with

recent scientific findings, supported by the European Food Safety Authority (EFSA, 2023b).

In Italy, the Ministry of Health, through the Istituto Zooprofilattico Sperimentale della Lombardia e dell'Emilia Romagna (IZSLER, Brescia, Italy), has relied on the expertise of the National Reference Centre for Animal Welfare (CRENBA, Brescia, Italy) to develop and provide farmers and veterinarians with a national evaluation system for animal welfare, integrated into the ClassyFarm national information technology (IT) platform (Bertocchi et al., 2018; Tomassone et al., 2024). ClassyFarm is intended to calculate for each farm at each inspection an aggregate herd welfare score and is available for different species and animal categories, including dairy cows. The ClassyFarm system for dairy cow welfare assessment is based on checklists made up of both resource-based measures and animal-based measures (ABMs) (Ventura et al., 2021). The checklists contain 5 distinct pools of questions, conventionally

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labelled as “areas”, which cover key farm characteristics related to welfare, namely management, structures, ABMs, biosecurity, and major hazards. To take into account the differences between the existing housing systems (HSs), specific checklists were produced, one for the loose housing system (LHS) and one for the tied housing system (THS). In the field, authorised veterinarians are in charge of fulfilling the checklists and loading the data into the ClassyFarm platform where a dedicated algorithm analyses data to provide the final output, i.e. the overall welfare score ranging from 0 % (poor welfare) to 100 % (excellent welfare; [Mauricio et al., 2025](#)).

The ClassyFarm system serves both public and private stakeholders and it assesses farm performance while suggesting interventions to enhance animal welfare ([Tomassone et al., 2024](#)) and improving the awareness about the negative effects of discomfort on animals, i.e. dairy cows with poor welfare are likely to get sick more frequently and not perform at their best ([Fernandes et al., 2021](#)). Welfare assessment on the farm is becoming increasingly important in Italy and plays a key role in the attribution of financial supports and premiums such as the EU’s Common Agricultural Policy (CAP) 2023–2027 ([Tomassone et al., 2024](#)).

Improving dairy cow welfare requires effort and investment, but it provides both direct and indirect benefits, which are often challenging to translate into direct economic losses or gains ([Fernandes et al., 2021](#)). In addition, it is valuable to understand which improvements in welfare can translate into tangible gains, e.g. milk quality, cows’ productivity, and market premiums. The debate over the precise definition and valuation of animal welfare continues, but economic analysis remains an effective way to clarify welfare priorities and to communicate them to farmers ([Christensen et al., 2012](#)).

Recent research has explored the ClassyFarm system ([Holighaus et al., 2023](#); [Mazza et al., 2021](#); [Moriconi et al., 2024](#)) and its link with milk-related performance ([Ginestreti et al., 2020](#); [Mauricio et al., 2025](#); [Zanon et al., 2024a, b](#)). However, to our knowledge, no study has considered ClassyFarm scores in relation to milk quality traits in Holstein and Simmental cows, differentiating between the two HSs. The objective of the study was to investigate (i) whether housing systems (LHS or THS) and farm breed composition (single- vs multi-breed) affect cows’ welfare scores assessed through ClassyFarm, and (ii) the association between ClassyFarm scores on individual milk quality traits and milk-related profits of Holstein and Simmental cows.

2. Materials and methods

2.1. ClassyFarm scores

The ClassyFarm scores were collected from 434 farms located in various areas of the Veneto region, in north-eastern Italy. Of these, 106 were THS-based and 328 LHS-based. The ClassyFarm assessment is typically carried out once a year by trained veterinarians, therefore for the present study a single assessment per farm was considered between August 2022 and November 2023. All the veterinarians assessed at least 2 farms. During the inspections, veterinarians collected information either from questions to the farmers or through their direct evaluation. Two different ClassyFarm checklists were used: one for LHS and one for THS both intended to evaluate four categories of animals: calves, heifers, lactating cows, and dry cows.

As per ClassyFarm organisation, both checklists are organized into 5 thematic areas with indicators: (i) biosecurity, (ii) management, (iii) structures, (iv) ABMs, and (v) major hazards ([IZSLER, 2023](#); [Supplementary Tables 1 and 2](#)). The biosecurity area includes indicators related to the control and prevention of major infectious diseases, while the management area focuses on general animal handling, farm operations, and staff training. Indicators in the structures area evaluate the adequacy of the facilities where animals are housed, including specific environments such as calving and hospital pens, as well as microclimatic conditions. The ABMs area includes both direct observations (e.g. cases

of lameness) and indirect indicators derived from available data sources, such as the national bovine registry (e.g. mortality records) or milk historical data (e.g. somatic cell count). The indicators of the major hazards area refer to the farm’s preparedness for emergencies, such as interruptions in the water or electricity supply, or the occurrence of a fire. These are not health-related emergencies, but technical and infra-structural events that can compromise the farm’s daily operations and animal welfare. As an example, the presence of alternative water supply sources in the farm is examined when attributing the major hazards score as well as the availability of alarm systems to signal fires or any malfunction in the ventilation system ([Supplementary Tables 1 and 2](#)).

Each indicator has specific instructions and guidelines for the trained veterinarian responsible for conducting the assessment and is evaluated with either a binary (poor/ fair) or a multiple-choice system (poor/ fair/ good). The number and content of the indicators varies between LHS and THS checklists as well as the weights and scores assigned to each indicator, and these are determined through expert opinion elicitation, based on a modified Delphi technique ([Bertocchi et al., 2018](#)). The LHS and THS checklists are built and scored differently to reflect the specific characteristics and constraints of the two most common HSs in Italy. However, both use common scoring formulas and a uniform 0–100 % scale ([Bertocchi et al., 2018](#); [Holighaus et al., 2023](#)). Once the checklist is completed, data are processed and validated by the ClassyFarm digital platform ([Moriconi et al., 2024](#)). The ClassyFarm algorithm calculates the scores for each thematic area as the sum of the scores assigned to the indicators belonging to that area and then it is expressed on a scale from 0 % (poor status) to 100 % (good status). Plus, it calculates the overall welfare score as a percentage (0–100 %), based on an arithmetic mean that considers the ABMs score and the total score of the management and structures areas ([Ginestreti et al., 2020](#); [Mazza et al., 2021](#)). Calculating the overall welfare score, the ClassyFarm algorithm assigns greater weight to ABMs, as they directly reflect animal outcomes and capture the combined effects of various input factors. The algorithm excludes the major hazards area from the calculation of the overall welfare score, while the biosecurity score is automatically included in the management area, as it appears as the last indicator ([Supplementary Tables 1 and 2](#)). The algorithm and scoring process behind the ClassyFarm system are not accessible to the public.

In the LHS checklist (105 indicators), the overall welfare score was determined from 19 ABMs combined with 77 management and structure indicators. For THS (99 indicators), the number of ABMs was 22, and the management and structure indicators totaled 68. The biosecurity and major hazards areas comprised the same number of indicators (15 and 9, respectively) in both checklists. The ClassyFarm assessment classifies the farms through the overall welfare score which indicates the level of risk of the farm:

- i) high risk: poor conditions of animals with negative implications for health and stress status;
- ii) medium risk: fair conditions under which animals in the herd are unlikely to experience negative welfare consequences;
- iii) low risk: good conditions, with the possibility for the animals to live positively, fulfilling and satisfying experiences ([Ventura et al., 2021](#)).

2.2. Individual milk data

Test-day records were retrieved from the official routine milk testing dataset of the Breeders Association of Veneto Region (ARAV, Vicenza, Italy). Specifically, only the test-day records collected from cows in the 434 selected herds within 200 days before and after the ClassyFarm assessment date were considered to ensure that welfare evaluation and milk recording occurred simultaneously. Only records of Holsteins (HO) and Simmentals (SI) from herds composed exclusively of these respective breeds were kept, to focus on the major dairy breeds in Italy. In 2023, HO and SI accounted for 82.7 % and 6.9 % of the total cows

officially registered, i.e. 76,134 and 6383 animals (Italian Breeders Association (AIA), 2023).

Along with the test-day records, the following information were available: days in milk (DIM), parity, and milk yield (kg/d), as well as fat, protein, casein, and lactose content (%), somatic cell count (SCC, cells/mL), differential somatic cell count (DSCC, %), and urea concentration (mg/dL). Milk samples were always preserved with Bronopol, transported to the ARAV milk laboratory, and analysed using the CombiFoss™ 7 (FOSS Electric A/S, Hillerød, Denmark). To achieve a normal distribution of data points, the somatic cell score (SCS) was calculated as $SCS = 3 + \log_2(SCC/100,000)$. Having both milk SCC and DSCC available, the number of polymorphonuclear neutrophils and lymphocytes excreted ($DSCC_N$, cells/mL) was calculated as indicated by Costa et al. (2021): $DSCC_N = (SCC \times DSCC)/100$. Similarly to SCC, the $DSCC_N$ was \log_2 -transformed through the same formula of SCS to obtain the differential somatic cell score (DSCS).

Only cows sampled from 5 to 400 DIM and with at least 3 test-day

records were considered. In addition, only herd-test-date with at least 3 samples cows were kept.

Farms were further classified based on breed composition as follows: single-breed Holstein herds included only Holstein cows (single-HO); single-breed Simmental herds included only Simmental cows (single-SI). Multi-breed herds consisted of both Holstein and Simmental cows, with a minimum of 10% representation of the less prevalent breed (326 single-HO, 38 single-SI, and 70 multi-breed herds, Fig. 1A). Multi-breed herds with the less prevalent breed representing less than 10% were excluded from this study. The dataset consisted of 175,022 test-day records from 35,108 lactating cows (32,814 HO and 2294 SI, Table 1).

In this study, the price of milk per liter (€/L) was calculated by adjusting a base price of €0.51 based on fat and protein content, and SCC through the CLAL platform available online (<https://www.clal.it/?seccion=plq>) in which conventional national thresholds for these traits are established to take into account both premiums and penalties. Moreover, the monetary value of milk produced by a single cow per day

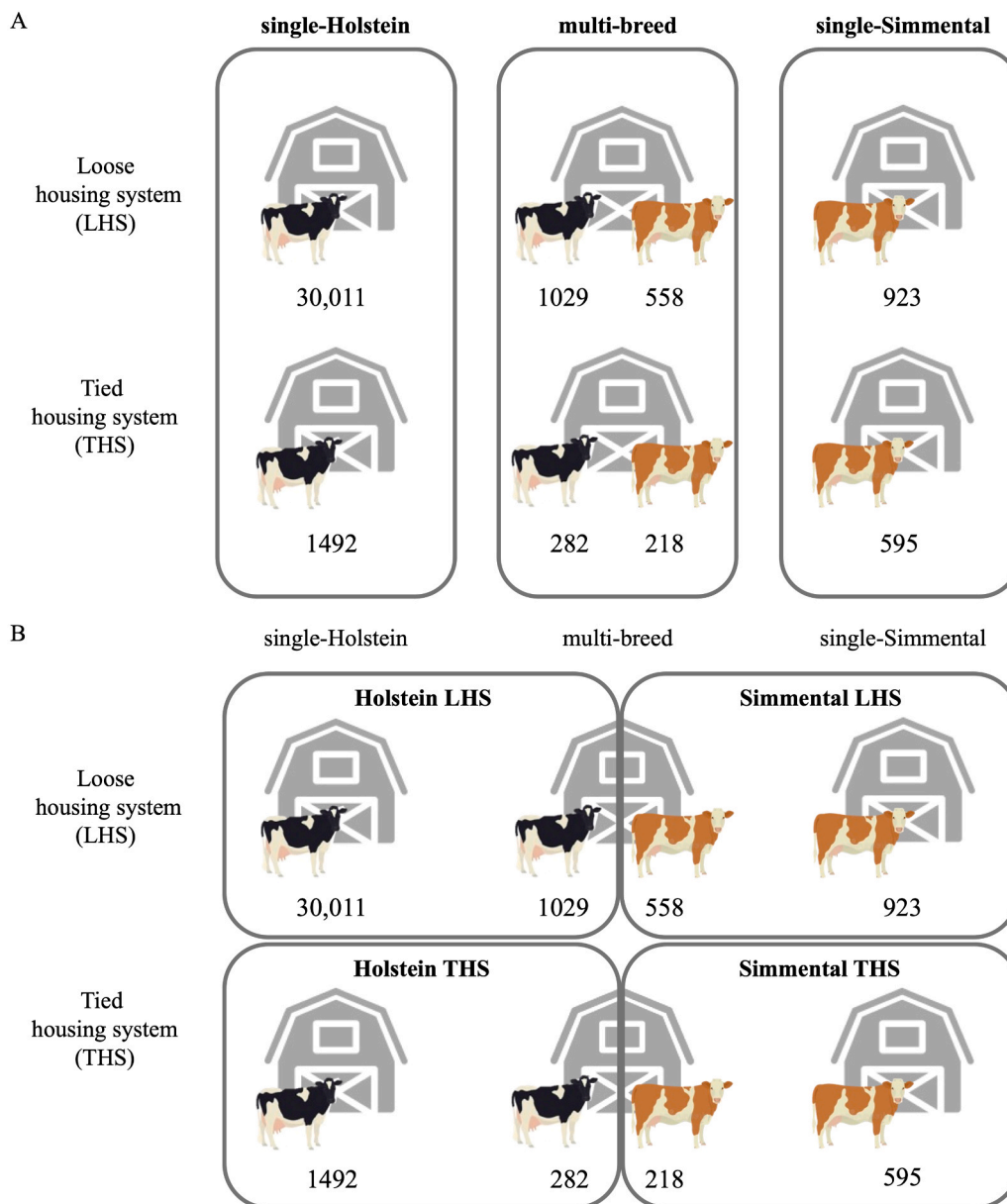


Fig. 1. The 3 subsets (and the lactating cows, n) used in the first model in which ClassyFarm scores were considered as dependent variables: single-HO, single-SI or multi-breed (A). The 4 subsets (and the lactating cows, n) used for the models in which ClassyFarm scores were considered as fixed effects: HO-LHS, HO-THS, SI-LHS, SI-THS (B).

Table 1
Data overview¹ according to the breed composition² of herds and housing system.

Item	Breed composition	Loose housing system	Tied housing system	
Lactating cows, n	single-Holstein	30,011	1492	
	single-Simmental	923	595	
	multi	Holstein	1029	282
		Simmental	558	218
Records, n	Holstein	153,746	6052	
	Simmental	1891	1932	
	multi	Holstein	5690	1481
		Simmental	3086	1144
Herds, n	single-Holstein	269	57	
	single-Simmental	16	22	
	multi	43	27	

¹ Cleaned database used for the statistical analyses (434 farms).

² Single-breed Holstein herds included only Holstein cows; single-breed Simmental herds included only Simmental cows. Multi-breed herds consisted of both Holstein and Simmental cows, with a minimum of 10 % representation of the less prevalent breed. Multi-breed herds with the less prevalent breed < 10 % were not included.

(hereinafter referred to as daily profit) was calculated (€/cow/d). Before statistical analysis, the distributions of ClassyFarm scores and milk traits were visually inspected to evaluate the distribution of data points.

2.3. Statistical analysis

2.3.1. ClassyFarm scores as dependent variable

The analysis of variance was performed in the R software v. 4.4.1 (R Core Team, 2024) for each ClassyFarm score (overall welfare, biosecurity, management, structures, ABMs, and major hazards) as the dependent variable. The single-HO, single-SI, and multi-breed herds were considered, as shown in Fig. 1 A, and the following mixed linear model was performed (“lme4” package; Bates et al., 2024):

$$y_{ijk} = \mu + HS_i + BC_j + (BC \times HS)_{ij} + V_k + e_{ijk}, \quad (1)$$

where y_{ijk} is the dependent variable (score); μ is the overall intercept of the model; HS_i is the fixed effect of the i_{th} HS type (i = LHS or THS); BC_j is the fixed effect of the j_{th} breed composition of herds (j = single-HO, single-SI or multi-breed); $(BC \times HS)_{ij}$ is the fixed interaction effect between breed composition and HS type; V_k is the random effect of the k_{th} veterinarian ($n = 14$) assumed to be distributed as $\sim N(0, \sigma_H^2)$, where σ_H^2 is the related variance; and e_{ijk} is the random residual assumed to be distributed as $\sim N(0, \sigma_e^2)$, where σ_e^2 is the residual variance. Multiple comparisons of least squares means (LSM) were performed in R with the “emmeans” package (Lenth et al., 2024) by using the Bonferroni adjustment with significance set at $P \leq 0.05$.

2.3.2. Welfare level as fixed effect

An additional model was performed using welfare scores as predictors and milk traits as response variables. For all milk quality traits, values deviating more than 3 SD from the respective mean were considered as missing. The analysis was performed for the 4 distinct subsets depicted in Fig. 1B, i.e. (i) Holstein cows in loose housing system (HO-LHS), (ii) Holstein cows in tied housing system (HO-THS), (iii) Simmental cows in loose housing system (SI-LHS), and (iv) Simmental cows in tied housing system (SI-THS). The linear mixed model adopted was:

$$y_{ijklm} = \mu + \beta_1(Welfare)_i + \beta_2(P)_j + \beta_3(D)_k + \beta_{23}(P \times D)_{jk} + C_l + H_m + e_{ijklm}, \quad (2)$$

where y_{ijklm} is the dependent variable (milk yield, fat content, protein content, casein content, lactose content, SCS, DSCS, urea concentration, milk price and daily profit); μ is the overall intercept of the model; Welfare _{i} is a covariate accounting for the effect of ClassyFarm overall welfare score with regression coefficient β_1 ; P_j is a covariate accounting for the effect of parity with regression coefficient β_2 ; D_k is a covariate accounting for the effect of DIM with regression coefficient β_3 ; $(P \times D)_{jk}$

is a covariate accounting for the interaction effect between parity and DIM with regression coefficient β_{23} ; C_l is the random effect of the l_{th} cow (31,040 in HO-LHS, 1774 in HO-THS, 1481 in SI-LHS, and 813 in SI-THS) assumed to be distributed as $\sim N(0, \sigma^2C)$, where σ^2C is the cow variance; H_m is the random effect of the m_{th} herd-test-date (2065 levels in HO-LHS, 541 levels in HO-THS, 387 levels in SI-LHS, and 340 levels in SI-THS) assumed to be distributed as $\sim N(0, \sigma_H^2)$, where σ_H^2 is the herd-test-date variance; and e_{ijklm} is the random residual assumed to be distributed as $\sim N(0, \sigma_e^2)$, where σ_e^2 is the residual variance.

By considering milk traits as dependent variables as in the model [2], additional analyses of variance were carried out for the other ClassyFarm areas' scores separately so that the fixed effect of welfare was given by management [3], structures [4], ABMs [5], biosecurity [6], and major hazards scores [7], as follows:

$$y_{ijklm} = \mu + \beta_1(Management)_i + \beta_2(P)_j + \beta_3(D)_k + \beta_{23}(P \times D)_{jk} + C_l + H_m + e_{ijklm}, \quad (3)$$

$$y_{ijklm} = \mu + \beta_1(Structures)_i + \beta_2(P)_j + \beta_3(D)_k + \beta_{23}(P \times D)_{jk} + C_l + H_m + e_{ijklm}, \quad (4)$$

$$y_{ijklm} = \mu + \beta_1(ABMs)_i + \beta_2(P)_j + \beta_3(D)_k + \beta_{23}(P \times D)_{jk} + C_l + H_m + e_{ijklm}, \quad (5)$$

$$y_{ijklm} = \mu + \beta_1(Biosecurity)_i + \beta_2(P)_j + \beta_3(D)_k + \beta_{23}(P \times D)_{jk} + C_l + H_m + e_{ijklm}, \quad (6)$$

$$y_{ijklm} = \mu + \beta_1(Major\ hazards)_i + \beta_2(P)_j + \beta_3(D)_k + \beta_{23}(P \times D)_{jk} + C_l + H_m + e_{ijklm}, \quad (7)$$

As done for [2], the 4 distinct subsets were analysed one by one. The regression coefficients of the welfare scores, their significance, and the model R^2 were considered for results interpretation and discussion.

3. Results

3.1. ClassyFarm checklists

During inspections for compiling the ClassyFarm checklists, data on the size of the herds were collected considering all categories (lactating cows, dry cows, heifers, and calves). The herds analysed in this study varied significantly in size. The single-HO herds averaged 239 lactating cows, 55 dry cows, 151 heifers, and 69 calves, whereas single-SI farms averaged 34 lactating cows, 8 dry cows, 17 heifers, and 9 calves. Multi-breed herds had averages of 58 lactating cows, 12 dry cows, 29 heifers, and 17 calves (Fig. 1 A). Specifically, single-HO herds averaged 248 lactating cows in LHS and 29 in THS, while single-SI herds had an average of 43 and 26 lactating cows in LHS and THS, respectively. Multi-breed herds averaged 67 lactating cows in LHS and 28 in THS. The two checklists, one for LHS (Supplementary Table 1) and one for THS

Table 2

F-values, significance¹ of the fixed effects (housing system, breed composition, and their interaction), and least squares means (standard error) for the ClassyFarm areas² from the first model [1]. Least squares means are reported for the fixed effects of housing system and breed composition. Means with different superscript letters within housing system or breed composition³ differ significantly ($P \leq 0.05$).

Area	Housing system			Breed composition				Interaction F-value
	F-value	Loose	Tied	F-value	Single Holstein	Single Simmental	Multi-breed	
Overall welfare	18.43***	82.40 ^a (1.21)	78.90 ^b (1.22)	0.39	80.50 ^a (1.11)	81.20 ^a (1.43)	80.20 ^a (1.28)	1.75
Management	4.95 *	80.70 ^a (1.92)	77.90 ^b (1.94)	7.41 ***	82.10 ^a (1.78)	77.50 ^b (2.25)	78.20 ^b (2.03)	0.93
Structures	12.47 ***	74.40 ^a (1.99)	69.40 ^b (2.01)	0.81	71.10 ^a (1.82)	71.80 ^a (2.39)	72.90 ^a (2.13)	2.73 †
Animal-based measures	16.16 ***	87.60 ^a (1.38)	84.00 ^b (1.39)	4.39 *	84.60 ^b (1.29)	87.90 ^a (1.61)	84.90 ^{ab} (1.46)	0.94
Biosecurity	26.85 ***	60.90 ^a (2.64)	51.60 ^b (2.66)	4.02 *	58.50 ^a (2.44)	56.70 ^{ab} (3.13)	53.50 ^b (2.80)	2.01
Major hazards	26.95 ***	54.30 ^a (3.90)	42.40 ^b (3.92)	1.31	50.30 ^a (3.67)	45.70 ^a (4.45)	49.10 ^a (4.08)	2.67 †

¹ *** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$, † $P < 0.10$.

² For the overall welfare score calculation, the score of major hazards was excluded as per ClassyFarm algorithm (Ginestreti et al., 2020).

³ Single-breed Holstein herds included only Holstein cows; single-breed Simmental herds included only Simmental cows. Multi-breed herds consisted of both Holstein and Simmental cows, with a minimum of 10 % representation of the less prevalent breed. Multi-breed herds with the less prevalent breed < 10 % were not included.

(Supplementary Table 2), were different in terms of number, content, weight, and score of the indicators. The average overall welfare score calculated for LHS (82.96 ± 5.59 %) was higher than that of THS (77.55 ± 5.13 %; data not shown). Generally, the individual scores of all areas (biosecurity, management, structures, ABMs, and major hazards) were higher in LHS compared to THS. The greatest differences between the two HSs were observed in the biosecurity and major hazards areas, while the smallest were in the ABMs area (86.63 % in LHS and 82.11 % in THS; data not shown).

3.2. ClassyFarm variability

The variability of the ClassyFarm system was analysed not only concerning the HS (LHS, THS) but also in relation to herd composition, categorized by breed type (single-HO, single-SI, and multi-breed), using equation [1] (Fig. 1A). The effect of HS was statistically significant in explaining the variability of the ClassyFarm score of the 5 areas and overall welfare (Table 2). Breed composition significantly affected management, ABMs, and biosecurity scores. On the other hand, the interaction between these two effects showed only a tendency for structures and major hazards scores.

The LSM of scores of ClassyFarm areas for the interaction between the fixed effect of breed composition and HS were presented in Fig. 2. For overall welfare and all single areas (i.e. biosecurity, management, structures, ABMs, and major hazards), single-HO herds in LHS had higher ($P < 0.001$) LSM scores compared to single-HO herds in THS. On the other hand, single-SI herds showed higher LSM scores in LHS than THS only for overall welfare ($P < 0.05$), structures ($P < 0.01$), and major hazards scores ($P < 0.001$). In multi-breed herds, LSM was statistically similar in overall welfare and all areas in both HSs, except for biosecurity score which was higher in LHS than THS ($P < 0.05$; Fig. 2).

Across types of breed composition, no differences were observed in overall welfare, structures, and major hazards (Table 2). However, management scores were higher in single-HO herds (82.10 ± 1.78 %), while multi-breed herds and single-SI herds (78.20 ± 2.03 % and 77.50 ± 2.25 % respectively) had similar scores. Conversely, the highest ABMs score was found in single-SI herds (87.90 ± 1.61 %; Table 2). Multi-breed herds (84.90 ± 1.46 %) and single-HO herds (84.60 ± 1.29 %) exhibited similar ABMs scores. In terms of biosecurity scores, multi-breed herds had the lowest LSM (53.50 ± 2.80 %) while single-HO herds had the highest (58.50 ± 2.44 %; Table 2).

3.3. Milk descriptive statistics

Descriptive statistics of milk traits of the four subsets (Fig. 1B) used in equations [2, 3, 4, 5, 6, and 7], created based on breed (i.e., HO, SI) and HS (i.e., LHS, THS), were reported in Table 3.

According to the CLAL platform, the fat content modified the price (€/L) with deductions applied if it was below 3.70 % and increased if it exceeded 3.80 %. Similarly, the protein content affected the price, with deductions for levels below 3.25 % and an increase for levels above 3.30 %. The SCC introduced further adjustments: low counts (below 150,000) resulted in a premium, while higher counts (above 350,000) led to penalties. Additionally, if the SCC exceeded 400,000, any premium for protein content over 3.30 % was removed. In general, milk from HO-LHS and SI-LHS reached a higher price compared to THS-milk, based on the fat and protein content as well as SCC (€ 0.514 /L and € 0.513 /L respectively; Table 3). The daily profit was higher in LHS cows, with HO cows with the highest value (€16.55/cow/d), followed by SI cows (€13.60/cow/d). Among THS cows, HO cows also had the highest daily profit at €12.77/cow/d (Table 3).

3.4. Regression equations

A linear mixed model was performed to evaluate the relationship between welfare (independent variable) and milk traits in the four subsets: HO-LHS, HO-THS, SI-LHS, and SI-THS (Fig. 1B). The regression coefficients of the different ClassyFarm scores for milk traits were listed in Table 4 for HO cows and in Table 5 for SI cows. The complete set of regression equations and their R^2 were reported in Supplementary Tables 3, illustrating the relationship between these traits and the predictor variables (ClassyFarm scores, parity, DIM, parity * DIM). In general, the regression equations of the 4 subsets for milk yield and daily profit had the highest R^2 (0.724–0.763; Supplementary Tables 3), suggesting that the predictors explain 72–76 % of the variability in milk yield and daily profit.

In general, many regression coefficients were weak or not statistically significant. In the case of HO-LHS cows, higher milk yield, lactose content, and daily profit were associated with higher overall welfare score and the scores of all other areas. For example, for every additional % point in welfare score, the coefficients for milk yield and daily profit were +0.312 kg/d and +€0.161/ cow/d, respectively (Table 4). Moreover, for every additional % point of welfare score, the coefficients for SCS and DSCS were negative, and this was also observed for management, ABMs, biosecurity, and major hazards in HO-LHS. The overall welfare score contributed to a few milk traits in other subsets, negatively in SI-LHS cows (i.e. milk yield, fat, protein, and urea) while positively in SI-THS (i.e. milk yield, urea, and daily profit; Table 5).

For every additional % point in the management score, the coefficients for milk yield ranged from +0.088 kg/d (in SI-THS) to +0.235 kg/d (in HO-LHS), while the coefficients for daily profit ranged from +0.045 €/cow/d (in SI-THS) to +0.121 €/cow/d (in HO-LHS). This positive trend was also observed considering the biosecurity score. In HO-THS and SI-THS cows, higher management and biosecurity

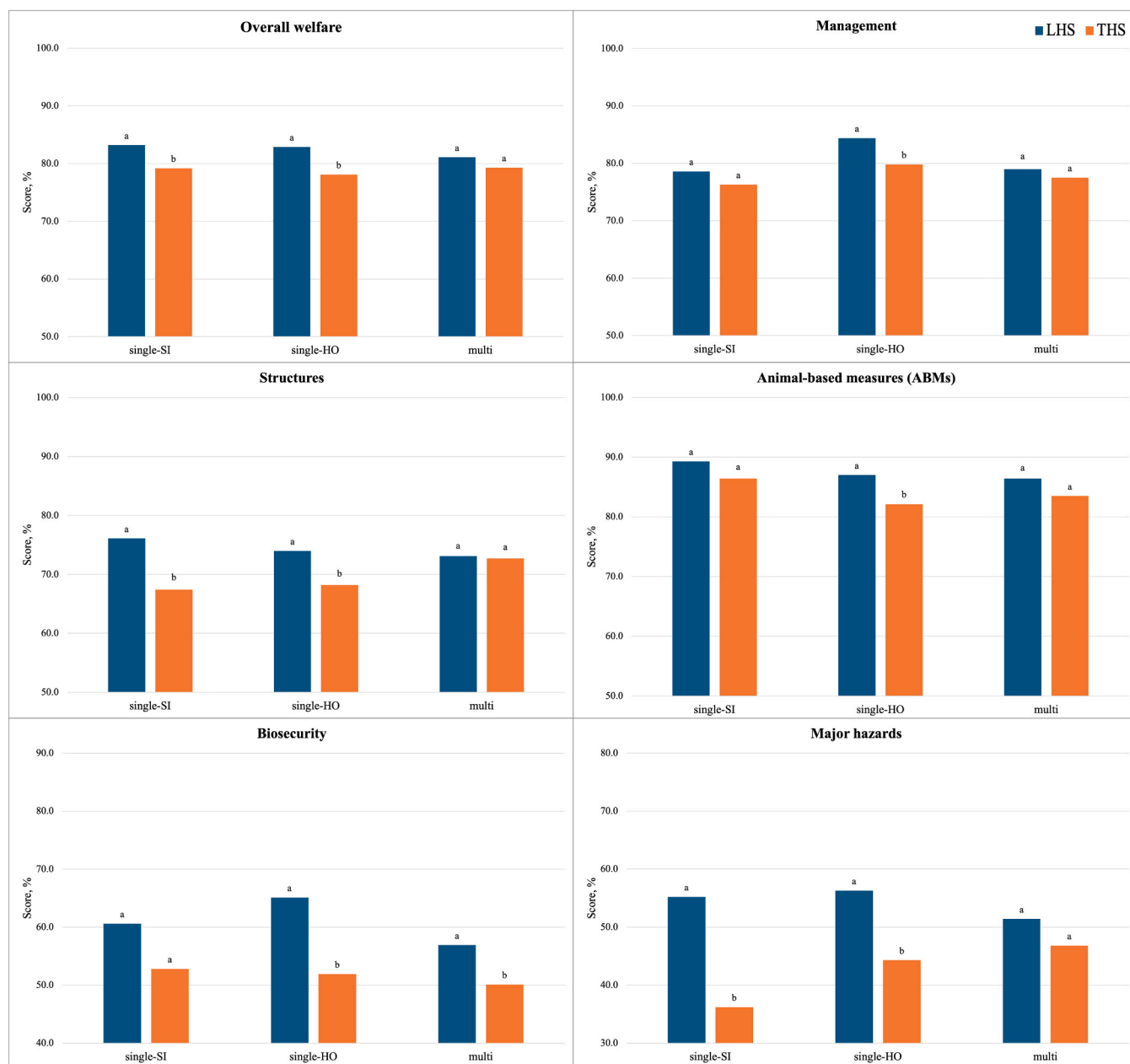


Fig. 2. Least squares means of ClassyFarm areas scores (%) of the first order interaction between fixed effect of breed composition¹ and housing system². Means with different superscript letters within type of breed composition are significantly different ($P \leq 0.05$).

¹ single-SI = Simmental single-breed herds; single-HO = Holstein single-breed herds.

² LHS= loose housing system; THS= tied housing system.

scores were associated with higher protein, casein, and lactose contents, and with lower SCS (-0.010 and -0.015, respectively). Moreover, a positive association between management score and fat was observed in THS cows of both breeds.

The coefficients for structures score contributed negatively to fat, protein, and casein content in HO-LHS and SI-LHS, while positively to urea concentration (+0.025 mg/dL) in SI-THS.

Regarding the ABMs score, several significant coefficients were found for milk traits in the HO subsets, but only a few when considering SI-LHS and SI-THS cows. In HO-LHS, the ABMs score was positively associated with milk yield, milk price, daily profit, and lactose % while negatively associated with protein and casein content, SCS, DSCS, and

urea. In HO-THS these coefficients were opposite except for protein and casein content. In SI-LHS cows, the ABMs score showed a negative coefficient with milk yield (-0.049 kg/d), whereas in SI-THS cows, it was positive with both milk yield (+0.218 kg/d) and daily profit (+ €0.111/cow/d).

An additional score point in the major hazard area was associated with higher milk yield, milk price, and daily profit in HO-LHS. In both HO-LHS and HO-THS, a higher major hazards score corresponded to a higher coefficient for lactose % and a lower one for SCS. The major hazards score did not affect any examined milk trait in SI-LHS milk while it contributed negatively only to milk yield, protein content, and daily profit in SI-THS cows (Table 5).

Table 3
Mean, SD, and range of milk traits¹ in the four subsets².

Traits	HO-LHS		HO-THS		SI-LHS		SI-THS	
	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
Milk yield, kg/d	35.47 (10.07)	2.00–99.00	26.60 (8.32)	2.00–64.30	26.20 (8.32)	3.10–64.50	22.90 (8.58)	1.90–63.30
Fat, %	3.96 (0.75)	1.72–6.20	3.94 (0.67)	1.90–5.97	3.93 (0.68)	1.85–6.03	3.90 (0.72)	1.80–6.06
Protein, %	3.44 (0.38)	2.31–4.57	3.41 (0.43)	2.30–4.69	3.53 (0.38)	2.41–4.60	3.43 (0.42)	2.22–4.65
Casein, %	2.72 (0.32)	1.76–3.68	2.69 (0.36)	1.67–3.78	2.79 (0.33)	1.86–3.71	2.71 (0.36)	1.75–3.78
Lactose, %	4.79 (0.18)	4.27–5.33	4.74 (0.18)	4.20–5.28	4.74 (0.18)	4.24–5.26	4.73 (0.18)	4.20–5.26
SCS	2.63 (1.99)	–3.64–9.64	3.09 (2.15)	–2.06–9.61	2.48 (1.98)	–3.64–9.63	2.83 (2.08)	–2.64–9.36
DSCS	1.82 (2.33)	–6.57–9.50	2.35 (2.52)	–6.38–9.45	1.68 (2.38)	–6.53–9.49	2.09 (2.09)	–5.44–9.07
Urea, mg/dL	22.76 (6.03)	4.70–40.90	21.48 (7.02)	3.70–42.50	22.12 (7.11)	4.40–41.20	20.65 (6.94)	3.80–41.60
Milk price ³ , €/L	0.514 (0.004)	0.504–0.516	0.513 (0.004)	0.504–0.516	0.514 (0.004)	0.504–0.516	0.513 (0.004)	0.504–0.516
Daily profit, €/cow/d	16.55 (4.32)	0.00–22.44	12.77 (2.65)	0.00–18.57	13.60 (2.28)	7.56–19.60	10.90 (4.33)	0.00–18.57

¹ SCS= somatic cell score; DSCS = differential somatic cell score.

² HO-LHS = Holstein cows in loose housing system (n = 31,040); HO-THS = Holstein cows in tied housing system (n = 1774); SI-LHS = Simmental cows in loose housing system (n = 1481); SI-THS = Simmental cows in tied housing system (n = 813).

³ Calculated using the CLAL online tool (<https://www.clal.it/?section=plq>).

Table 4

Overview of the regression coefficients of the different ClassyFarm scores¹ for milk traits² in Holstein cows in the loose and tied housing systems. Coefficients in italics are not significant.

Loose housing system							
Milk trait	Overall welfare	Management	Structures	ABMs	Biosecurity	Major hazards	
Milk yield, kg/d	+ 0.312	+ 0.235	+ 0.134	+ 0.100	+ 0.175	+ 0.049	
Fat, %	- 0.006	- 0.0004	- 0.006	- 0.001	+ 0.0002	- 0.001	
Protein, %	- 0.003	- 0.001	- 0.002	- 0.001	- 0.001	- 0.001	
Casein, %	- 0.002	- 0.001	- 0.001	- 0.001	- 0.001	- 0.00001	
Lactose, %	+ 0.001	+ 0.001	+ 0.001	+ 0.0004	+ 0.001	+ 0.0003	
SCS	- 0.018	- 0.016	- 0.002	- 0.012	- 0.008	- 0.002	
DSCS	- 0.014	- 0.013	+ 0.001	- 0.012	- 0.007	- 0.002	
Urea, mg/dL	- 0.037	+ 0.009	- 0.004	- 0.065	+ 0.012	+ 0.015	
Milk price, €/L	+ 0.00003	+ 0.00002	- 0.000003	+ 0.00002	+ 0.00001	+ 0.00003	
Daily profit, €/cow/d	+ 0.161	+ 0.121	+ 0.069	+ 0.052	+ 0.090	+ 0.025	
Tied housing system							
Milk trait	Overall welfare	Management	Structures	ABMs	Biosecurity	Major hazards	
Milk yield, kg/d	- 0.068	+ 0.205	- 0.042	- 0.207	+ 0.134	+ 0.019	
Fat, %	- 0.008	+ 0.004	- 0.003	- 0.009	- 0.0001	+ 0.001	
Protein, %	- 0.002	+ 0.007	- 0.001	- 0.006	+ 0.001	+ 0.001	
Casein, %	- 0.002	+ 0.006	- 0.001	- 0.006	+ 0.002	+ 0.001	
Lactose, %	- 0.0004	+ 0.002	+ 0.001	- 0.003	+ 0.002	+ 0.001	
SCS	- 0.010	- 0.010	- 0.007	+ 0.003	- 0.015	- 0.005	
DSCS	- 0.001	- 0.010	- 0.004	+ 0.013	- 0.020	- 0.004	
Urea, mg/dL	+ 0.153	+ 0.013	+ 0.022	+ 0.171	+ 0.072	- 0.018	
Milk price, €/L	+ 0.00002	+ 0.00003	+ 0.00001	- 0.00001	+ 0.00002	+ 0.00001	
Daily profit, €/cow/d	- 0.034	+ 0.106	- 0.021	- 0.106	+ 0.069	+ 0.010	

¹ ClassyFarm scores were: overall welfare, management, structures, animal-based measures (ABMs), biosecurity and major hazards.

² SCS= somatic cell score; DSCS = differential somatic cell score.

4. Discussion

4.1. ClassyFarm variability

Improving animal welfare has a relevant social impact and an ethical component. Aligning with the “One Welfare” concept, dedicated strategies and actions are known to substantially promote animal welfare and farmers’ well-being, and, in turn, the profitability of dairy herds (Swanson, 2024). First, enhanced welfare practices lead to healthier cows, which tend to have better milk yield and quality, face lower veterinary costs, and have longer productive lifespans (Fernandes et al., 2021). Moreover, by adopting and maintaining high welfare standards, farmers meet eligibility criteria for subsidies, ensuring financial support that can further enhance farm operations. In light of this, the current study aimed to deepen the existing knowledge on the sources of variability influencing cow welfare levels, assessed through ClassyFarm checklists, namely HSs (LHS or THS) and breed composition (single- vs. multi-breed; Table 2).

In general, LHS-cows obtained higher ClassyFarm scores in all areas

regardless of the breed composition (Fig. 2). The cow’s ability to move freely and comfortably is a key factor in promoting welfare, and research suggests that restrictive environments may contribute to several health issues. This emphasizes the need for HSs that allow natural behaviors and minimize confinement stressors (Boyer et al., 2023). The THS is considered one of the most restrictive HS for dairy cattle (Boyer et al., 2023) but is still widely used in farms located in specific contexts, such as small-scale mountain farms (Holighaus et al., 2023; Zanon et al., 2024a, b). Biosecurity and major hazards accounted for the greatest differences in terms of scores between HSs, with the lowest scores obtained by THS farms (51.08 % and 47.09 % respectively). The THS farms, usually less developed and small (Holighaus et al., 2023), are constrained by topographical and structural limitations, which hinder compliance with many of the required criteria (Zanon et al., 2024b). Furthermore, THS farms typically provide access to pasture in some periods of the year in mountain areas (Holighaus et al., 2023), but, oppositely to the consumers’ general opinion, access to outdoor pasture does not always translate into better welfare conditions for dairy cows. Based on some studies, while animals at pasture tend to behave more

Table 5

Overview of the regression coefficients of the different ClassyFarm scores¹ for milk traits² in Simmental cows in the loose and tied housing systems. Coefficients in italics are not significant.

Loose housing system						
Milk trait	Overall welfare	Management	Structures	ABMs	Biosecurity	Major hazards
Milk yield, kg/d	- 0.025	+ 0.142	- 0.061	- 0.049	+ 0.069	- 0.005
Fat, %	- 0.007	- 0.006	- 0.003	- 0.001	- 0.003	- 0.0001
Protein, %	- 0.002	+ 0.0002	- 0.002	- 0.00001	+ 0.001	- 0.0004
Casein, %	- 0.001	+ 0.0001	- 0.002	+ 0.001	+ 0.000004	- 0.0002
Lactose, %	- 0.001	- 0.0002	- 0.001	- 0.001	+ 0.001	+ 0.0003
SCS	- 0.007	- 0.005	+ 0.00003	- 0.010	+ 0.002	+ 0.0004
DSCS	- 0.001	- 0.002	+ 0.004	- 0.007	- 0.001	+ 0.001
Urea, mg/dL	- 0.112	+ 0.041	+ 0.094	- 0.055	+ 0.069	- 0.014
Milk price, €/L	- 0.00002	+ 0.00002	- 0.000002	- 0.00002	+ 0.000003	+ 0.0000003
Daily profit, €/cow/d	- 0.012	+ 0.074	- 0.032	- 0.024	+ 0.036	- 0.003
Tied housing system						
Milk trait	Overall welfare	Management	Structures	ABMs	Biosecurity	Major hazards
Milk yield, kg/d	+ 0.161	+ 0.088	- 0.036	+ 0.218	+ 0.111	- 0.076
Fat, %	+ 0.003	+ 0.008	- 0.001	- 0.003	+ 0.002	- 0.001
Protein, %	+ 0.004	+ 0.005	+ 0.001	- 0.00002	+ 0.002	- 0.002
Casein, %	+ 0.004	+ 0.004	+ 0.001	- 0.0001	+ 0.002	- 0.002
Lactose, %	- 0.0002	+ 0.001	- 0.0002	- 0.001	+ 0.001	- 0.001
SCS	- 0.020	- 0.015	+ 0.001	- 0.015	- 0.012	- 0.001
DSCS	- 0.026	- 0.017	- 0.001	- 0.018	- 0.011	- 0.003
Urea, mg/dL	+ 0.118	+ 0.095	+ 0.025	+ 0.033	- 0.040	- 0.002
Milk price, €/L	+ 0.00001	+ 0.00001	- 0.00001	+ 0.00002	+ 0.00002	- 0.000004
Daily profit, €/cow/d	+ 0.083	+ 0.045	- 0.018	+ 0.111	+ 0.057	- 0.038

¹ ClassyFarm scores were: overall welfare, management, structures, animal-based measures (ABMs), biosecurity and major hazards.

² SCS= somatic cell score; DSCS = differential somatic cell score.

naturally, such an environment can be challenging due to stressors like energy deficit (Fulkerson et al., 2008; Wilkinson et al., 2020), parasites, variable climate, and predators (Spigarelli et al., 2020). The overall welfare scores were good in both HSs, accompanied by favourable results in management and ABMs. This reflects farmers' deep awareness and commitment to maintain and improve high welfare standards for their animals (Zanon et al., 2024a), aligning with contemporary welfare requirements.

Within breed composition, single-HO herds achieved the highest scores in management and biosecurity areas compared to the other subsets (Fig. 1 A, Fig. 2), with LHS herds performing better than THS herds. These findings might be partially explained by the higher average number of lactating cows observed in single-HO herds within the LHS context, which could imply greater availability of resources (e.g. advanced equipment, trained personnel) and a broader adoption of forefront management practices to minimize and control stressors (Adriaens et al., 2023). Similarly, in the study by Mauricio et al. (2025), larger farms received a higher management score. Indeed, the management area included indicators related to the daily care activities done by stockpersons (e.g. cleanliness of drinkers and bedding material, milking routine, hygiene of udder and milking equipment, management of feed and water; Supplementary Tables 1 and 2). Biosecurity, on the other hand, included indicators aimed at preventing the introduction and spread of diseases (Ventura et al., 2021). Biosecurity was expected to align with management results, as it was incorporated within the management area. However, herd size is not always a reliable indicator for specific characteristics such as farming system (intensive vs. extensive), equipment quality, facility modernity, management efficiency, or staff competence. For instance, although large HO-LHS farms may benefit from advanced infrastructures, smaller family-run HO-THS farms might achieve high welfare standards through more attentive care practices.

Single-SI herds obtained the highest average score in ABMs compared to single-HO and multi-breed herds. SI cows, being a dual-purpose breed, demonstrate optimal resistance to intramammary infections and overall robustness (Zanon et al., 2021). Mattiello et al. (2011), examining 5 Italian cattle breeds in THS (including HO and SI), found that local breeds like SI exhibited a significantly lower prevalence

of pathological conditions (i.e. integument alterations, lameness) compared to the more productive HO cows, as they are better adapted to their environment. Some of these conditions can be found in ABMs area (Supplementary Tables 1 and 2), which is fundamental in overall welfare score calculation, as it allows for a more precise diagnosis of cow welfare conditions (e.g. body condition score, udder health, mortality rates) (Ventura et al., 2021).

Generally, it emerges that multi-breed herds obtained lower scores compared to single breed herds. Managing a single breed simplifies farming practices, including feeding strategies and milking routines (Zanon et al., 2021), which likely promotes uniformity in welfare practices.

4.2. Benefits of high welfare

We further explored potential associations between welfare scores, assessed by ClassyFarm, and milk quality and production traits, considering the HO-LHS, HO-THS, SI-LHS, and SI-THS (Fig. 1B). Overall, the milk yield and quality were in line with what has been reported by other studies on HO and SI cows (Table 3), with average milk yield that was higher in HO cows (Koknaroglu et al., 2021; Manuelian et al., 2019) and SCS and DSCS lower in SI milk compared to HO milk (Penasa et al., 2014; Magro et al., 2023). On average, protein and casein content were higher in the milk of SI cows, as observed by Koknaroglu et al. (2021) and Manuelian et al. (2019).

In general, many regression coefficients were non-significant or weak. However, some of our results offer a strategic and novel perspective, indicating that higher welfare levels are associated with favourable milk production and quality traits, and potential economic advantages in farms adopting different HSs and managing one or more breeds. Although consistent differences were observed among the four subsets, in terms of HS, breed (Fig. 1B), and herd and data numerosity (Table 1), farmers may benefit from placing greater attention on management and biosecurity, as these were associated with desirable outcomes. This is because an increase in management or biosecurity scores by 1 % was associated with a higher milk yield and daily profit across all four subsets (Tables 4, 5). Additionally, in THS cows, higher management or biosecurity scores corresponded to higher protein, casein, and

lactose contents, and to lower SCS values. From an operational perspective, the management and biosecurity areas include indicators whose scores can be more readily improved (Supplementary Tables 1 and 2), whereas it is unlikely that a farmer would renovate housing facilities (structures area) after each ClassyFarm inspection.

The HO-LHS cows appeared to benefit more from the higher welfare scores compared to the other three subsets, probably because of the efficiency of these specialized herds. For a hypothetical HO-LHS herd of 100 lactating cows, a 1 % increase in overall welfare score could correspond to an estimated annual profit improvement of approximately €5876.5 ($€0.161/\text{cow}/\text{d} \times 100 \text{ cows} \times 365 \text{ d}$; Table 4), reflecting a potential increase in milk yield of 11,388 kg/year ($0.312 \text{ kg}/\text{d} \times 100 \text{ cows} \times 365 \text{ d}$). Should welfare scores continue to improve, potential gains may also rise (e.g., a 5 % improvement could correspond to ~€29,382.5/year). Although the coefficient for milk price (€/L) associated with overall welfare is not significant (Table 4), the combined effect of higher milk yield and daily profit suggests the possibility of annual economic benefits. Similarly, in HO-LHS farms, higher scores in other ClassyFarm areas were associated with favourable milk quality traits (Table 4), like higher lactose and lower SCS and DSCS. The inverse correlation of lactose content with SCC (and DSCC) was already well-documented in the literature (Cinar et al., 2015), and higher lactose content was associated with lower SCC and, in turn, better quality of milk and milk products (Cinar et al., 2015; Costa et al., 2020).

In HO-THS farms, higher management and biosecurity scores were associated with higher milk production. For example, in an average herd of 20 lactating cows, a 1 % increase in the management score could correspond to an estimated annual profit difference of approximately €773.8 ($€0.106/\text{cow}/\text{d} \times 20 \text{ cows} \times 365 \text{ d}$), along with greater milk yield ($0.305 \text{ kg}/\text{d} \times 20 \text{ cows} \times 365 \text{ d} = 2226.5 \text{ kg}/\text{year}$). In hypothetical larger herds of 100 lactating cows, the profit could reach around €3869 annually. In the study of Zanon et al. (2024a), an increase in both biosecurity and overall welfare scores was associated with a rise in predicted annual profitability per cow in THS farms. Higher milk quality (i.e. higher fat, protein, casein, lactose contents, and lower SCS; Table 4) also appeared associated with higher welfare levels, potentially supporting better economic outcomes. A reduction in milk fat, protein, casein, and lactose content can be significant in cases of subclinical and clinical mastitis (Bochniarz et al., 2023), underlying poor welfare levels. Furthermore, this can impair coagulation properties and so, quality for cheese-making processes (Bochniarz et al., 2023).

The performance of SI cows exhibited modest positive associations with higher welfare levels, as assessed by the ClassyFarm system. For example, in a LHS herd with 100 SI cows in lactation, the regression coefficients indicated a potential annual profit increase of €2701 ($€0.074/\text{cow}/\text{d} \times 100 \text{ cows} \times 365 \text{ d}$) for a 1-point increase in the management score or by €1314 ($€0.036/\text{cow}/\text{d} \times 100 \text{ cows} \times 365 \text{ d}$) for a 1-point increase in the biosecurity score (Table 5).

Likewise, in THS farms with 20 SI cows, a +1 % increase in overall welfare score was associated with greater milk yield (+1175.3 kg/year) and profitability (+€605.9/year), potentially up to €3029/year in herds with 100 SI cows (Table 5). Moreover, a higher biosecurity score corresponded to higher protein, casein, lactose %, and lower SCS, while higher management score corresponded to higher fat, protein, casein contents, and lower SCS and DSCS (Table 5). This highlights the value of investing in better welfare practices, offering a clear incentive for farmers even in small-scale realities and peculiar contexts such as those of THS farms with local breeds (Zanon et al., 2024a).

4.3. Relevance for the farmers

The on-farm welfare assessment using recognized systems is becoming increasingly important worldwide. In Italy, in particular, the farm welfare score provided by ClassyFarm plays a crucial role in the allocation of funds under the EU's Common Agricultural Policy (CAP) 2023–2027 by the Italian Ministry of Agriculture, Food Sovereignty and

Forests (Tomassone et al., 2024). Nonetheless, the ClassyFarm welfare assessment remains voluntary, but it enables Italian farmers to access markets that require official certifications (IZSLER, 2023). For example, the recent animal welfare certification “Sistema di Qualità Nazionale per il Benessere Animale - SQNBA” (Italian National Quality System for Animal Welfare), implemented in 2025 (Decree of October 23, 2024), relies on the ClassyFarm platform to verify compliance with its access requirements (Zanon et al., 2024b).

Overall, our findings suggest that the welfare level does not necessarily align with the concept of milk performance, since the higher ClassyFarm scores do not always result into better milk yield or composition. The results, such as non-significant or weak regression coefficients (e.g. ABMs in HO-THS or structures in SI-LHS), should be interpreted with caution, because the ClassyFarm system assesses the overall intra-herd welfare by evaluating categories different from lactating cows, i.e., dry cows, heifers, and calves, which are not directly connected to milk characteristics and a cow's individual milk yield. This lack of direct connection is supported by the presence of numerous non-significant regression coefficients. Furthermore, complex interactions among ClassyFarm indicators may still be hidden and unexplored. Milk quality deserves more investigation to confirm or exclude causality and better understand the associations observed in this study.

However, interestingly, higher management and biosecurity scores were associated with higher milk yield in the 4 subsets. These findings emphasize the essential role of human involvement and commitment in ensuring dairy herd welfare, since both management and biosecurity areas are based on attentive daily practices done by farm operators (Supplementary Tables 1 and 2) (Hansen and Østerås, 2019). In this sense, farmers' benefits also need to be discussed in the framework of the “One Welfare” concept and not merely in economic terms, highlighting the interconnectedness of animal welfare, human well-being, and environmental sustainability (Tarazona et al., 2019).

5. Conclusions

To our knowledge, this is the first study investigating the association between the ClassyFarm welfare scores and individual milk yield and quality traits in Italian HO and SI reared in two different HSs. Although many coefficients were weak and non-significant, we identified potential benefits associated with higher management and biosecurity scores in all subsets (HO-LHS, HO-THS, SI-LHS, and SI-THS), especially for milk yield and economic traits. This means that farmers who commit to improving or maintaining high welfare standards for their dairy herds may ultimately achieve higher income and farm profitability. In turn, this strengthens their welfare and financial stability, allowing them to reinvest more resources into their farms and animals, creating a positive cycle of growth and welfare enhancement. The sample size could be expanded in the future, particularly for Simmental cows, as well as to other breeds, to further deepen the knowledge on the topic. Our findings provide valuable insights for farmers using these husbandry systems, supporting strategic welfare decisions and practices that can enhance the farm's sustainability and reputation in the long term.

CRedit authorship contribution statement

Silvia Sabbadin: Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Angela Costa:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization. **Valentina Lorenzi:** Writing – review & editing, Visualization, Validation, Supervision, Formal analysis. **Francesca Fusi:** Writing – review & editing, Visualization, Validation, Supervision, Formal analysis. **Luigi Bertocchi:** Writing – review & editing, Visualization, Supervision, Project administration, Conceptualization. **Silvia Magro:** Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Massimo De Marchi:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Investigation,

Funding acquisition, Conceptualization.

Ethics statement

Not applicable.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT (OpenAI) in order to improve the readability and language of the manuscript. After using ChatGPT (OpenAI), the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

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

Acknowledgments

The authors acknowledge the Breeders Association of Veneto Region (ARAV, Vicenza, Italy) for technical support and the veterinarians who performed the ClassyFarm evaluations.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.prevetmed.2025.106666](https://doi.org/10.1016/j.prevetmed.2025.106666).

Data availability

None of the data were deposited in an official repository. The data that support the study are available from the corresponding author upon reasonable request.

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