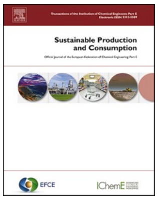
Sustainable Production and Consumption 55 (2025) 203–216

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc



What is a better chicken? Exploring trade-offs between animal welfare and greenhouse gas emissions in higher-welfare broiler systems

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ARTICLE INFO

Editor: Dr Pan He

Keywords:
Animal welfare
Broiler
Carbon footprint
Slower-growing
Stocking density
Trade-offs

ABSTRACT

Due to the animal welfare concerns in conventional methods of rearing broilers, chicken raised for meat, there is a push towards transition to higher welfare methods. However, this results in trade-offs as some aspects of higher welfare systems reduce production efficiency and thus increase greenhouse gas emissions. These trade-offs have however rarely been studied. This study aims to further the understanding by comparing the impact of reducing stocking density and switching to slower-growing broiler hybrids on broiler welfare and greenhouse gas emissions. Impacts on broiler welfare were determined by synthesizing quantitative welfare indicators from recent studies which assessed the welfare of broilers at different stocking densities and/or growth rates. The impact on greenhouse gas emissions from introducing these changes were modelled for chicken meat produced in Swedish broiler systems. Then, the magnitude of trade-offs associated with a reduced stocking density and/or use of slower-growing broilers were determined based on how these impacted broiler welfare and greenhouse gas emissions. The largest trade-offs were found when using slower-growing hybrids, since while this increased broiler welfare considerably, it also increased greenhouse gas emissions. The magnitude of the trade-offs was largely dependent on the growth rate of the slower-growing hybrid. Slower growth rates increased feed intake, and hence greenhouse gas emissions, but increased greenhouse gas emissions were partly offset by reduced emissions from parent animals. Trade-offs were smaller when reducing the stocking density in broiler houses, due to a moderate improvement of welfare but only a slight impact on greenhouse gas emissions. This study highlights the existing tensions between improving broiler welfare and minimizing greenhouse gas emissions and the need for tools to navigate these trade-offs. However, as greenhouse gas emissions from broiler production remain considerably lower than those of other livestock when higher welfare methods are used, we question whether minimizing greenhouse gas emissions should be a priority when conflicting with improving broiler and breeder welfare.

1. Introduction

Addressing practices related to the production and consumption of livestock products represent key opportunities to mitigate the food systems' environmental impact (Poore and Nemecek, 2018; Springmann et al., 2018). Nevertheless, while evaluating options to improve the environmental sustainability of livestock production, it is also important to consider the impact on the animals' wellbeing. Conflicts have been found between animal welfare and some options to mitigate greenhouse gas (GHG) emissions in livestock production, often revolving around efficiency (Llonch et al., 2017; Shields and Orme-Evans, 2015). Including both environmental sustainability and animal welfare in assessments is therefore crucial but, to date, rarely done (Bartlett et al., 2024; Lanzoni et al., 2023).

Trade-offs are especially evident in the case of chickens raised for meat, termed broilers. These birds are efficient feed converters and decades of genetic selection focusing on production traits has yielded broilers which convert feed and reach slaughter weight at record rates (Dawkins and Layton, 2012; Neeteson et al., 2023). As feed is the hotspot of greenhouse gases from chicken meat production, the high rates which broilers convert feed into liveweight (measured by the feed-conversion rate (FCR)) has substantially lowered the GHG emissions per broiler (Costantini et al., 2021; Tallentire et al., 2018a). Therefore, the carbon footprint, i.e. the total amount of GHGs emitted per unit of

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https://doi.org/10.1016/j.spc.2025.02.015
Received 28 October 2024; Received in revised form 11 February 2025; Accepted 17 February 2025

meat, is considerably lower for chicken meat compared to meat from other animals (Poore and Nemecek, 2018). However, conventional methods of rearing broilers, where flocks of 10,000–40,000 birds are raised indoors at stocking densities varying between 33 and 42 kg/m^2, and the high growth rates of modern broiler hybrids especially, are linked to substantial welfare concerns for the broilers themselves and their parents, the broiler breeders (EFSA, 2023; Hartcher and Lum, 2020). For broilers, issues include high prevalences of various leg disorders and weaknesses, which are painful and hinder movement (EFSA, 2023; Nicol et al., 2024). The resulting inactivity may aggravate existing or cause new leg disorders and inhibit the expression of natural behaviours (EFSA, 2023; Nicol et al., 2024) Broilers are further affected by high rates of cardiovascular diseases and mortality rates (Hartcher and Lum, 2020; Nicol et al., 2024). The high growth rates have also resulted in the need to severely restrict parent breeders' access to feed to prevent excessive weight gain and obesity, and the correlated adverse effects on their welfare and fertility (Arrazola et al., 2022; EFSA, 2023; Hartcher and Lum, 2020). However, the feed restriction causes prolonged hunger and stress, and results in abnormal and aggressive behaviours (Arrazola et al., 2022; EFSA, 2023; Hartcher and Lum, 2020).

In response to the welfare concerns about the conventional methods of rearing broilers, higher-welfare systems have been developed. A key part of these systems includes the use of slower-growing broiler hybrids which have better welfare than the hybrids currently used in conventional systems (Nicol et al., 2024). These hybrids are defined as growing at rates below 50 g/d, compared to the fast-growing hybrids that are used in conventional systems which grow at >60 g/d (EFSA, 2023; Nicol et al., 2024). The welfare benefits of slower-growing hybrids include lower prevalences of the various disorders and diseases that contribute to negative welfare in broilers (EFSA, 2023; Nicol et al., 2024) and may also reduce the required feed restriction for the broiler breeders and the related welfare consequences (Arrazola et al., 2022; Arrazola and Torrey, 2021) or remove the need to restrict access to feed altogether (EFSA, 2023). However, using slower-growing broilers inevitably sacrifices production efficiency as the longer rearing period leads to a higher FCR, which increases the emissions from feed production (Tallentire et al., 2018a) and thus the carbon footprint of the chicken meat (Mostert et al., 2022; WRI, 2024). The extent to which the carbon footprint is increased is largely dependent on the hybrid-specific growth and feed conversion rates. For instance, the breeding company Aviagen estimate that the use of their slower-growing hybrids could increase GHG emissions per kg carcass weight by 6–40 %, depending on the FCR of the hybrid (Avendaño et al., 2017; Neeteson et al., 2023). Other assessments estimate that GHG-emissions could increase by 24 % (ADAS, 2024) or 15–28 % (Mostert et al., 2022). However, if soya sourced from regions with high levels of deforestation are a part of the diet and if these emissions are included, the lower protein need of slower-growing hybrids' can mitigate the increased emissions caused by the higher feed requirements partly (Tallentire et al., 2018b) or fully (Mostert et al., 2022).

In addition to the use of slower-growing hybrids, higher welfare systems also reduce the stocking density, i.e. the space available per bird, as the stocking densities used in conventional systems have been connected to negative welfare outcomes (EFSA, 2023). Stocking density is an important determinant of broiler welfare due to its close connection with leg health and overall behaviour, and reducing the stocking density has been found to reduce prevalences of leg disorders (Bailie et al., 2018; Pedersen and Forkman, 2019; van der Eijk et al., 2023) and to improve broilers' walking ability and activity (Averós and Estevez, 2018; BenSassi et al., 2019; van der Eijk et al., 2023). Furthermore, higher space allowances per broiler have also been shown to promote overall activity and expressions of positive behaviours (van der Eijk et al., 2022; Vas et al., 2023). Stocking broilers at lower densities is also likely to increase GHG-emissions as a higher portion of some emissions, e.g. from energy use, are allocated to each broiler (Leinonen et al., 2014). Previous assessments have found that a reduced stocking density affects GHG-emissions (Cesari et al., 2017; Leinonen et al., 2014). However, broilers stocked at the lower stocking density were slaughtered 4 days earlier to reach the target stocking density in Leinonen et al. (2014) (resulting in a lower FCR and so also lower GHG emissions) while Cesari et al. (2017) assumed a higher FCR at higher stocking densities. As FCR is generally not impacted by changes in stocking density (Averós and Estevez, 2018; van der Eijk et al., 2023) findings of these assessments may therefore not be applicable to other situations.

Due to the growing demand for chicken meat produced in higher welfare systems, the trade-offs between improving broiler welfare and minimizing environmental pressures are increasingly relevant. The demand is unlikely to be met by existing higher welfare systems, such as organic and free-range systems, as these suffer from high costs and consequently low market shares (EPRS, 2019; Staudigel and Trubnikov, 2022). A recent development are the so-called intermediate systems where slower-growing broilers are reared indoors at slightly lower stocking densities. These may offer a more viable alternative to conventional systems due to their lower price premium (van Horne, 2020; Vissers et al., 2019). The prevalence of intermediate systems in Europe is increasing rapidly, driven by welfare certification schemes, such as the international Better Chicken Commitment (BCC, 2023) and the Dutch Beter Leven (Bos et al., 2023). This has led to questions of how the changes introduced by intermediate systems impact the welfare, environmental impact, and economic viability of broiler production and so how trade-offs should be handled (AVEC, 2024; Bos et al., 2023). However, while numerous studies have investigated how features of intermediate systems impact broiler welfare (Averós and Estevez, 2018; de Jong et al., 2022; Nicol et al., 2024) and a few the impact on the GHG emissions of chicken meat production (Mostert et al., 2022; Tallentire et al., 2018a) very few studies have integrated both aspects in assessments, which is essential to determine whether trade-offs exist, and if so, to what extent. The Dutch Greenwell project has previously assessed the broiler welfare, environmental impact, and economic performance of conventional and intermediate systems (Bos et al., 2023). However, the studied intermediate systems introduced multiple welfare features including the use of slower-growing broilers, lower stocking densities, environmental enrichment, and access to a covered veranda (de Jong et al., 2022). While providing valuable insights, the project did not study the impacts of individual welfare features. Developing an understanding of the impacts of specific features is essential to identify the features where trade-offs are likely to arise, which in turn is needed to navigate tensions. This study aims to contribute knowledge to this gap by investigating the anticipated conflict between improving broiler welfare and minimizing GHG emissions. Specifically, the study assesses how a less intense rearing of broiler under Swedish conditions, through a reduced stocking density and/or adoption of slower-growing hybrids, affect 1) the welfare of broilers and broiler breeders, and 2) the carbon footprint of produced chicken meat. This is followed by a discussion of the trade-offs that arise when reducing the stocking density and/or using slower-growing broilers, whether these trade-offs are inevitable, and if so, how they may be handled.

2. Material and methods

2.1. Study overview

The study consisted of a systematized review to identify the impacts of reducing stocking densities and/or switching to slower-growing broilers on broiler welfare and analysing how an introduction of these welfare features impact GHG-emissions, which were modelled from a life-cycle perspective based on Swedish data. While aspects of environmental sustainability other than GHG-emissions are also highly relevant, we here focus on GHG-emissions as the carbon footprint of meat has shown to function as a proxy for several other environmental indicators (Röös et al., 2013), as the low carbon footprint of chicken meat is often emphasized (Costantini et al., 2021; Llonch et al., 2017), and as the discourse on trade-offs between environmental sustainability and higher animal welfare is often centered around increased GHG-emissions (AVEC, 2024; Bos et al., 2023; Kyriazakis et al., 2024). In short, potential trade-offs in higher welfare systems which introduced one of three interventions: slower-growing hybrids, lower stocking densities, or a combination of both, were determined in three steps:

1. Impacts on broiler and breeder welfare – Impacts of the three interventions were determined by synthesizing data on a set of welfare indicators found in literature.
2. Impact on GHG-emissions – Effects of introducing the three interventions on the carbon footprint in Swedish broiler systems were determined.
3. Investigation of trade-offs – The relationship between the impact on broiler and breeder welfare and GHG-emissions were determined for each intervention to identify trade-offs and their extent.

2.2. *Literature review of animal welfare indicators*

2.2.1. *Objective of the review*

Broiler welfare is dependent on a range of factors and many indicators are available to assess it (de Jong, 2019; EFSA, 2023). In a recent report on the welfare of broiler on farms, EFSA (2023) compiled a list of indicators which measure multiple aspects of welfare, making them suitable to assess the overall state of a broiler flock. The indicators (referred to as iceberg indicators by EFSA) and their associated welfare consequences, as well as methods for measuring the indicator, are shortly summarized in Table 1. Some indicators were not measured in any of the identified articles and are therefore not mentioned below. For a more detailed description and complete list, see EFSA (2023).

To determine the implications of reduced stocking density and/or growth rates on broiler and broiler breeder welfare, a systematized review was conducted (Grant and Booth, 2009). As variations between studies, such as the study design and farm management, could confound the results and the effect of the intervention, only studies with intra-study comparisons, i.e., broiler welfare at multiple stocking densities and/or growth rates, were considered. Additionally, as the focus of the study was to investigate the effects of reduced stocking densities and growth rates in conventional broiler production, studies assessing organic or free-range systems were not included. To reflect modern hybrids and management practices, the search was limited to studies conducted in the past 10 years and having a sample size of 1000+ birds per intervention.

Table 1
The iceberg indicators proposed by EFSA and measured in at least one study identified in the literature review. In addition to a brief description of the indicator and its welfare implications, the most common ways to measure the indicator are also presented.

Indicator	Description	Measured as
Mortality Rate	Occurs during rearing, often preceded by painful disorders.	% Mortality.
Carcass Condemnation	Rejections at slaughterhouse due to disorders which signal poor welfare conditions on farm.	% Condemnation.
Walking Impairment	A partial or full impairment causes inactivity, negative mental states, and stress.	Scored visually using a 6-point scale.
Foot-pad Dermatitis (FPD)	Inflammation to foot and toe pad which is painful and may cause walking impairment, reduced activity, and lower intakes of feed and water.	Scored visually using a 3- or 5-point scale.
Hock Burn	Inflammation to the hocks, similar effects as foot-pad dermatitis.	Scored visually using a 3- or 5-point scale.
Wounds	Birds can be wounded in multiple ways. Wounds are painful for the affected individual.	Scored visually using a 3-point scale.
Plumage Cleanliness	Important to maintain heat, and protect against moisture and infections. Dirty plumage can indicate inability to perform comfort behaviours and disorders causing discomfort or pain.	Scored visually using a 4-point scale.
Plumage damage	Damaged by other birds or surroundings. Painful, hinders expression of natural behaviours, may indicate high-stress levels.	Scored visually using a predetermined protocol.
Fear response	Birds may suffer from high levels of fear.	Novel object test, human approach test, tonic immobility.

2.2.2. *Search and screening*

The literature search was performed in two databases: Scopus and the Web of Science Core Collection. As proposed by the Collaboration for Environmental Evidence (2022), the search query was divided into three parts: 1) Target, 2) Intervention, 3) Outcome. Terms within a search string were connected using the Boolean operator “OR” while the search strings were combined using the Boolean operator “AND”. To limit findings to relevant articles focused on the target, search string 1 was searched for in the article's title. Search strings 2 & 3 were searched for in the Article Title, Abstract and Keywords.

1. Broiler*, Chicken*, Breeder*
2. (Stocking Densit*), Slow*
3. Welfare, Health

After removing duplicates, the screening of articles was done at Title, Abstract, and Full-Text levels. During the screening process, articles were excluded if they did not meet the eligibility criteria, which were:

1. Eligible Target: Broiler chickens or broiler breeders raised in conventional houses.
2. Eligible Intervention: Studies broilers at two or more stocking densities and/or slower- and fast-growing breeds.
3. Eligible Outcome: Measures of animal welfare using the iceberg indicators proposed by EFSA (2023).

The following exclusion criteria were further applied:

1. Articles published before 2014.
2. Sample size smaller than 1000 birds per treatment.
3. Lack of quantitative data of the outcome of the interventions.
4. Data confounded with the effect of other interventions.
5. Article language other than English.

2.2.3. *Data extraction and compiling of indicators*

Data were extracted from all articles which fulfilled the eligibility requirements. Of interest was the trial's sample size, the measured welfare indicators and whether the indicator(s) differed between treatments. The magnitude of the intervention, e.g. what stocking densities and/or growth rates were studied, was also extracted. If welfare indicators were determined on multiple occasions the last measurement was preferred as welfare consequences usually increase with age and body weight (EFSA, 2023; Tainika et al., 2023). When quantitative data were presented in figures only, it was extracted using the WebPlotDigitizer software (Rohatgi, 2022).

Since the severity of some welfare concerns varies, e.g. full walking impairment represents a larger welfare concern than a partial impairment, it is common practice to give the proportion of birds in each severity group. When this was the case for the welfare indicators; gait score, foot-pad dermatitis, hock burn, cleanliness and wounds, the indexes proposed in the Welfare Quality protocol (2009) were used to calculate an aggregated value that accounted for the varying severities in the reported published study. No index was available for wounds, so the unweighted prevalence of wounds was used.

To enable the compilation of welfare indicators within a study and comparisons of the total welfare consequences between interventions, welfare indicators need to be aggregated into a single score. Animal welfare indexes have been developed for this purpose, with the ultimate aim of quantifying the total animal welfare performance (e.g. Welfare Quality, 2009; de Jong, 2019; Tallentire et al., 2019). These indexes are however criticized for a lack of transparency, with consequent questions about the validity and ethical robustness of findings (Lanzoni et al., 2023; Sandøe et al., 2019).

For the purposes of this study, a novel method was developed to allow a transparent compiling of welfare indicators. The method differs from other welfare indexes in that it aims to determine the relative differences between two systems rather than quantifying the absolute performance of each. As the literature search identified studies where the only distinction between two systems was the intervention, variations in welfare performance, therefore, should be attributable only to the intervention, i.e. the slower-growing hybrid or lower stocking density. The Relative Improvement of an intervention was determined in three steps: (1) For each study, the Relative Improvement of a welfare indicator was determined on an indicator-by-indicator basis (Eq. (1)), (2) By combining results for each welfare indicator across in all studies, the Average Relative Improvement per indicator was determined, and (3) the Overall Relative Improvement was determined by averaging the Relative Improvement of all welfare indicators.

$$\text{Relative Improvement of Welfare Indicator per Study} = \frac{\text{Intervention} - \text{No Intervention}}{\text{No Intervention}} \tag{1}$$

If a study found no significant difference between two measurements, the relative difference between them was set to zero.

2.3. Assessment of GHG-emissions

To examine the effect of a reduced stocking density and/or use of slower-growing broilers on GHG-emissions, the carbon footprint of chicken meat produced in Swedish conventional systems was compared to three theoretical scenarios. The first scenario reduced the stocking density from 36 kg/m^2, which is commonly used in Swedish conventional systems, to 24 kg/m^2, which represents the lowest stocking density used by commercial intermediate systems (Vissers et al., 2019). The second scenario used slower-growing broilers stocked at the stocking density typical for Swedish systems, i.e. 36 kg/m^2. Since there is a large range of slower-growing hybrids, two distinct slower-growing hybrids were considered to account for differences between hybrids. The two chosen hybrids were the moderately-slow growing Ranger Classic and the slow-growing Hubbard JA757. To study the impact of combining both welfare measures, the third scenario stocked the slower-growing hybrids at 24 kg/m^2.

The GHG emissions were modelled from a life-cycle perspective. A recent study assessing the carbon footprint of chicken meat produced in Swedish conventional systems using fast-growing hybrids (Ross 308) (RISE, 2022), represents the most up-to-date assessment of Swedish broiler production and was hence used as the primary data source. The study provided the composition and the carbon footprint of typical feed mixes for Swedish farms. Additionally, it detailed the emissions from (1) transport of feed, (2) production of and transport of bedding materials, and (3) post farm activities. Energy use in broiler houses was extracted from a report by the Swedish Poultry Meat Association (n.d.-a, n.d.-b) and the emission factors of energy sources from Gode et al. (2011) and Sandgren and Nilsson (2021). Manure production from broilers and broiler breeders was found in the Swedish National Inventory Report (SEPA, 2023) and emission factors for methane as well as direct and indirect nitrous oxide emissions from manure handling were taken from IPCC (2019).

To model the GHG emissions from the three theoretical scenarios with lower stocking rates and slower-growing broilers, we adjusted the characteristics of the broiler hybrids and the production system to reflect these alternative systems. Since there is a lack of data on the performance of slower-growing broilers in Swedish systems (conventional systems represent 99 % of production), characteristics of the slower-growing hybrids were provided by reports from the Dutch Greenwell project (Mostert et al., 2022; van Horne, 2020). The Dutch Greenwell project were used as the primary source of input data for the alternative systems as it currently represents the only LCA conducted on intermediate broiler systems available in the literature (Kyriazakis et al., 2024). Data not found in the two primary sources, such as the mortality and rejection rate, were complemented by other sources (Table 2). It was not possible to determine the composition of a feed mix optimized for slower-growing broilers in the Swedish context and the slower-growing birds were therefore assumed to be fed the same feed mix as birds in the conventional system. The characteristics of the three studied broiler hybrids are summarized in Table 2.

The longer rearing periods of slower-growing broilers can be expected to result in a higher energy use in stables and higher production of manure per broiler over its lifetime. Therefore, the emissions from these activities were scaled in relation to the length of the rearing period. For instance, the rearing period of the Hubbard JA757 is 60 % longer than that of the Ross 308 and emissions from energy use and manure storage are therefore 60 % larger. Additionally, slower-growing hybrids have smaller breast muscles than fast-growing hybrids and thus a lower meat yield; 2.5- and 3.5 %-point lower meat yield per kg carcass weight for Ranger Classic and Hubbard JA757 hybrids respectively compared to the fast-growing hybrid Ross 308 (van Horne, 2020).

Broiler houses are heated, ventilated and lit at a fixed rate per m^2 (van Horne, 2020) and the amount of bedding material per m^2 can also be assumed to be consistent. Consequently, emissions from these activities are constant per house and independent of the number of reared birds. Therefore, a lower stocking density means that fewer birds are reared per house and so a higher proportion of the emissions from these activities will be allocated per broiler.

The GHG emissions were assessed at retail-gate and emissions are presented as the kg CO_2-eq per kg bone-free packaged chicken meat, i.e. as available to consumers. The activities that contributed to emissions at farm-gate were related to the rearing of the broilers and broiler breeders: production and transport of feed and bedding material, energy use in broiler houses, and emissions from manure. Post-farm emissions were assumed to be equal for all systems and to have come from energy and resource use at the slaughterhouse, during transport and packaging (Fig. 1). Land use change related emissions were not included in the assessment as Swedish broiler farms source non-deforestation certified soya beans (RISE, 2022).

As broiler production results in multiple products, primarily meat and offal, allocating impacts between the two are important (Costantini et al., 2021). While economic allocation is commonly used in life-cycle assessments of chicken meat (Costantini et al., 2021; Mostert et al., 2022; Usva et al., 2023), this should be avoided when possible according to the ISO standard on LCA (ISO, 2006a, 2006b). Rather, emissions were allocated by the mass relationship between chicken meat and offal, of which meat represents 93.5 % for fast-growing strains and 92.5 % for slow-growing strains (Weimer et al., 2022). However, since this analysis focuses on the relative emissions across scenarios, the choice of allocation method has a limited impact on the overall results.

3. Results and discussion

3.1. Animal welfare

3.1.1. Literature search

The literature search was performed on the 26th of March 2024 and yielded 784 articles (521 after the removal of duplicates). After

Table 2
Characteristics of the three broiler hybrids used in the studied systems.

	Fast	Mod-Slow	Slow	*Sources Fast*	*Sources Mod-Slow, Slow*
Broiler hybrid	**Ross 308**	**Ranger Classic**	**Hubbard JA757**		
Slaughter age (Days)	35	49	56	(RISE, 2022)	(Mostert et al., 2022)
Mortality (%)	3.2	1.9	2.2	(RISE, 2022)	(Neeteson et al., 2023), (Forseth et al., 2023b)
Carcass condemnation (%)	2.8	0.67[a]	0.65	(SBA, 2024)	(Baxter et al., 2021), (Forseth et al., 2023a)
Feed Conversion Ratio	1.52	1.82	2.10	(RISE, 2022)	(Mostert et al., 2022)
Mortality breeders	8	8	6	*Ida Ljungkvist, pers. comm.*	(Mostert et al., 2022)
Breeder hens per cockerel	12.5	12.5	12.5	*Ida Ljungkvist, pers. comm.*	(Mostert et al., 2022)
Eggs per breeder hen	160	173	221	(Swedish Poultry Meat Association, n.d.-a, n.d.-b)	(Mostert et al., 2022)
kg feed/breeder hen[b]	49.2	50.9	49.2	*Ida Ljungkvist, pers. comm.*	(Mostert et al., 2022)
kg bone free meat/kg CW[c,d]	0.77	0.74[b]	0.74[b]	(RISE, 2022)	(RISE, 2022; van Horne, 2020)
kg CW[d]/broiler	1.6	1.7	1.7	(SBA, 2024)	(Mostert et al., 2022)
kg CW[d]/breeder hen	4.3	2.3	1.6	*Ida Ljungkvist, pers. comm.*	(Mostert et al., 2022)
kg CW[d]/breeder cockerel	5	3.6	3.5	*Ida Ljungkvist, pers. comm.*	(Mostert et al., 2022)

[a] As no data of the rejection rate of Ranger Classic was found, it is approximated with another mod-slow hybrid (Hubbard Redbro), extracted from Baxter et al. (2021).

[b] Includes feed for one cockerel per 12.5 breeder hens.

[c] Value from RISE but adjusted for a lower breast yield (2.5–3.5 %-point) than Ross 308, as presented by van Horne (2020).

[d] Carcass Weight.

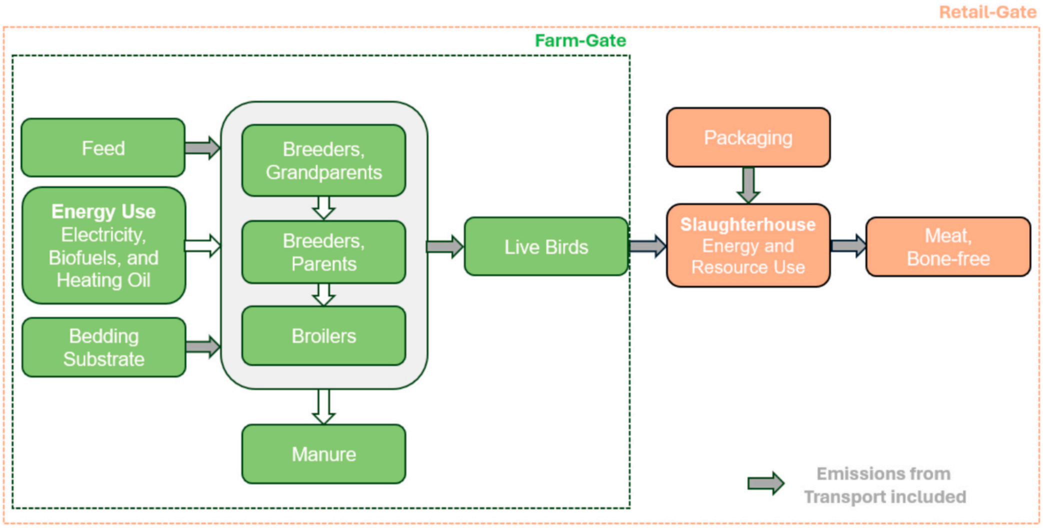

Fig. 1. System boundaries of the studied broiler system.

screening of titles, abstracts, and full texts, and excluding all articles which did not meet the eligibility criteria, 26 articles remained. Excluded articles and reasons for exclusion are compiled in Supplementary Information (SI) 1. Four studies were further excluded as they, although fulfilling the eligibility criteria, were deemed unable to answer the study's research question due to their respective study designs. Of these, two articles compared the performance of antibiotic-free systems (Iannetti et al., 2021; McKeith et al., 2020), one used welfare data older than 10 years (Gocsik et al., 2016), and the last one compared a modern fast-growing hybrid to its equivalent from 1972 (Steenfeldt et al., 2019). Of the 22 articles which were included in the review, five instances were found where multiple papers were published from the same scientific trial, each paper with its own focus. Data from these papers were compiled and considered as one study. The review process is summarized in Fig. 2 in a flow diagram adapted from (Haddaway et al., 2018) and all the articles included in the quantitative synthesis are presented in Table S.1 in SI 2.

3.1.2. Study samples, designs and indicators used

Only one trial was found to investigate the welfare of slower-growing broiler breeders (Arrazola et al., 2022; Arrazola and Torrey, 2021) and no quantitative synthesis was therefore performed for parents to slower-growing broilers.

Of the 14 identified unique studies on broilers, five assessed the effect of growth rates, eight the impact of stocking densities, and three the combination of both. Two trials, van der Eijk et al. (2022, 2023) and Rayner et al. (2020) studied two interventions each and reported results individually. As for sample sizes, six of the 14 unique studies assessed 5000 to 15,000 birds, one 80,000, while another four studied samples between 200,000 and 400,000 broilers. The three largest sample sizes were Baxter at 800,000, Bailie et al. (2018) at 2 million and Forseth et al. (2023a, 2023b), at 64 million broilers.

For trials assessing broiler hybrids of different growth rates, the most common study design was to compare one fast-with one slower-growing hybrid. One trial compared one fast- against two slower-growing hybrids (Rayner et al., 2020) while another trial assessed the welfare of 16 broiler hybrids divided into 4 groups based on growth rate (Santos et al., 2022; Torrey et al., 2021). In general, the growth rate of slower-growing hybrids varied between 41 and 53 g per day and between 55 and 65 g per day for fast-growing hybrids. In all trials, the growth rate differed by at

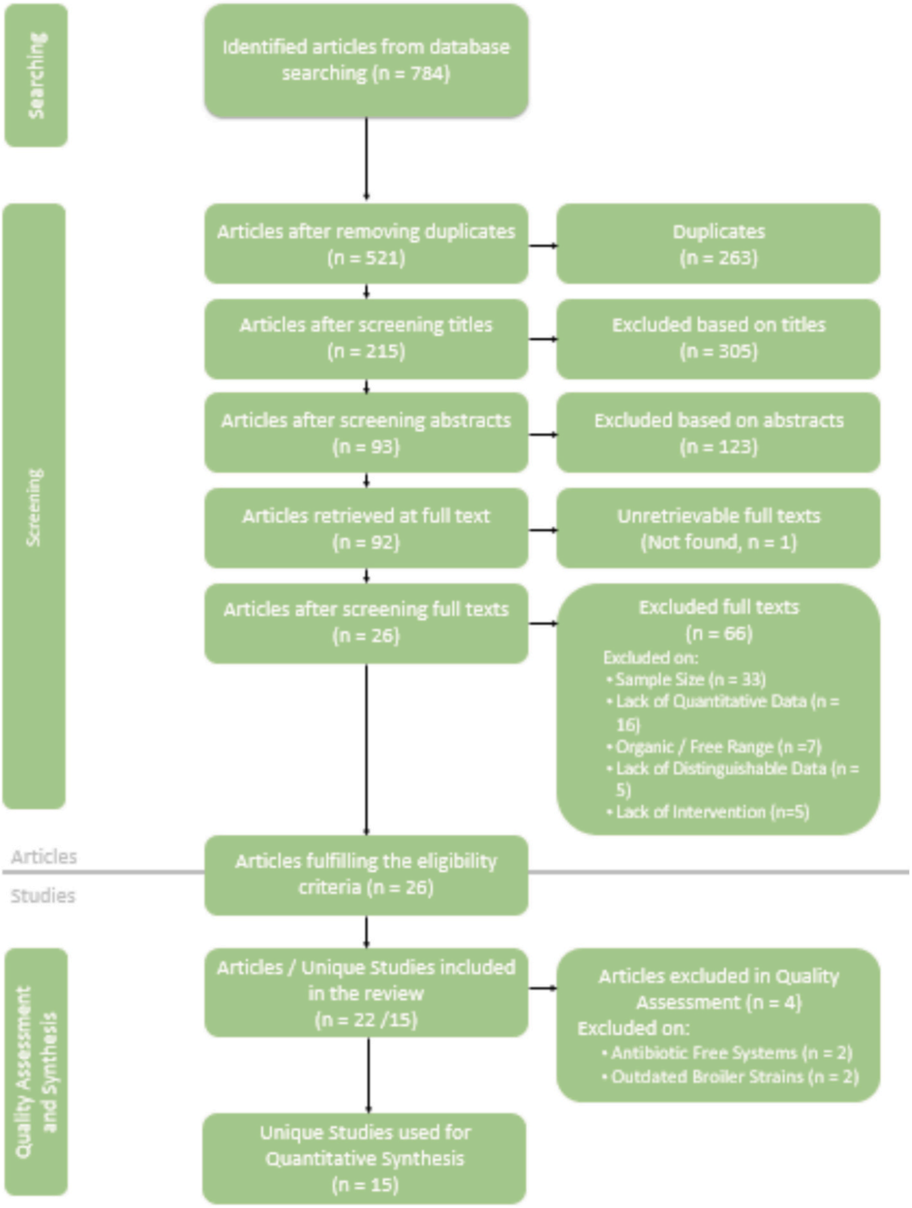

Fig. 2. Flow Chart of the search, screening, and synthesis stages of the literature review.

least 10 g per day between the fast- and slower-growing hybrid. The stocking density used in studies that compared slower- and fast-growing broilers were between 30 and 34 kg/m^2. In trials where the combined effect of growth rate and stocking density was assessed, slower-growing broilers were stocked at 23–30 kg per m^2 and fast-growing broilers at 29–35 kg per m^2. Studies on stocking density investigated the effect of two or multiple stocking densities, where the high and low limits varied between 34 and 42 kg per m^2 and 24–34 kg per m^2 respectively.

All iceberg indicators proposed by EFSA were measured in two or more studies each (Table 3), except for stereotyped behaviour, piling and smothering, and lethargy which were not measured in any. Information about the sample size, interventions, and indicators measured in each study is summarized in Table S.1 in SI 2. All indicators were however not studied for all interventions.

Large variations were found in the methods used to measure broilers' fear levels, including variations of the human approach, novel object, and tonic immobility tests. As a result, different indicators were reported and so findings related to broiler fear levels could not be quantitatively determined and are therefore not included further in the quantitative synthesis.

Table 3
Number of studies measuring each welfare indicator.

Indicator	Fear	Cleanliness	Plumage Damage	Wounds	FPD[a]	Hock Burn	Lameness	Mortality	CC[b]
No. of studies	5	5	2	4	12	13	11	13	5

[a] Foot-pad dermatitis.
[b] Carcass Condemnation.

3.1.3. Impacts on broiler welfare

Using slower-growing hybrids was associated with considerable Relative Improvement for all indicators except hock burn (2 %) and cleanliness (0 %), leading to an Overall Relative Improvement of 37 % (Table 4). Comparatively, a reduction in stocking density resulted in little or no improvement of most welfare indicators, except for lameness, wounds, and foot-pad dermatitis (Table 5) leading to an Overall Relative Improvement of only 11 %.

However, some of the included studies stocked broilers at densities above 36 kg per m^2 and results may therefore not be applicable to the Swedish context. When all datapoints over 36 kg per m^2 were excluded, a lower Relative Improvement was found for most indicators (Table 6) except for wounds, which in the one study remaining improved by 50 %, leading to an Overall Relative Improvement of 10 %. The simultaneous reduction of growth rate and stocking density had the largest impact on broiler welfare of the three interventions and significant improvements were found for all indicators, with an Overall Relative Improvement of 63 % (Table 7).

Consequently, using slower-growing hybrids seems to be a more effective approach to improve overall broiler welfare than stocking broilers at lower densities. This is coherent with earlier studies which have found growth rate to be an effective predictor of overall welfare (EFSA, 2023; Nicol et al., 2024) while stocking density is primarily connected to indicators related to leg health (Averós and Estevez, 2018; Pedersen and Forkman, 2019). Simultaneously reducing the growth rate and stocking density seems to have synergistic effects overall, which is in accordance with trials that studied this (Rayner et al., 2020; van der Eijk et al., 2022). However, the low number of studies and large between-study variability makes it difficult to determine how much the higher Relative Improvement of welfare indicators compared to using only slower-growing broilers is due to the added benefits of a combined approach contra study variability.

Overall, large between-study variations were found for all three interventions (Visualized in Figs. S1–3 in SI3). While this synthesis investigates the impact of two aspects, broiler welfare is in reality dependent on a range of factors (de Jong, 2020; EFSA, 2023) and variations between studies can be expected due to differences in study design, rearing environment, and the used broiler hybrid. While the methodology was developed in anticipation of this issue, it is impossible to avoid the effects of these confounding variables completely when combining the findings of multiple studies. The low number of articles and the fact that some welfare indicators were rarely measured, likely adds to the uncertainty. A further potential cause of the large between-study variations is that the welfare improvements of the interventions were determined relative to a reference point, i.e. the highest stocking density or growth rate assessed in the study, which differs between studies. The impact of reducing stocking densities is known to depend on the initial stocking density as well as the size of the reduction, e.g. reducing the stocking density from 45 to 40 kg/m^2 will have a different impact than reducing it from 25 to 20 kg/m^2 and larger reductions will generally result in larger improvements of welfare indicators (Buijs et al., 2009; EFSA, 2023). Nevertheless, while the between-study variations signals that the size of the improvements of welfare indicators should be viewed as indicative rather than exact, the ability of this method to account for the differences between studies, farms, and regions is a strength of this synthesis as opposed to case studies, perhaps making the findings of the synthesis more generalizable.

While the welfare benefits of rearing slower-growing compared to fast-growing broilers is clear, the benefits of the difference in growth rate of the slower-growing hybrids is less clear, as studies tend to treat growth rates as binary (fast vs. slow growth) rather than a sliding scale. The studies that compared multiple slower-growing hybrids found little or no differences between hybrids of different growth rates (Rayner et al., 2020; Santos et al., 2022; Torrey et al., 2021) and results from other studies are also inconclusive. The Dutch Greenwell Project found differences between systems that used moderately slow- and slow-growing hybrids, but the system which used the slow-growing hybrid also introduced additional features to improve broiler welfare, such as a reduced stocking density, environmental enrichment of stalls, etc. and the difference between the systems may therefore not be due to the different hybrids (de Jong et al., 2022). Further studies are therefore needed to investigate if, and how much, welfare differs between slower-growing hybrids of varying growth rates, as this has a close tie to the size of trade-offs (see Section 3.3).

Importantly, the iceberg indicators proposed by EFSA (2023) only measure negative welfare states, which has been the primary focus of previous reviews (Averós and Estevez, 2018; Nicol et al., 2024; Pedersen and Forkman, 2019) as well as this synthesis. However, there is a growing recognition of the importance of positive welfare states and behaviour (Boissy et al., 2007; Mellor and Beausoleil, 2015). Both lower stocking densities (van der Eijk et al., 2022; Vas et al., 2023) and growth rates (Nicol et al., 2024) have been found to contribute to this. Future studies and reviews should therefore pay extra attention to how a reduced stocking density and/or growth rate impacts indicators of positive welfare, as these may impact the conclusions found in this study.

3.1.4. Applicability to Swedish farms

The literature review of impacts on broiler welfare did not find any studies conducted in Sweden. To assess whether findings of the review are applicable to the Swedish context, they were compared to the welfare indicators that are publicly available for Swedish conventional systems, which are: mortality rate: 3.2 % (RISE, 2022), carcass condemnation: 2.8 % (SBA, 2024), and prevalence of foot-pad dermatitis: 5 % (Swedish Poultry Meat Association, 2023a).

Swedish broiler farms must comply with more extensive legislation compared to other European countries, and are therefore perceived to achieve higher welfare (Sandøe et al., 2022). All but one study which studied the impact of stocking density reported a higher prevalence of foot-pad dermatitis, regardless of the stocking density, compared to the Swedish average, which is currently 5 % (average stocking density in Sweden is 36 kg/m^2) (Fig. 3). Limiting foot-pad dermatitis has been a major goal for Swedish broiler producers over the past 20 years (Algers and Berg, 2001) and the comparatively low rates of foot-pad dermatitis is further evidence that contact dermatitis may be more dependent on environmental conditions than stocking density (Dawkins et al., 2004). As the studies included in the literature review mostly found higher rates of foot-pad dermatitis than the Swedish average, the Relative Improvement of a reduced stocking density on foot-pad dermatitis may therefore not be applicable to the Swedish context. However, this does not necessarily mean that a reduction of stocking density would not impact the rates of foot-pad dermatitis in Swedish broiler farms. For instance, EFSA (2023) estimated that cases of foot-pad dermatitis could be eliminated by reducing the stocking density to 11 kg/m^2.

Table 4

Relative Improvement (%) of using slower-growing hybrids per indicator and overall.

Indicator	Cleanliness	Plumage damage	Wounds	Lameness	FPD[a]	Hock burn	Mortality	CC[b]	Overall
Relative Improvement ± Standard Deviation (%)	0 ± 0	63	84	22 ± 8	40 ± 43	2 ± 3	38 ± 22	52 ± 21	37 %
No. of studies (No. that found no significant difference)	2(2)	1(0)	1(0)	3(0)	4(1)	4(1)	5(1)	3(0)	

[a] Foot-pad dermatitis.

[b] Carcass Condemnation.

Table 5
Relative Improvement (%) of reducing stocking density per indicator and overall.

Indicator	Cleanliness	Wounds	Lameness	FPD[a]	Hockburn	Mortality	CC[b]	Overall
Relative Improvement ± Standard Deviation (%)	4 ± 6	27 ± 38	8 ± 11	35 ± 51	3 ± 3	0 ± 0	0 ± 0	11 %
No. of studies (No. that found no significant difference)	3(1)	2(1)	5(2)	6(2)	6(2)	7(7)	2(2)	

[a] Foot-pad dermatitis.
[b] Carcass Condemnation.

Table 6
Relative Improvement (%) of reducing stocking densities below 36 kg/m^2, per indicator and overall.

Indicator	Cleanliness	Wounds	Lameness	FPD[a]	Hockburn	Mortality	CC[b]	Overall
Relative Improvement± Standard Deviation (%)	5 ± 3	53	2 ± 4	6 ± 11	1 ± 1	0 ± 0	0 ± 0	10 %
No. of studies (No. that found no significant difference)	2(0)	1(0)	5(3)	5(2)	4(1)	4(4)	2(2)	

[a] Foot-pad dermatitis.
[b] Carcass Condemnation.

Table 7
Relative improvement (%) of simultaneously adopting slower-growing hybrids and reducing the stocking density per indicator and overall.

Indicator	Plumage damage	Wounds	Lameness	FPD[a]	Hock burn	Mortality	CC[b]	Overall
Relative Improvement ± Standard Deviation (%)	100	99	58 ± 26	51 ± 64	19 ± 33	34 ± 28	78	63 %
No. of studies (No. that found no significant difference)	1(0)	1(0)	3(0)	2(0)	3(2)	3(0)	1(0)	

[a] Foot-pad dermatitis.
[b] Carcass Condemnation.

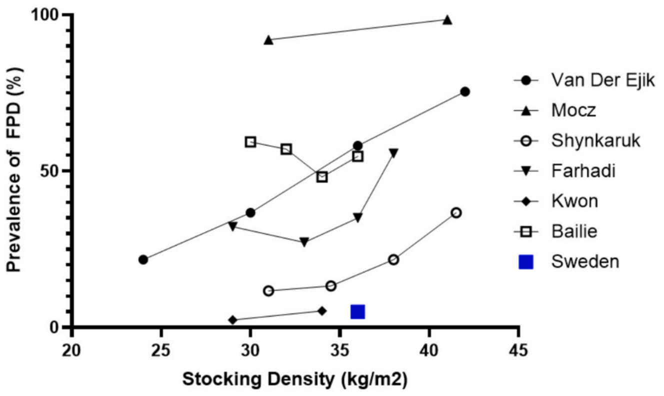

Fig. 3. Prevalence of foot-pad dermatitis found in studies assessing the effect of stocking density (black lines) and the Swedish average (blue square). FPD (Foot-pad dermatitis).

Using slower-growing hybrids will likely reduce mortality and carcass condemnation, as almost all studies found slower-growing hybrids to have lower rates than that of Swedish farms (Fig. 4). It is less clear whether the use of slower-growing broilers would reduce the rates of foot-pad dermatitis in Sweden (which is based on mainly fast-growing broilers) as slower-growing broilers were found to have higher rates of foot-pad dermatitis than the Swedish average in some studies, while lower in others (Fig. 5). However, all studies found that slower-growing broilers had lower rates of foot-pad dermatitis compared to fast-growing broilers raised under similar conditions. Foot-pad dermatitis is largely dependent on litter quality and controlling environmental conditions (Dawkins et al., 2004). Thus, it may be that rearing slower-growing broilers under Swedish conditions would further reduce the already low prevalence of foot-pad dermatitis in Swedish farms.

3.2. *Effects on GHG emissions*

Reducing stocking density to 24 kg per m^2 was estimated to increase the carbon footprint of Swedish chicken meat only marginally (1 % at retail-gate). In comparison, using a moderately slow- or slow-growing hybrid was estimated to increase the carbon footprint by 15 % and 30 % at retail-gate, respectively, and by 17 % and 32 % if the hybrids were stocked at 24 kg per m^2. Similar to previous studies, (Costantini et al., 2021; RISE, 2022), feed accounted for the largest share of GHG emissions, approximately 80 % (Fig. 6a). Emissions from energy and resource use increased substantially in all theoretical scenarios (25–40 % when reducing stocking density or using slower-growing hybrids, 80–100 % when combining both), as did emissions from manure storage for slower-growing hybrids (20–40 %). However, due to the low share of these emission sources in the overall footprint, these increases did not impact the footprint substantially.

Consequently, whether the carbon footprint of chicken meat is impacted was determined by the extent to which the introduction of a welfare feature (change in stocking density or hybrid) affects the feed requirement or composition. As stated in the introduction, FCR is usually independent (Averós and Estevez, 2018) or only slightly affected by a change in stocking density (van der Eijk et al., 2023). However, the FCR is affected by the growth rate. The large differences found between the moderately slow- and slow-growing hybrids (15 % and 30 % greater than the fast-growing hybrid) mirrors the findings of earlier assessments (Mostert et al., 2022; Neeteson et al., 2023) and is an important takeaway. While the increased carbon footprint of slower-growing broilers is relevant, discussions should further include which hybrids (within the range from moderate to slow growing) would be adopted as this is an important determinant of how much GHG-emissions will increase.

Interestingly, increased emissions of slower-growing broilers were partly offset by reduced emissions from their parents and grandparents (Fig. 6a–b). While slower-growing breeders have lower feed requirements, due to lower growth rates and similar rearing lengths as fast-growing broiler breeders, all hybrids end up consuming approximately the same amount of feed due to the severe feed restriction of fast-growing broiler breeders (Arrazola et al., 2022; Mostert et al., 2022). Reduced emissions in slower-growing hybrids are possible since fewer breeders are required to produce the same number of broilers, due to lower mortality rates in the breeders and longer fertility periods which allows each breeder to provide more eggs (Arrazola et al., 2022; Mostert et al., 2022). This illustrates the importance of including breeders in

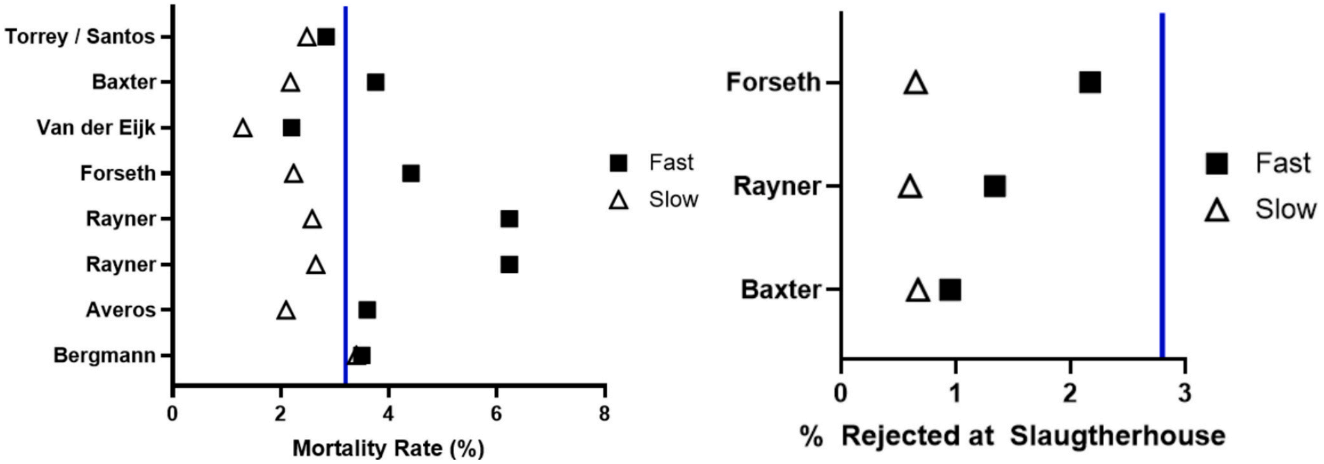

Fig. 4. Mortality (left) and carcass condemnation (right) in identified studies for slower-growing (white triangles) and fast-growing (black squares) broilers compared to the Swedish average (blue line). FPD (Foot-pad dermatitis).

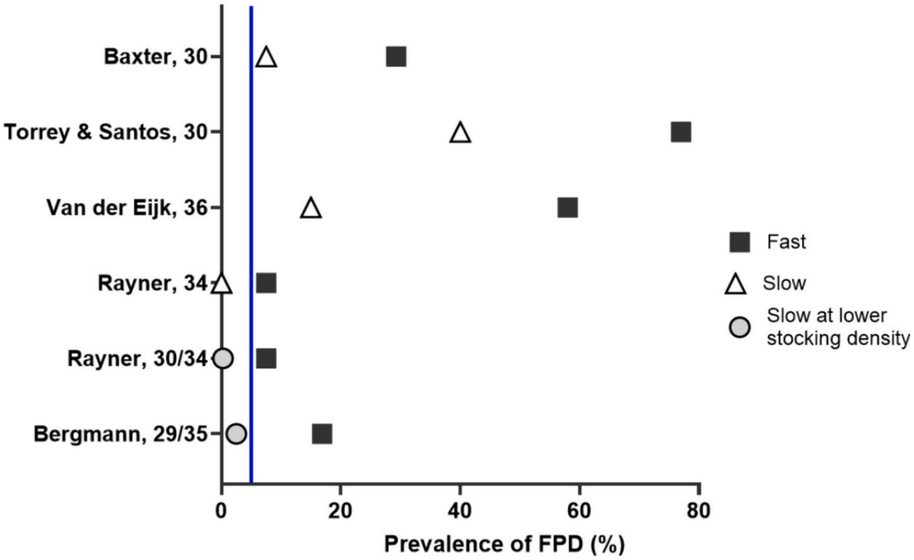

Fig. 5. Prevalence of foot-pad dermatitis in assessed studies for fast-growing broilers (black squares), slower-growing broilers (white triangles), slower-growing broilers stocked at lower stocking densities (grey circles) compared to the Swedish average (blue line). FPD (Foot-pad dermatitis).

assessments of the carbon footprint of slower-growing-broilers, which is not always done (e.g. Tallentire et al., 2018a; Neeteson et al., 2023; ADAS, 2024).

It is important to note that a feed mix optimized for slower-growing hybrids within the Swedish context could not be determined due to limited data and the complex nature of feed optimization. All three studied broiler hybrids were therefore assumed to be fed with the same feed mix, which is optimized for the needs of fast-growing hybrids. Earlier studies have indicated that the increased feed requirements of slower-growing-hybrids can be offset partially or in full due to lower protein requirements, especially if emissions from land use change are included (Mostert et al., 2022; Tallentire et al., 2018a). Therefore, our assessments likely overestimate how much GHG-emissions would be increased by switching to slower-growing broiler hybrids.

3.3. Identifying trade-offs

The level of conflict between broiler welfare and GHG-emissions was explored by dividing the percentage increase in GHG-emissions by the Relative Improvement of welfare each of the different interventions. The closer the ratio is to 1, the potentially greater the conflict. The biggest conflict (ratio 0.4–0.9) was found for a switch to slower-growing broilers (Fig. 7). The smallest conflict (ratio 0.1) was associated with reducing stocking densities in conventional broiler houses, mainly due to the limited impact on the carbon footprint, as explained previously.

The size of the conflict for switching to slower-growing broiler hybrids is largely dependent on which hybrid is used. Since a switch to the slow-growing hybrid increased the carbon footprint substantially more than a switch to the moderately slow-growing hybrid, larger trade-offs are found. This is assuming that slower-growing hybrids of varying growth rates achieve similar welfare outcomes, which was discussed in Section 3.1.3. If this is the case, there may be an optimal growth rate where trade-offs are minimized by improving welfare without large losses in production efficiency. Future studies should therefore investigate if, and to what extent, welfare differs between broilers of different growth rates to identify whether a sweet spot exists. Using moderately slow-growing broilers may also mitigate, but not resolve, the issues related to the feed restrictions of broiler breeders (Arrazola et al., 2022; Arrazola and Torrey, 2021). Future discussions of the optimal growth rate for animal welfare and production efficiency must therefore include the welfare of broiler breeders in assessments.

Better than only changing to slower-growing hybrids would be also

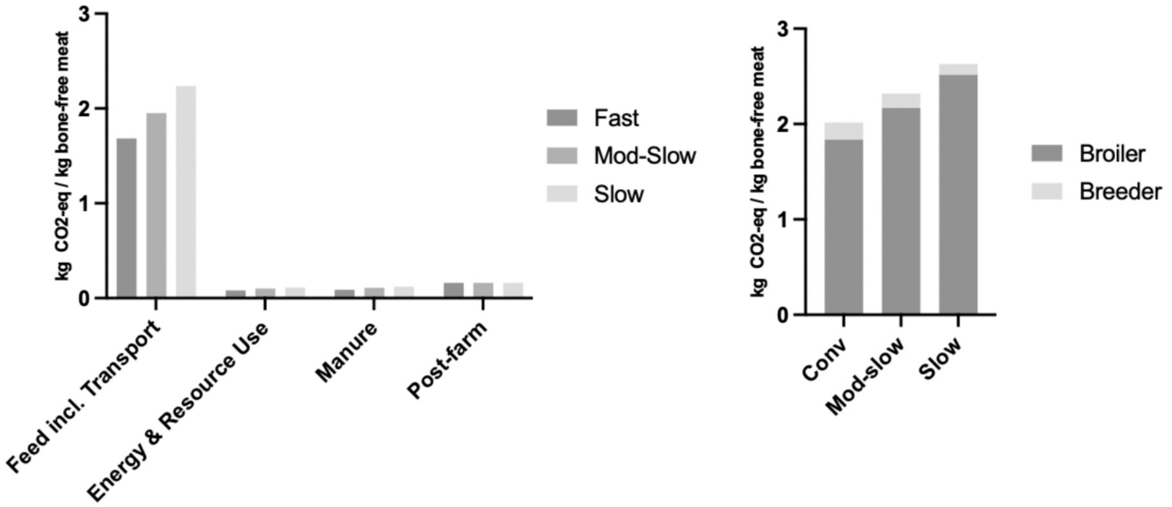

Fig. 6. a (Left) and b (Right). Emissions per kg of bone-free meat at retail gate, aggregated for activities (left) and broilers and breeders (right). Fast–Fast-growing, Mod-Slow - Moderately slow-growing and Slow-Slow growing.

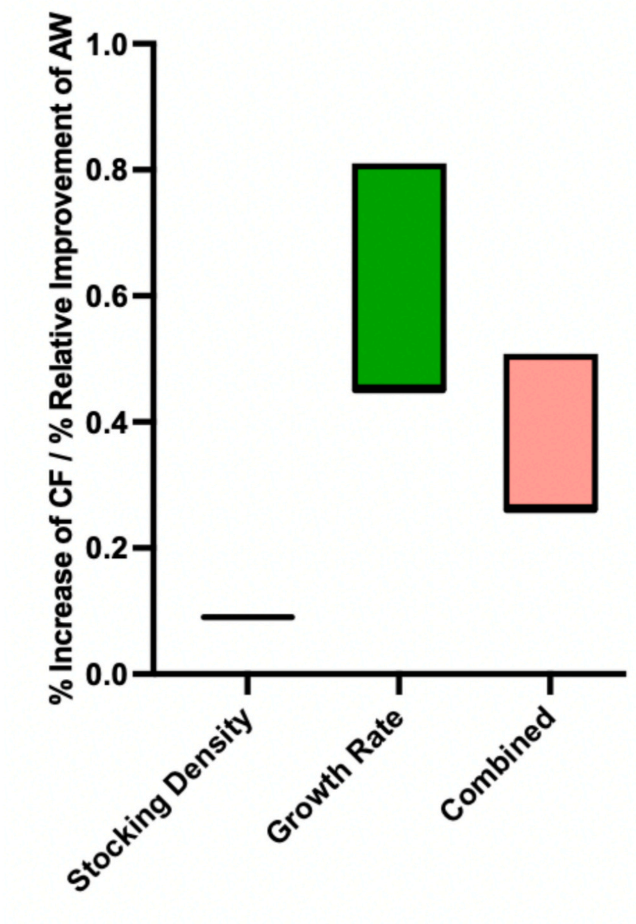

Fig. 7. Relative Improvement of greenhouse gas (GHG) emissions at retail gate per Relative Improvement of Animal Welfare (AW) for reduced stocking densities, slower-growing broilers, and a combination of both. The high end of the blocks represents the value for the slow-growing hybrid, and the low end the value for the moderately slow-growing hybrid.

to stock them at lower densities as this leads to a more positive ratio between the percentage Relative Improvement in welfare and the percentage increase in GHG-emissions (Fig. 7). This lower level of conflict, and hence reduced trade-offs, are a consequence of synergistic effects on broiler welfare while only increasing the carbon footprint slightly (Fig. 7).

3.3.1. *Is conflict inevitable?*

As this study has highlighted, tensions exist between improving broiler and breeder welfare and minimizing GHG emissions connected to the broiler hybrid. Implications of this will be analyzed in two parts. First, it is investigated whether the conflict is inevitable or if it can be resolved or reduced through proper management, breeding for welfare and production efficiency, or through options that reduce the size of the conflict. Then, in a second part, the discussion turns to how trade-offs deemed inevitable can be navigated.

For all broiler systems, proper farm management is critical to enable high levels of welfare. Because of this, large variations are found between farms with similar characteristics as well as overlaps between conventional and higher-welfare systems (de Jong et al., 2022; Forseth et al., 2023a, 2023b). Since some conventional farms perform as well as intermediate systems that use a lower stocking density and slower-growing hybrids, proponents argue that conventional systems should be preferred as they can reach similar levels of welfare through optimal stockmanship (AVEC, 2024; Neeteson et al., 2023; Swedish Poultry Meat Association, 2023b). On the other hand, intermediate systems consistently achieve higher welfare and experience less variations between farms, which suggests a higher resilience to external factors (de Jong et al., 2022; Forseth et al., 2023a, 2023b). Similarly, various strategies are proposed to mitigate the detrimental effects of feed restriction on broiler breeders, but none have so far been shown to eliminate issues nor the chronic effects of prolonged hunger (EFSA, 2023). Counter-arguments are therefore raised that the intermediate system should be preferred, as they are more likely to achieve higher levels of welfare consistently (Murphy and Legrand, 2023).

Other proponents argue that continuous genetic selection can eliminate the welfare concerns of fast-growing broiler hybrids while maintaining productivity levels, thus removing the need for slower growing-hybrids (Dawkins and Layton, 2012; Neeteson et al., 2023). These arguments are based on the success of a recent emphasis on welfare aspects in breeding goals which have reduced the severity of some welfare issues (Hartcher and Lum, 2020; Neeteson et al., 2023). However, recent studies continue to find substantial differences between slower- and fast-growing hybrids signaling that, so far, the updated breeding goals of fast-growing hybrids have not resolved welfare concerns (Nicol et al., 2024). It is also unlikely that a continued genetic selection can eliminate the need to severely feed restrict broiler breeders of high growth rates (Neeteson et al., 2023).

Finally, reducing the size of the conflict can be achieved by introducing changes that improve one aspect without severely affecting other aspects. As detailed above, genetic selection for welfare traits and proper management of broiler flocks can partly alleviate welfare concerns in conventional broiler systems. Additionally, changes to the rearing conditions can be made, such as providing access to an outdoor range and environmental enrichments in broiler houses, as well as achieving lighting, temperature, and humidity levels optimal for broiler welfare (EFSA, 2023). Providing more space per broiler through a reduced stocking density can improve the leg health of broilers and increase positive welfare states (van der Eijk et al., 2023, 2022; Vas et al., 2023) while only impacting GHG-emissions slightly. However, due to the importance of growth rate on broiler and breeder welfare it is unlikely that considerable welfare improvements can be achieved without a reduction of growth rate (Nicol et al., 2024; Riber and Wurtz, 2024).

Options to mitigate GHG-emissions without impacting broiler welfare mainly revolve around reducing the emissions associated with feed production (Kyriazakis et al., 2024). This can be done through incorporating environmental considerations in the optimization of feed mixes (Tallentire et al., 2017), replacing high-impacting ingredients with local alternatives (Leinonen and Kyriazakis, 2016), novel feed ingredients (Tallentire et al., 2018b), or human-inedible feeds (van Hal et al., 2019). These options can be used to reduce the impact of broiler production in general, independent of which broiler hybrid is used. A second set of options are opportunities to mitigate the increased GHG-emissions of slower-growing broilers based on, for instance, their different nutritional needs, lower mortality rates, and higher productivity of breeders, which reduce the differences between fast- and slower-growing hybrids (Mostert et al., 2022; Tallentire et al., 2018b). However, no study has to this point examined how much GHG-emissions of conventional or higher-welfare systems could be reduced if mitigation options are realized, which is required to determine to what extent trade-offs are inevitable.

3.3.2. *Handling trade-offs*

Even if mitigation options are realized, trade-offs may to some extent be inevitable. To navigate trade-offs, future discussions should consider the absolute performance of different broiler systems as well as what levels of broiler and breeder welfare and of GHG-emissions are deemed acceptable. For instance, it can be questioned whether the need to minimize GHG emissions from poultry is as important as the need to improve welfare. The welfare issues prevalent in broiler systems are perceived to be amongst the most pressing in the livestock sector (Clark et al., 2016; Hartcher and Lum, 2020) while GHG emissions from broiler production are considerably lower than those from the production of other meats, regardless of the system (Poore and Nemecek, 2018; WRI, 2024). As an example, the carbon footprint per kg of Swedish bone-free pork and beef meat at retail gate are 2.4–2.7 and 17–19 times higher, respectively (Moberg et al., 2020), than chicken meat from the two slower-growing hybrids analyzed in this study. The potential to mitigate emissions from the livestock sector by minimizing GHG emissions from the poultry sector is therefore considerably lower than it is from other alternatives available to the livestock sector (Herrero et al., 2016; Poore and Nemecek, 2018). If improving broiler and breeder welfare is deemed more important than minimizing GHG emissions, the increased GHG emissions associated with a move to higher welfare broiler systems can be mitigated partly through technical options or mitigated fully by reducing consumption of chicken meat or, even more effectively, of ruminant meat which emits considerably more GHG (Resare Sahlin et al., 2020; WRI, 2024).

There are other aspects in which trade-offs may arise. In addition to affecting environmental sustainability, using higher-welfare methods of rearing broilers is likely to increase production costs due to higher feed and space requirements (van Horne, 2020). However, these costs can be mitigated by the higher productivity levels of slower-growing broiler breeders in combination with the lower mortality and carcass condemnation rates, and higher slaughter weights and payment rates per broiler (CIWF, 2023). The net impact on production cost is therefore uncertain. Producing slower-growing broilers in the United States is estimated to increase costs by 11–25 %, depending on the broiler hybrid and how changes occur (Lusk et al., 2019). In Europe, a study commissioned by the European broiler sector projected that adopting the European Chicken Commitment (ECC), where slower-growing broilers are stocked at 30 kg/m^2 and provided environmental enrichment, would increase costs by 38 % per kg of meat (ADAS, 2024). However, the only large-scale broiler producer to have adopted the ECC, the Norwegian company Norsk Kylling, reported that the transition was possible without a price increase as production costs were fully mitigated (CIWF, 2023). Lastly, reports from the Netherlands, where a widespread transition to intermediate systems has occurred, indicate that production costs are 17–37 % higher than conventional systems judged per kg carcass weight. The highest price increase (37 %) is found for the Beter Leven certification which have requirements of higher-welfare methods that go beyond those of the ECC (de Jong et al., 2022; van Horne, 2020). The relationship between production costs and higher-welfare methods should therefore be investigated further in different contexts and include options to mitigate costs from increased feed and space requirements. If production costs are indeed higher when broilers are reared using higher-welfare methods, this can be addressed through higher market prices. Consumers are well aware of the welfare concerns around conventional production (Clark et al., 2016) and segments willing to pay a price premium for higher-welfare chicken meat have been identified in several populations (Clark et al., 2017; Lusk, 2018; Saatkamp et al., 2019). Market-driven forces, such as retailers and those managing certification schemes, also have considerable influence to enable transition to higher-welfare systems. Furthermore, these stakeholders can ensure that farmers are compensated for their increased costs, which for instance is what enabled the transition in the Dutch context (Bos et al., 2023; Esbjerg et al., 2022; Saatkamp et al., 2019). Additionally, (inter) national legislation can also be a strong driver for higher animal welfare (Sandøe et al., 2022). For instance, Sweden have stricter animal welfare regulations than the standards set through EU directives and, as a result, are perceived to achieve higher broiler welfare than other European countries (Sandøe et al., 2022).

Future studies should consider additional aspects which are connected to the conflict between improving broiler and breeder welfare and maximizing production efficiency (and thus GHG-emissions). From an environmental sustainability standpoint, including more indicators would be desirable, especially indicators of food-feed competition and circularity, as broilers are currently consuming large amounts of human-edible feed (Mottet et al., 2017; van Hal et al., 2019). Other important aspects include those of social sustainability, such as indicators of antibiotic use (Slegers et al., 2024; Vissers et al., 2021). Importantly, stakeholders' perceptions of what the current challenges of the broiler sector are and what is desirable may differ, and future studies should consider potential tensions and integrate all relevant aspects of sustainability in assessments. This can for instance be accomplished through a multi-criteria assessment, which has previously been used to compare conventional systems to free-range and organic systems (Rocchi et al., 2021, 2019) but never to intermediate systems.

3.4. *Limitations*

Some limitations of the study have already been discussed. For broiler welfare, collecting secondary data through a literature review rather than from specific flocks impacts the results, as differences in study design and quality may have been missed. It also resulted in high variability, especially for those welfare indicators which are seldom measured. Furthermore, the synthesis could not include aspects of breeder welfare, as only one trial was identified, and neither could it consider any indicators of positive welfare states for broilers. Therefore, this study was not able to fully compare the welfare implications of conventional and intermediate systems. For calculations of the GHG-emissions, slower-growing broilers were assumed to be fed the same diet as fast-growing hybrids, which may lead to an overestimation of how much more GHG-emissions are emitted. A more detailed discussion of these is available in Section 3.1.3 (broiler welfare) and Section 3.2 (GHG-emissions).

The use of secondary data is further connected to other limitations. Since quantitative data used to determine impacts on broiler welfare and GHG-emissions come from different sources, they are not paired. Therefore, this study is not able to consider the variations found between broiler flocks for both broiler welfare (de Jong et al., 2022; Rayner et al., 2020) and GHG-emissions (Mostert et al., 2022; Usva et al., 2023). In reality, some farms may perform better than others in both aspects resulting in lower trade-offs, similar to what Bartlett et al. (2024) found for pig production. To limit the impact of comparing unpaired data, this study focused on relative impacts. This allowed for trade-offs to be identified and for the performance of different systems to be compared relative to each other, which is a unique contribution. However, this study does not advance the understanding of the absolute impacts of different broiler systems which is highly important as it is tied to what changes are desirable. Rather, the findings of this study provide an indication of the magnitudes of the trade-offs that arise when higher-welfare methods are used.

Lastly, this study used climate impact as the only indicator for environmental sustainability. However, there may be trade-offs and interrelationships between minimizing greenhouse gas emissions and other environmental pressures that this study does not account for. Furthermore, other aspects of environmental sustainability may also have different relationships with broiler and breeder welfare than those outlined above. Therefore, these warrant further investigation in future research.

4. Conclusion

This study has investigated conflicts between improving the animal welfare and greenhouse gas emissions of broiler production by studying the trade-offs that arise when the stocking density in broiler houses is reduced and/or slower-growing broiler hybrids are used. Reducing stocking densities were associated with low trade-offs due to the minimal increase of greenhouse gas emissions and moderate improvements of welfare indicators. Comparatively, using slower-growing hybrids had a substantial impact on both animal welfare and greenhouse gas emissions and thus represented (4–8 times) larger trade-offs. The higher greenhouse gas emissions of slower-growing hybrids were primarily the result of higher feed requirements, and the magnitude of trade-offs were therefore largely dependent on the growth, and related feed conversion, rate of the specific slower-growing hybrid. A reduced number of parent animals partly offset the increased greenhouse gas emissions of using slower-growing hybrids. The trade-offs of switching to slower-growing hybrids were reduced (by almost a half) by stocking slower-growing broilers at lower densities, as this improved welfare indicators considerably more than it increased greenhouse gas emissions. Importantly, this study highlights the tensions between maximizing broiler welfare and minimizing greenhouse gas emissions and the importance of the hybrid's growth rate for both. While these trade-offs can be reduced through options that improve one aspect without impacting the other detrimentally, conflict may to some extent be inevitable. This is especially true as trade-offs likely exist with other aspects of sustainability. For instance, conventional and higher welfare systems may differ in terms of economic performance and viability and in other aspects of environmental and social sustainability such as indicators of circularity and antibiotic usage. Thus, navigating tensions may require decisions of what is deemed most important. In the case of broiler welfare and greenhouse gas emissions, we question whether the need to minimize greenhouse gas emissions of broiler production is as pressing as improving broiler welfare since greenhouse gas emissions from broilers reared with higher welfare methods remain substantially lower than other livestock. To move forward, we emphasize the need for comprehensive assessments that include all relevant aspects and stakeholders to determine how inevitable trade-offs should be navigated as well as what a more sustainable broiler production entails and how this may be achieved.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2025.02.015.

CRediT authorship contribution statement

L. Karlsson: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **L. Keeling:** Writing – review & editing, Supervision, Methodology, Conceptualization. **E. Röös:** Writing – review & editing, Supervision, Project administration.

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.

Acknowledgements

Elin Röös was supported by the research project “The Retail for Sustainability Project - ReSuS” (Grant number 2021-02327) and Linda Keeling was supported by the research project “Integrating improved animal welfare and sustainable development within the Swedish broiler industry” (Grant number 2022-0006). Both projects were funded by the governmental research council for sustainable development FORMAS.

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