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Potential environmental benefits of enforcing best available technology in the Swedish dairy cattle systems

Sanna Pasanen[a,*], Karin Alvåsen[b], Mattias Eriksson[a], Jonas Christensen[c], Ingrid Strid[a]

[a] Department of Energy and Technology, Swedish University of Agricultural Sciences, P.O. Box 7032, 750 07 Uppsala, Sweden
[b] Department of Clinical Sciences, Swedish University of Agricultural Sciences, P.O. Box 7054, 750 07 Uppsala, Sweden
[c] Ekolagen Miljöjuridik AB, Östra Ågatan 53, 75322 Uppsala, Sweden

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ABSTRACT

Animal-based food production places significant strain on environmental resources, yet much of its mitigation potential remains untapped. Sweden's Environmental Code (1999) mandates resource efficiency and waste minimization, but its application to reduce on-farm losses in agriculture has not been fully explored. This study examines the potential environmental impact of targeting animal losses through the enforcement of the Environmental Code on Swedish cattle farms.

Using data from 4222 dairy cattle farms, we demonstrate that reducing losses on farms exceeding the median loss rate could lead to 2800 t of additional meat reaching the food supply chain annually (34 % reduction in losses), decrease the CO_2e associated with meat losses by 52,000 t, and recover €15 million in revenue losses. While these reductions represent a small fraction of Sweden's total agricultural emissions, the study suggests the potential could be even greater if applied to all livestock farms nationwide.

Importantly, Sweden's Environmental Code aligns with EU legislation, making these findings highly relevant not only for Sweden but also for other EU countries with similar regulatory frameworks.

1. Introduction

The agricultural sector significantly contributes to environmental burdens, with animal-based foods being particularly impactful (Hallström et al., 2014; Campbell et al., 2017). Food production is responsible for approximately 17 million tonnes of greenhouse gas (GHG) emissions per year, and animal-based foods account for 57 % of this (Xu et al., 2021). Beef and cow's milk are particularly impactful commodities (Karwowska et al., 2021; Xu et al., 2021). Meat from ruminants, such as cattle, is particularly concerning due to its low feed conversion ratio and inefficiency in converting dietary nitrogen, making its production resource-intensive and environmentally burdensome (Röös et al., 2013; Seidel Jr. and Whittier, 2015; Angelidis et al., 2019).

Herzon et al. (2024) and Henn et al. (2024) advocate for a comprehensive restructuring of livestock systems, emphasizing the need for both a reduction in scale and enhanced management practices to align with planetary boundaries. Others, like (Vittuari et al., 2019) and Beal et al. (2023), emphasize the importance of policies and incentives to encourage better practices in production and to limit excessive consumption, especially in regions where meat consumption far exceeds sustainable levels.

Adopting a life cycle perspective highlights the resource-intensive nature of meat production, emphasizing the importance of minimizing waste and losses throughout the supply chain. Studies have shown significant meat losses throughout the supply chain. For example, 23 % of meat is lost from the primary production to consumption stages in Europe (Karwowska et al., 2021), and 13 % of Swedish beef is lost from farm to fork (Strid and Eriksson, 2024). In Swedish abattoirs, meat losses during the slaughtering process are low (0.1 %) (Johansson, 2024), but primary production sees higher losses, reaching 8.5 % annually (Strid et al., 2023). Dairy breeds are seeing the greatest effect, with losses of 12 %, while beef and crossbreeds see lesser effects, with losses of 5.6 and 5.2 %, respectively. The majority of beef produced in Sweden originates from dairy breeds, making up 50 % of delivered carcass weight (*ibid.*).

Given the major impact of beef losses, all available methods and tools must be considered to improve supply chain efficiency and reduce consumption. In the Swedish context, one potentially impactful tool would be the utilization of the already existing Environmental Code (referred here as the Code), suggested by Eriksson et al. (2023) and Christensen et al. (2024). The Code promotes sustainable development

* Corresponding author.
E-mail address: sanna.pasanen@slu.se (S. Pasanen).

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and mandates the conservation of raw materials and energy, and the reduction of waste and harmful substances (SFS, 1998:808, Chapter 2, Section 5). Enforcing the Code to curb wasteful behaviour and practices within the food system could improve resource efficiency, particularly in terms of land use and water use (Cattaneo et al., 2021). Further, Mann and Kaiser (2023) analysed the unsuccessful attempts to implement greener agricultural policy initiatives in Switzerland. Their findings identified key reasons for these failures, including concerns over reduced self-sufficiency and the negative impact on farmers' income. Considering these challenges, the study concluded that broader food policy measures, focusing on waste reduction and resource optimization, could more effectively achieve environmental objectives for more sustainable agricultural practices. This idea resonates with the Swedish context, where enforcing the Environmental Code could tackle food waste in a manner that simultaneously supports sustainability goals. By integrating such measures within the framework of the Code, Sweden could address key challenges in food production and consumption without compromising self-sufficiency or economic viability. However, authorities responsible for enforcing this legislation, from local to national levels have so far not prioritized the implementation in practice as most of the focus has been on larger point sources of emissions, typically effluents from industries (Escudero Saukko, 2020).

An examination of court cases referencing the phrase 'not sparingly using resources' did not yield any results for the period between 1998 and 2023 (Escudero Saukko, 2020; personal communication, Christensen). Nevertheless, the Code may have indirectly contributed to resource efficiency. This influence could be seen, for example, in land use within the physical planning process or in energy efficiency when granting permits for new developments. However, such impacts may not be reflected in the database of court cases.

When applying the Code to enforce preferred behaviours, such as reducing emissions, authorities can require the adoption of best available technology, which includes technological solutions, breed selection and management practices (Thews et al., 2017; Michanek and Zetterberg, 2021). However, the enforcement of best available technology must be adapted to each sector (Cattaneo et al., 2021). Abattoirs and dairies, for instance, differ significantly in their processes and objectives, requiring tailored solutions to address their unique operational challenges in order to reduce waste.

To understand the potential of the Code to lower food losses and waste within the food system, particularly regarding meat losses, a scenario quantifying the potential outcomes arising from the implementation of best available technology could provide valuable insights. The hypothesis of this study is that best available technology in the dairy sector, regarding meat waste from dairy herds, can be defined as having a lower loss rate than other comparable farms. In this study, the best available technology is defined as farms with loss rates below the current median for each farm type. This hypothesis could be falsified if farms are not comparable at all or if loss rates are so uniform that it becomes impossible to differentiate between better and worse performance.

To compare farm types, we considered that beef can originate from different breeds and farms with varying production strategies, such as suckler calf systems, specialized beef production, specialized dairy production, or dual-purpose dairy/beef production (Strid et al., 2023). These production systems are expected to have discrepancies in average loss rates. Consequently, each breed and farm type would require its own median benchmark. To simplify the analysis and demonstrate the study hypothesis, we focused exclusively on dairy breeds and categorized farms into three distinct types based on their production profiles. To verify variability within each farm type, we analysed the distribution of loss rates among individual farms.

By focusing on meat loss rates within dairy farms, this research provides insights into how the existing Environmental Code could be applied to reduce losses and improve sustainability in the Swedish beef sector. These findings are intended to support policymakers, industry stakeholders, and the scientific community in evaluating strategies to enhance resource efficiency and reduce environmental impacts.

The objective of the study was to explore the potential environmental benefits of enforcing the existing Swedish legislation, under which loss rates exceeding the present median for each farm type would be considered unlawful and subject to reduction down to the median level.

The study was organized around four main aims:

1. Identifying meat loss rates for dairy breeds at individual farms in Sweden.
2. Determining the median loss rate and the distribution of loss rates for each of the three farm types.
3. Quantifying the potential beef savings by reducing loss rates above the median down to the median level.
4. Assessing the potential economic value for farmers and the environmental benefits, particularly in terms of reduced carbon footprint, of minimizing meat waste.

In the meat sector, the best available technology can be defined as achieving a low loss rate, which indicates that a farm has minimal losses relative to its production volumes compared to other farms. However, due to diversity of farm types, such as specialized beef, specialized dairy, or dual-purpose farms, comparisons should only be made among similar farm types. The average loss rates among these farm types can be expected to present major discrepancies (Strid et al., 2023), with each farm type needing their own benchmark. This approach has been successfully applied in the catering industry (Eriksson et al., 2023) to assess the potential benefits of enforcing waste reduction, but the corresponding potential for the beef industry is yet unknown.

This study therefore aims to quantify meat loss rates at individual farms in Sweden, based on reported mortality and recorded slaughter weights. In addition, it explores different perspectives on loss quantification and reduction potential through counterfactual scenarios. The goal of the present study is to explore the potential of using legislation to enforce practices that prevent losses to make the food system more sustainable.

2. Methods and material

Material Flow Analysis (MFA) was the fundamental method of the study and was used to analyse the flows of produced and lost animals, including their corresponding carcass weights, at individual farms in Sweden. MFA is a well-established method which enables a detailed, systematic and quantitative analysis of the material flows in a system (Brunner and Rechberger, 2016), and has previously been used to study farm level loss of beef at national scale in Sweden (Strid et al., 2023), and post-farm gate losses of beef in the Italian beef supply chain (Amicarelli et al., 2021).

With MFA, beef flows within the Swedish cattle production system were analysed at farm level. This included a summary of the number of cattle per farm which was then converted into the corresponding meat yield (carcass weight). This meat yield was subsequently multiplied by emission factors and economic data to estimate the environmental impact and financial implications of loss reduction.

2.1. System boundaries

The system boundaries considered in this study include the farm site at the lowest resolution and then aggregated to the Swedish national level for all included farm sites. For each farm site, the flows of cattle exiting the farm, and if applicable entering the farm from other farms, were considered (Fig. 1). The exit pathways were: Transferred as live animal to other farm, sent to abattoir slaughter, Home-slaughtered, Deceased/Euthanized on-farm with or without sent to destruction facility. The entry pathway was: Transferred as live animal from another farm. These flows were summarized on a yearly basis to make up the

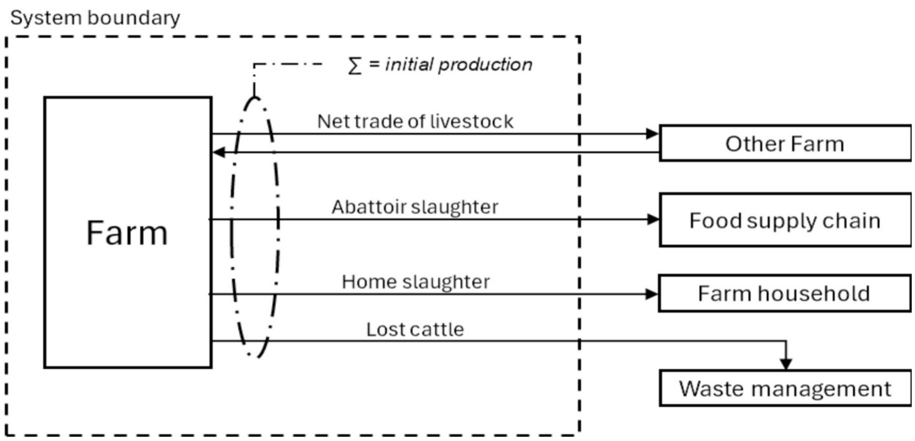

Fig. 1. The studied yearly flows of each individual farm.

farm's initial production (the production before losses).

The number of animals present at the start of each year, as well as newly born individuals, were not included in this calculation. However, slaughtered cattle, stillborn calves, and deceased cattle on the premises are included. Lastly, to ensure a holistic representation of the mass balance, livestock movement is also accounted for in terms of selection criteria and categorization.

The study scope is limited to farms with dairy breeds, as Strid et al. (2023) have concluded that dairy females constitute a hot spot for beef losses, closely followed by males of the same breed. This higher dairy cow mortality is due to multiple risks related to the dairy production system (Alvåsen et al., 2014), making it a good target for waste reduction policies.

2.2. Main data source

This study utilised data from the central register of bovine animals (CDB) maintained by the Swedish Board of Agriculture (SBA). The CDB register contains detailed information on all Swedish cattle, such as holding site, sex, age, breed, and life events (SJVFS, 2021:13; European Commission, 2000). In accordance with EU legislation (European Union, 2019; European Union, 2021), all farmers must report to their national register the events of each individual cattle, such as birth, inter-farm site movements, on-farm death, or slaughter throughout their lives.

Each animal is linked to a specific holding site number, enabling the count of animals per farm site. However, one farming enterprise can have several farm sites if the distance between animal facilities exceeds 500 m. For simplicity, the present study refers to each farm site as one farm, but in practice, some of the sites are owned by a common farm enterprise, meaning that the legal accountability would refer to the average value of these farm sites.

The raw data extracted from CDB (SBA, 2022a) provided the foundation for this study. Based on the breed registered in CDB, the cattle were sorted into three different breed groups: dairy, beef, and crossbreeds. However, a single cattle farm may have several breeds depending on production niche, meaning they might produce both dairy and meat and, therefore, use breeds adapted for each purpose.

2.3. Selection and classification of data

Since authorities can only demand the use of Best Practice from professional actors, in accordance with the Swedish Environmental Code (Chapter 2, Section 3, first paragraph), there was a need to exclude small, hobby-based farms from the material. The CDB registry does not include information regarding how the animals are used and, for the purpose of this study, professional farms were defined as holding a minimum of 10 registered cattle each of the years studied. All farms not fulfilling these criteria were excluded from the analysis.

Likewise, since the study seeks to inform future actions within the dairy beef sector, farms lacking production for the food supply chain (*i.e.*, animals sent for abattoir slaughter) for all six years were considered as discontinued farms and were excluded from further analysis.

There were 9832 farms with dairy cattle in Sweden, representing 53 % of all livestock farms in the country (Fig. 2). These farms may also have other breed types, but all farms included in this study have dairy cattle, and the loss calculations focus solely on dairy cattle. The requirement for at least 10 animals excluded 5570 farms, and the need to send at least one cattle to slaughter removed another 40 farms. This left 4222 farms with 650,340 registered cattle, covering 43 % of the original number of farms with dairy cattle and 92 % of the registered dairy breed cattle.

Outliers were attributed to anomalies in net trades (Eq.1) affecting initial production values (Eq.2). When farms purchase more cattle than they sell, net trade become negative, resulting in a negative loss rate. A loss rate over 100 % could indicate a negative net trade but with higher slaughter and loss amounts, leading to a small initial production value. The outliers were included in all calculations to maintain the integrity of the data but were excluded from visual presentation. To ensure outliers had less influence on the materials, the median value was used rather than the mean value.

To establish fair industry benchmarks for implementing Best Available Practice, farms needed to be grouped based on normal waste levels. A previous study (Ayala et al., 2024) highlighted the importance of categorizing farms according to specific characteristics, as this helps to capture the significant heterogeneity within agricultural systems. Strid

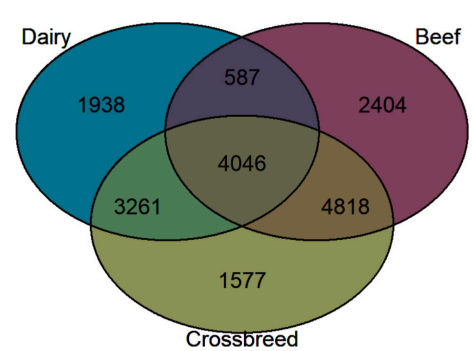

Fig. 2. Venn diagram illustrating the distribution of farms with dairy cattle (Dairy), beef cattle (Beef), and crossbred cattle (Crossbreed). The diagram shows how dairy farms may also raise beef or crossbred cattle, but the study focuses solely on losses related to dairy cattle. The numbers represent the total number of farms in each category, with the intersections highlighting overlap across categories.

et al. (2023) also showed that adult female dairy breeds have considerably higher loss rates than other cattle, further underlining the need to classify farms based on key factors such as the proportion of adult females. This categorization, defined as the percentage of dairy females aged 24 months or older, referred to as cows, sent for slaughter at each farm, resulted in the emergence of three distinct groups (Fig. 3):

2.3.1. Specialized beef

The first group (represented by purple bars in Fig. 3) comprised farms with less than 25 % of abattoir-slaughtered cattle being cows. These farms typically purchase dairy calves for fattening from neighbouring dairy farmers and, thus, have a low number of female cattle ≥24 months sent to the abattoir. The group included a total of 888 farms.

2.3.2. Dual purpose

The second group (represented by blue bars in Fig. 3) comprised 1248 farms with 25–75 % of abattoir-slaughtered cattle being cows. These farms produce both milk and beef from cows and heifers that are considered unsuitable for further insemination or as replacements in the herd. Farms in this group keep their male calves for fattening for beef production. Consequently, these farms have a higher prevalence of cow slaughter than the specialized beef group.

2.3.3. Specialized dairy

The third group (represented by green bars in Fig. 3) included 2087 farms with more than 75 % of the abattoir-slaughtered being cows. This group of farms niched to milk production, thus keeping the heifers for replacement and selling the male calves. Hence, a vast majority of the slaughtered cattle from this farm type consists of cows.

2.4. Curation of data

This study is based on an analysis of factual meat losses on farm level. Accordingly, the definition of lost meat in this study refers to the actual reported number of cattle that died or were euthanised on-farm converted into their corresponding carcass weight (*i.e.* the weight they would have had as skinned and eviscerated whole carcass with bones) at the time of death. The carcass weights used in this research originated from *Regina* (SBA, 2022b), an official database collecting slaughter weights. These weights varied by breed, age and sex of the animal. The conversion of cattle lost on-farm (*i.e.*, euthanized or those that died unassisted) to carcass weight assumes that the weight of these animals is equivalent to that of slaughtered animals. As the cause of death is not reported to the CDB, it is not possible to estimate how much of the carcass could have ended up as food for human consumption.

2.5. Calculations of carcass weights and loss rate

To convert the number of cattle to carcass weight per farm, the carcass weight for each age group and sex was multiplied by the number of cattle in that age group and sex per farm. Conversion to carcass weight included the total registered cattle per farm and all event codes reported by farmers (born, stillborn, sold, bought, abattoir slaughter, home slaughter[1]) and lost cattle per farm. More details on the data and calculations can be found in the supplementary material.

To calculate the mass of meat initially produced at each farm, net trade (Eq. 1), which is the difference between sold and bought cattle, along with meat from abattoir slaughter, home slaughter, and on-farm losses (including stillborn animals, euthanized animals, and those that died unassisted) were considered (Eq. 2). This total, referred to as initial production, represents the total amount of meat intended for the food supply chain.

$$\text{Net trade} = \text{sold} - \text{bought}. \tag{1}$$

$$\text{Initial production} = \sum(\text{net trade} + \text{abattoir slaughter} + \text{home slaughter} + \text{on farm losses}). \tag{2}$$

The relative loss of meat (loss rate) was calculated based on the work of Strid et al. (2023) as a share of the total outflow, expressed as losses of carcass weight per farm to initial production (Eq. 3).

$$\text{Relative loss of meat (\%)} = (\text{Total losses}/\text{Initial production})^{*}100. \tag{3}$$

2.6. Potential loss reduction through legislative enforcement

This scenario aims to estimate the potential for reducing on-farm meat loss, generated emissions, and economic impact, if the median loss rate is adopted as a feasible level achievable through current best practices. This choice is based on the intentions expressed in the preparatory work for the Code (Swedish Government, 1997, p.17) 98:45, part 2, p. 17), which specifies that the best available technology should be economically and practically feasible for the sector. By setting the median loss rate as an upper limit, loss rates above this threshold would be considered unlawful, compelling actors to reduce their loss rates accordingly.

Since 50 % of farms already maintain losses at or below the median, this suggests that effective measures to manage on-farm meat losses are already in place. Furthermore, as these measures reflect current practices, they are grounded in the economic feasibility of the agricultural sector. The median level was applied separately to the three groups: specialized beef, dual-purpose, and specialized dairy. It was assumed that all farms currently exceeding the median loss level could reduce their losses to meet this benchmark. Integrating this approach into environmental regulations could, therefore, be a practical and effective strategy for reducing on-farm losses.

2.7. Alternative perspective on meat losses

This counterfactual scenario explores an alternative approach to quantifying meat losses, representing the potential carcass weight animals would have achieved if they had survived to slaughter age, rather than their actual weight at death. While this provides a useful contrast to the reported and factual meat losses, it may overestimate actual meat loss, as slaughter typically occurs across a range of ages and not all animals follow the average growth trajectory. This approach can provide an important perspective and transparency to meat losses. It should therefore be interpreted as a theoretical upper-bound estimate rather than a precise prediction of meat loss.

Animals were classified as premature deaths if they died below the

[1] Home slaughter refers to the on-farm slaughter of cattle by the farmer, with the meat used exclusively for consumption within the household (SBA, 2024b).

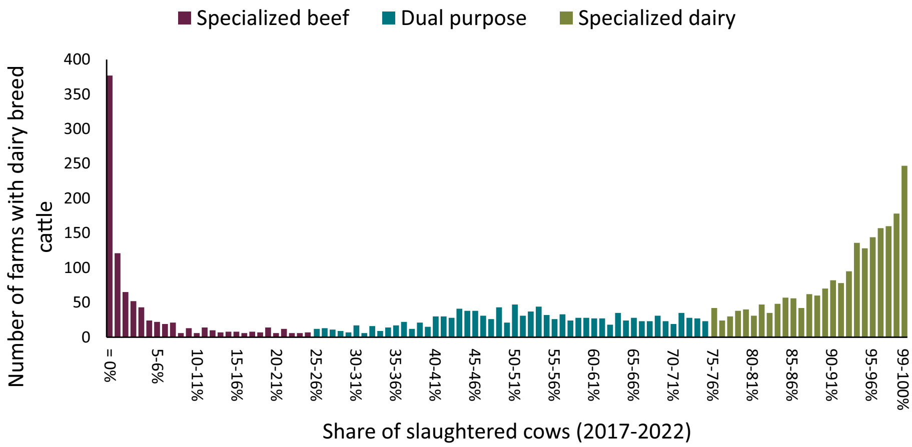

Fig. 3. Categorization of selected farms ($n = 4222$) based on production practices, defined by the share of slaughtered cows: 0–25 %, 25–75 %, and 75–100 %.

interpolated average slaughter age for their sex and were assigned the average carcass weight of animals at slaughter age. The same farm groups (specialized beef, dual-purpose, and specialized dairy) were maintained for this scenario. Calculation of average slaughter age and carcass weights is provided in the e-supplementary material.

2.8. Calculation of carbon footprint and lost revenues

Considering beef as the only output, the carbon footprint corresponding to the lost meat were calculated using emission factors of tonnes of CO_2e per tonne of carcass weight based on a study by von Greyerz et al. (2023). The emission factors applied were based on cradle-to-gate LCA methodology, encompassing all emissions from birth until animals leave the farm, including feed production, enteric fermentation, manure management, and on-farm energy use. These factors therefore capture the complete on-farm carbon footprint of animals regardless of whether they reach slaughter or die on-farm.

The carbon footprint factors are 22 kg CO_2e per kg CW for specialized beef, 21 for dual purpose, and 16 for specialized dairy (Table 1). The meat loss for each farm in each group was multiplied by the corresponding emission factor to quantify the CO_2e associated with the lost meat. Through substitution, this quantifies the emissions that could be avoided when meat losses are reduced, as the additional meat reaching slaughter would substitute equivalent production elsewhere in the system.

To estimate the financial impact of meat losses, the total carcass weight of lost animals was multiplied by the average slaughter value per kg carcass weight. This calculation provides an estimate of lost revenue rather than a profitability measure, since production costs have not been subtracted. We acknowledge that variable costs are incurred during animal rearing, with these costs being lower for animals that die young and higher for older animals that die on-farm. An alternative approach would be to present gross margin, where costs are subtracted from revenue. However, this more thorough economic analysis was not within the scope of this study.

The revenue calculations were based on estimated slaughter values (SBA, 2024a, 2024b) (Table 1). Additionally, on-farm mortality incurs destruction cost of 600 € per tonne CW, excluding VAT (Swedish Agricultural Services Ltd, 2023). This cost would be avoided if animals survived to slaughter.

Table 1
Carbon footprint (*CF*) factors (von Greyerz et al., 2023) and average slaughter prices in Sweden 2023 (SBA, 2024a) per group in this study.

Group	*CF* (kg CO_2e/kg CW)	Slaughter value (€/ kg of CW)
Specialized dairy	16	4.6[a]
Dual purpose	21	4.8[b]
Specialized beef	22	5.1[c]

[a] Cow, conformation O, fat cover class 3, according to the European Union's EUROP grid method of carcass classification (European Commission et al., 2024).
[b] Average value based on prices for young bull and cow carcass value.
[c] Young bull, conformation R, fat cover class 3, according to the European Union's EUROP grid method of carcass classification (European Commission et al., 2024).

3. Results

An average of 8200 t of dairy breed meat carcass weight was lost annually during 2017–2022, from the 4222 studied farms. This loss corresponds to 150,000 t of CO_2e/year and a cost of €44 million/year from lost revenue and carcass destruction costs. The average meat loss per farm was 1.9 t, corresponding to 37 t of CO_2e and a revenue loss of €10,500 annually. The median farm had an annual loss of 0.95 t of meat, equivalent to a loss rate of 10 %.

If the share of farms exceeding the median could reduce losses to this level, the meat losses generated would be reduced by 34 %, corresponding to a potential saving of 2800 t/year of meat. This waste reduction would decrease the CO_2e associated with meat losses by 52,000 t/year and reduce monetary losses by €15 million/year. However, the reduction potential varies greatly depending on what type of production the farms are focused on, as illustrated in Fig. 4. The next section explores the reduction potential for farms specialized in dairy production, dual-purpose production, and specialized beef production.

3.1. Specialized dairy

In the specialized dairy sector, the 2087 farms lost a total of 4800 t of meat annually, representing the highest loss rate of 17 %. These losses

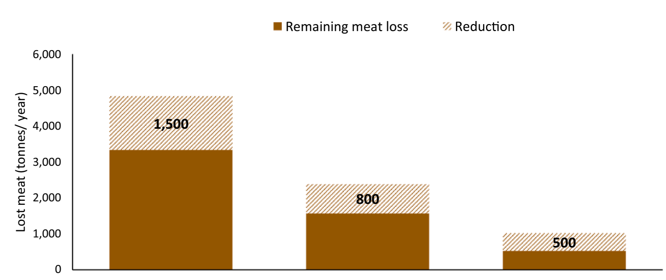

Fig. 4. Yearly meat losses, where the dashed portion represents the potential reduction in losses if farms exceeding the median loss rate reduce their losses to the median level.

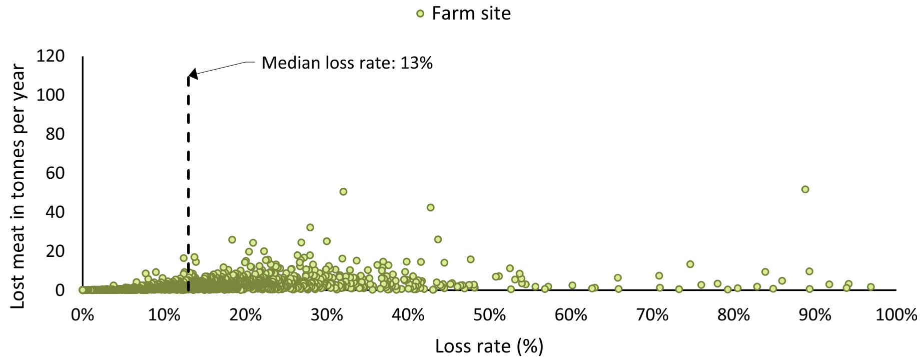

Fig. 5. Meat losses in tonnes per farm specialized in dairy plotted against the corresponding loss rate. The dashed line represents the median loss rate for this specific group.

corresponded to 77,000 t of CO_2e and €25 million in revenue losses each year. Each farm lost an average of 2.3 t per year, representing 37 t of CO_2e and €12,000 in lost revenue annually. The median farm in this group experienced a loss rate of 13 %. The distribution of each farm's meat losses in relation to the farm loss rate is shown in Fig. 5. The 1043 farms above median loss rate lost an average of 3.6 t of meat per year, corresponding to 57 t of CO_2e and a lost revenue of €18,500.

If the farms with a loss rate exceeding the median loss rate reduced the loss rate to 13 %, annual meat losses would be reduced by 31 %, leading to 1500 t of additional meat reaching slaughter, which represents 23,900 t of CO_2e, and €7.7 million in revenue each year. At the farm level, this reduction translates to 1.4 t of additional meat reaching slaughter, corresponding to 23 t of CO_2e, and €7400 in reduced revenue losses annually.

3.2. *Dual purpose*

The dual-purpose group, which combines dairy production with bull fattening ($n = 1247$), lost 2400 t of meat annually, resulting in a loss rate of 13 %. These losses corresponded to 50,100 t of CO_2e and a revenue reduction of €13 million each year. On average, 1.9 t of meat were lost per farm annually, representing 40 t of CO_2e and a revenue loss of €10,400. The distribution of meat losses for each farm in relation to their loss rate is shown in Fig. 6, where the median loss rate of 9.6 % is indicated. The 623 farms above the median loss rate lost an average of 3.1 t of meat per year, corresponding to 64 t of CO_2e and loss of €16,000 in revenue per year.

By limiting losses to the current median threshold of 9.6 % for this group (Fig. 6), 34 % of waste could be reduced. This would result in 820 t of additional meat reaching slaughter, representing 17,000 t of CO_2e, and achieving cost savings of €490,000 by avoiding carcass destruction. Additionally, this approach could generate up to €4 million in revenue if these cattle could be sent for slaughter instead. On average, each farm could reduce meat losses by 1.3 t of meat per year, representing 27 t of CO_2e and preventing revenue losses of €7100 per year.

3.3. *Specialized beef*

Farms specializing in dairy bulls ($n = 888$) experienced the lowest meat losses, with 1000 t lost per year, equating to a loss rate of 5.4 %. These losses represent a carbon footprint of 22,000 t of CO_2e and lost revenue of €5.7 million annually. Each farm lost an average of 1.1 t of meat per year, corresponding to 25 t of CO_2e and a revenue loss of €6500. The median farm had a loss rate of 3.4 %. The median is plotted in Fig. 7, along with the distribution of every farm's meat loss in relation to their respective loss rates. The 444 farms above median loss rate lost an average of 2 t of meat per year, corresponding to 44 t of CO_2e and a revenue loss of €11,000 per year.

The quantification of meat losses showed that an additional 500 t of meat could enter the food supply chain, representing 11,000 t of CO_2e, and €2.8 million in revenue could be recovered annually if the waste was limited to the current median loss on farms specializing in beef from dairy breeds. This is equal to a 48 % reduction of losses within this group of farms.

3.4. *Alternative perspective on meat losses*

This scenario calculated meat losses based on the weight animals would have achieved at slaughter maturity, instead of their actual weight when they died on-farm. The results show an increase of meat losses by 116 %, from 8200 t to 17,800 t per year. These meat losses represent a carbon footprint of 370,000 t of CO_2e and a revenue loss of €88 million.

The group with specialized dairy farms showed that if all animals

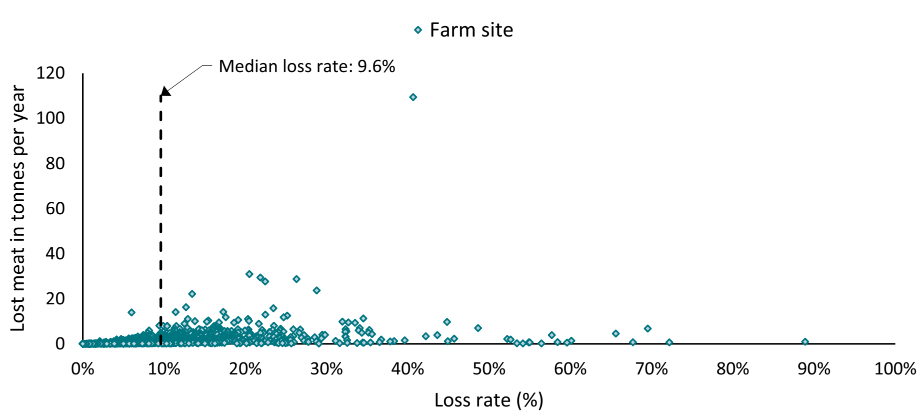

Fig. 6. Meat losses in tonnes per dual purpose farm plotted against the corresponding loss rate. The dashed line represents the median loss rate for this specific group.

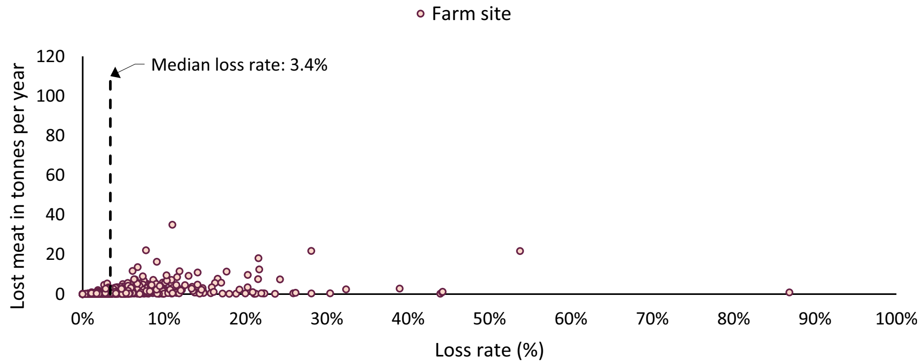

Fig. 7. Meat losses in tonnes per specialized beef farm plotted against the corresponding loss rate. The dashed line represents the median loss rate for this specific group.

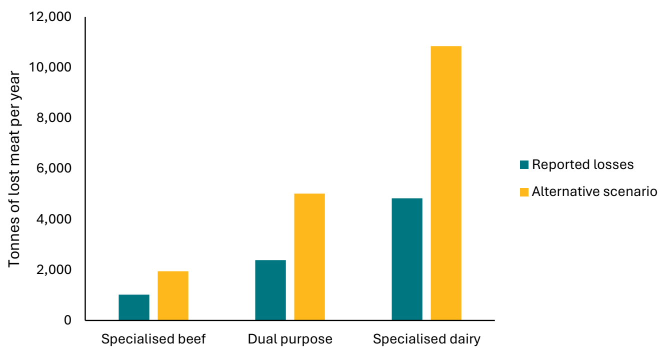

Fig. 8. Meat losses under reported conditions *versus* alternative scenario by farm type. Reported losses reflect actual carcass weight at time of death, while alternative scenario estimates potential losses based on theoretical slaughter weight at maturity. Values shown in tonnes of lost meat per year.

that died prematurely survived, they could have produced 10,800 t of meat in CW (Fig. 8), which is an increase of 125 % compared with the reported losses (4800 t of CW). These counterfactual meat losses represent 240,000 t of CO_2e and a revenue loss of €55 million.

Dual-purpose farms showed a similar increase (110 %) in meat losses. If all cattle that died prematurely had survived to average slaughter age, the total potential loss would reach 5000 t (Fig. 8), representing a carbon footprint of 105,000 t of CO_2e and a revenue loss of €24 million.

The specialized beef farms would nearly double their losses, reaching 2000 t of meat, if prematurely deceased cattle had survived and been slaughtered at the appropriate age (Fig. 8). This represents a 91 % increase compared to the actual reported losses. The carbon footprint and revenue losses would reach 31,000 t of CO_2e and €9 million, respectively.

4. Discussion

The farms included in this study lost an average of 2 t of meat per farm annually, with 60 % of all meat loss occurring at the 2087 specialized dairy farms. These farms had an average loss rate of 17 %, equivalent to 2.3 t of lost meat per farm per year. This is primarily because dairy farms prioritize milk production over meat, leading to lower-value meat from older dairy cows. Additionally, dairy cows tend to live longer than fattening bulls, increasing their risk of on-farm mortality (Thomsen, 2023; Alvåsen et al., 2014). As cows age, the risk of complications, such as claw or leg disorders and mastitis, increases (Alvåsen et al., 2014). Calving is a high-risk event and approximately one-third of on-farm cow mortality occurred within the first month after calving (Thomsen, 2023, Alvåsen et al., 2014).

There are discrepancies between farms, indicating room for improvement through the implementation of existing routines and technologies. Many farms manage to achieve low loss levels, and these can be found across all three groups. Within the specialized dairy group, 235 out of 2087 farms had a loss rate below 6 %, suggesting that existing knowledge is sufficient but needs better implementation on farms with high losses.

It is the variations in loss rates that provide the grounds for the possibilities to reduce losses down to the levels of the most efficient farms. If all farms had the same loss rates, there would be no learning potential within the system to utilize. The variations we found were large enough to enable a substantial reduction if the high-loss farms would learn from the low-loss farms how to produce beef with low losses.

Loss rates are not likely to reach zero, as there will be many cases where harm to an animal is hard to predict and therefore not possible to prevent. Additionally, some animals may need to be sacrificed because they are undergoing medical treatment or are too ill to be suitable for food. Since half of all Swedish dairy breed farms currently achieve a loss rate below the median loss level, this should be viewed as a moderate benchmark for all to strive for.

Building on this understanding of farm-specific variations, it is critical to consider policy measures that address these disparities and enforce reductions on farms with the greatest potential for loss reduction. Given the diversity in farming practices, a 'one-size-fits-all' solution may not be realistic. It is essential that these measures are tailored to the specific conditions and operational practices of each farm type. The present study suggests using the median loss rate as a benchmark, which could be enforced through the Environmental Code or other regulatory measures. Furthermore, adopting the median loss level offers flexibility, as it adjusts to the current loss levels within each specific group. As losses decrease, a new median level is generated, offering a realistic and adaptable benchmark that reflects each group's unique conditions and production systems. It is important, however, to view this median as a starting point, not the final goal for waste reduction. By enforcing the median loss rate, this study shows that all three farm groups could collectively reduce losses by 34 %, leading to 2800 t more meat reaching the food supply chain annually.

Beyond the direct reduction of lost meat, the baseline losses in this study contribute approximately 2.3 % to Sweden's total agricultural emissions (The Swedish Environmental Protection Agency, 2023). Bringing overall meat losses down to the median loss rate across the three farm types could improve emission efficiency by reducing wasted emissions, where 52,000 t of CO_2e are currently associated with animals that do not reach the food supply chain. This represents nearly 1 % of total agricultural emissions in Sweden. Additionally, increased meat output could yield economic benefits amounting to €15 million. This underscores the potential for improved efficiency in meat production, along with increased profitability for farmers through reduced on-farm mortality. To put the scale of these wasted emissions in perspective, the 52,000 t CO_2e can be compared to the Climate Leap, the Swedish climate investment program, which so far has granted €1300 million for measures reducing greenhouse gas emissions by 2.8 million tons annually (The Swedish Environmental Protection Agency, 2024).

Specialized beef group has the greatest relative reduction potential, with a possible 48 % of their meat losses able to be saved each year. Dual-purpose farms follow with 34 %, while specialized dairy farms had a lower potential at 31 %.

The differences in reduction potential are due to multiple factors, including differences in number of farms, loss levels, meat value, opportunities for optimization, and animal management practices. The group specializing in beef includes the lowest number of farms, with only 444 farms needing to reduce their losses, whereas a larger portion of specialized dairy farms (1043) face similar challenges. Another aspect to consider is the 50 % of farms below the median that experience such low losses, yielding a median loss rate of only 3.4 %. Consequently, the other 50 % of farms (above the median) face a particularly challenging target for reducing their losses to such a low level, resulting in a high relative reduction potential. However, meat from farms specializing in beef typically has a higher market value, which encourages these farms to continuously adopt measures to reduce on-farm losses.

The farms specializing in dairy have the lowest reduction potential at 31 %, even though this group accounts for a larger share of total meat losses. This is mainly explained by the greater overall losses at these farms, which results in a high median loss rate of 13 %. Another important aspect to acknowledge is that farms specialized in dairy focus on milk production, meaning meat from cows is often viewed as a by-product, leading to less emphasis on optimization of meat quality. The low reduction potential could thus suggest that these farms may find it challenging to adopt practices focused on reducing meat losses. This may be because their investments in improving animal health and longevity are likely prioritized towards maximizing milk output.

It is important to note that most farmers already have a vested interest in ensuring that their cows maintain healthy and productive. One of the biggest challenges they face is determining the appropriate time to send the cows to slaughter, as they need to ensure that the animals are fit for transport.

When an animal shows early signs of illness or lameness, it can create a dilemma for farmers. These cases fall within a grey area, requiring careful judgment. Farmers may hesitate to send an animal with early symptoms to the abattoir, concerned that transportation could worsen its condition or compromise its welfare. Additionally, there is a risk of animal welfare reports at the slaughterhouse, as veterinarians are required to flag any issues. To avoid these risks, farmers may ultimately choose to euthanize the animal on-farm and send the carcass for destruction.

However, cattle farmers are not alone in facing these types of dilemmas. This phenomenon has been observed in other food-producing sectors, such as bakery (Ghosh and Eriksson, 2019; Weber et al., 2023) and fresh fruit and vegetables (Eriksson et al., 2012). Producers or retailers often choose to avoid the risk of scrutiny over food safety and product quality, even though this increases the likelihood of on-farm losses.

Building on the previous analysis, the data indicates that there is a large potential for targeted interventions in both specialized beef and specialized dairy farms. However, it is important to recognize distinct operational conditions and objectives when developing these interventions, particularly for farms with high losses. The idea of addressing farms with the highest waste, which have the greatest potential for improvement, has previously been suggested for various parts of the food supply chain, including consumers (Malefors et al., 2024), canteens (Eriksson et al., 2017), tourist hotels (Obersteiner et al., 2021) and bakery products (Brancoli et al., 2019), but the potential for cattle farms has so far been overlooked. If the livestock sector manages to reduce losses, the new median will become lower, necessitating continuous adjustments to the level of Best Available Technology to match this new standard. This creates a scenario where the sector must constantly improve to set levels. However, future definitions of Best Available Technology may be based on criteria other than just the median level of losses.

As this study addresses a novel area, it is important to acknowledge certain limitations. For instance, some farms experience substantial meat losses each year but still fall below the median loss rate. This occurs because they produce a large quantity of meat by selling more cattle than they buy, which influences the 'initial production' factor in the calculation of the loss rate. Consequently, if legislation is enforced, as suggested in this study, these farms may not be effectively addressed. Conversely, some farms above the median loss rate may have lower total meat losses, but their loss rates may appear high because they purchase a large number of cattle.

Further limitations include the assumption that the weight of cattle that died on-farm is the same as that of cattle sent for abattoir slaughter, which might not always be accurate. A Finnish study found that mastitis and digestive disorders were the leading causes of on-farm death in dairy cows (Hagner et al., 2023). These illnesses can cause weight loss and poor body condition, leading to an overestimation of usable meat losses, as sick cows may be significantly thinner or emaciated. Moreover, the voluntary nature of reporting stillbirths could result in an underestimation of total losses, since not all cases may be reported.

Relying on self-reported data can lead to potential inaccuracies. Mistakes such as keying errors could occur but are considered to have only a minor impact on data integrity. Furthermore, while non-compliance may lead to deductions in EU subsidies, there remains a possibility of fraudulent reporting, which can distort collected data (Funke).

A hypothetical example of fraudulent behaviour could occur if a farmer home slaughters cattle, reports it as lost, and then sells it for consumption. Even though this behaviour lacks economic incentives for the farmer, its actual frequency remains uncertain. Nevertheless, it could compromise the integrity of the data in this study, leading to an overestimation of losses. The legal framework permits farmers to slaughter an unlimited number of cattle themselves for household consumption (SBA, 2024b), but this meat cannot be sold to consumers outside the household. However, this channel is likely the one farmer would choose if they intended to sell the meat illegitimately. Thus, as home slaughter is accounted for as food and not meat losses, the integrity of the data in this study is maintained.

While reducing losses at the farm level might seem like a straightforward way to lower emissions, since fewer animals would be raised in vain, the actual outcome is far more complex. Providing nuance to this complexity, Cattaneo et al. (2021) emphasize a perspective influenced by market dynamics and consumer behaviour, while Wang et al. (2021) highlight food security and resource sustainability.

If fewer losses lead to an increased supply of meat, market prices may drop, making meat more attractive to consumers and potentially driving up demand (Cattaneo et al., 2021). This could incentivize further production, potentially offsetting the initial environmental gains. The extent to which this occurs depends on the strength and speed of price transmission through the supply chain. This highlights the need to consider both economic mechanisms and consumer behaviour when evaluating the true impact of loss reduction. Similarly, Wang et al. (2021) stress that reducing food loss and waste can improve food security by lowering food prices, benefiting consumers in developing countries where food costs represent a larger portion of household budgets. However, they also highlight the rebound effect, where reduced waste leads to higher consumption, which could diminish the long-term environmental benefits of food loss reduction. In combination, these insights further underscore the complexity of evaluating the effects of loss reduction strategies and demonstrate that their consequences extend beyond the farm. Nevertheless, market responses to reduced farm losses may be influenced by other policy instruments as well. Here, fiscal measures such as climate taxes on food consumption could alter the relative prices of different food products, thereby affecting consumption patterns (Moberg et al., 2019; Röös et al., 2021). Also, dietary guidelines and trade regulations can either amplify or counteract price-driven consumption changes. The complexity of such policy interactions is illustrated in Sweden, where health authorities recommend reduced meat consumption while government policy emphasizes domestic production and food security priorities (Long, 2024). These market and policy interactions add another layer of complexity to evaluating the environmental impact of loss reduction, as do the underlying assumptions about emissions calculations themselves.

Furthermore, the emission calculations in this study represent the carbon footprint of lost meat but reduced on-farm mortality would not necessarily lead to emission reductions. This is a matter of methodological considerations regarding emission accounting. The emission calculations represent the carbon footprint associated with animals that currently do not reach the food supply chain. If more animals survive to slaughter age, total system emissions could actually increase, as these animals would continue emitting CO_2e throughout their extended lifespan.

The environmental implications of reduced mortality depend on system boundaries and methodological choices. A farm-level perspective focusing solely on on-farm effects might show increased total emissions as animals live longer. A market-oriented approach considers that additional meat reaching Swedish markets will not increase consumption, but instead substitute production elsewhere, particularly given the demand-driven nature of the meat value chain. It is not likely that abattoir will slaughter more cattle because more cattle is available on Swedish farms, unless there are economic incentives for abattoirs to increase slaughter due to increased demand from retail. However, both perspectives provide valid insights depending on the analytical purpose, with market-oriented assessment being particularly relevant for the counterfactual scenario in this study.

An alternative perspective, not explored in this study, would be to examine whether improved survival rates could allow the same meat production from fewer animals overall. For instance, if fewer animals die on-farm, farmers might need fewer replacement animals, potentially reducing total herd size and system emissions. However, such analysis would require careful consideration of herd management strategies and how emissions are allocated between milk and beef production.

Despite these limitations, the alignment of our findings with previous studies suggests that our methodology remains robust and reliable. For instance, the 13 % loss rate found in this study aligns with Strid et al. (2023), who reported a 12 % loss rate for dairy breeds in Sweden. The small difference likely stems from variations in timeframe and the inclusion of net trade data, which Strid et al. (2023) did not account for. Similarly, Lindow and Andersson (2022) found a 14 % loss rate for Swedish cattle farms, where the slight difference in value may be due to differences in calculation methods and terminology.

Ultimately, to reduce meat losses on Swedish farms, it is necessary to address the systemic issues contributing to on-farm deaths, particularly in the dairy sector. A first step would be to incentivize farmers to prioritize preventative care, thus reducing on-farm mortality. This could be achieved by enforcing the use of best available technology through the already existing Environmental Code. However, it is crucial that regulatory authorities prioritize and rigorously enforce these provisions as outlined in the Code, ensuring that farm inspections not only monitor compliance but also provide support to farmers in reducing losses and improving resource management. Additionally, as this study highlights, even a moderate waste reduction target could have a major potential, as beef is a valuable commodity with a substantial climate footprint. Given that many farms already achieve low loss rates, new innovations are not necessarily needed; instead, the implementation of suitable technologies, priorities, and routines on farms that currently experience higher levels of meat loss is required. This is supported by findings by Tseng et al. (2021), who demonstrated that optimizing existing management practices, rather than relying on entirely new innovations, can enhance sustainability in agricultural systems. This focused effort could reduce the impact from beef production, contributing to a sustainable transition of the food system.

Within the EU, the Waste Framework Directive (Directive 2008/98/EC, revised in 2018) provides the overarching legal framework for waste management, with food waste prevention ranked as the top priority in the waste hierarchy (European Parliament, 2024). The directive commits Member States to promoting food waste reduction in line with UN Sustainable Development Goal 12.3. This requires measurement, reporting, and potential adoption of EU-wide reduction targets by 2030. This shared regulatory framework means that the enforcement approach examined here could be replicated across EU Member States, contributing to both climate targets and waste prevention goals through existing environmental legislation. Although primary production is currently exempted from the Waste Framework Directive's food waste reduction requirements, the necessary data infrastructure for loss quantification already exists through mandatory livestock traceability systems. EU regulations require all cattle to be registered in national databases, creating comprehensive records of births, movements, slaughter, and on-farm deaths (European Union, 2016, European Union, 2019; European Union, 2021). Quantifying losses at farm-level enables assessment of current loss magnitudes, which provides valuable baseline information. Increased knowledge is a fundamental prerequisite for change, whether it occurs through voluntary initiatives or regulatory measures.

Regulatory frameworks have the potential to enforce a substantial reduction of on farm meat losses, provided that the relevant laws are implemented. However, regulatory enforcement must be coupled with farmer education and advisory support to ensure that farms have both the capability and knowledge to respond effectively to compliance requirements. If compliance with the resource-saving provisions of the Code is actively monitored on farm level by regulatory authorities and strictly adhered to, this could create incentives for farmers to adopt best available technology.

In addition to regulatory efforts, farmers' collective action, supported by advisory bodies, extension services, and the Swedish Board of Agriculture, can play a crucial role in disseminating best available technology. Such support is particularly important for addressing information or skills gaps that may constrain farmers' ability to reduce mortality. This could strengthen the effectiveness of climate measures and contribute to a more sustainable agricultural sector.

5. Conclusions

This study reveals substantial potential for reducing meat losses across Swedish dairy cattle farms, with implications extending beyond national borders. A total of 8200 t of meat is lost annually, primarily at specialized dairy farms, (4800 t, 17 % loss rate). On average, nearly 2 t of meat are lost per farm, corresponding to approximately 35 t of CO_2e and €10,300 per farm each year.

If farms currently above the median loss rate were to reduce their losses to this median level, it would result in an overall 34 % decrease. This translates to 2800 t of additional meat reaching the food supply chain annually, representing nearly 1 % of Sweden's total agricultural emissions. The potential impact is substantial, demonstrating that existing legislation is adequate but requires rigorous enforcement to achieve meaningful results.

These findings have broader European relevance through the shared regulatory framework provided by the EU Waste Framework Directive. The Swedish Environmental code provisions examined here aligns with EU environmental legislation. Similar enforcement approaches could therefore be implemented across Member States, contributing to EU-wide climate and waste prevention objectives.

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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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crsust.2025.100306.

Data availability

I have shared the file with my data in the Attach File Step

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