Animal 19 (2025) 101499

Contents lists available at ScienceDirect

Animal

The international journal of animal biosciences

Potential climate performance of modern fast- and slow-growing broiler genotypes

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ARTICLE INFO

Article history:
Received 26 August 2024
Revised 21 March 2025
Accepted 24 March 2025
Available online 2 April 2025

Keywords:
Broiler feed
Broiler genetics
Energy efficiency
Global warming potential
Growth rate

ABSTRACT

Genetic selection aiming to improve the feed efficiency is believed to have a significant role in reducing the environmental impacts of livestock production. The aim of this study was to quantify the global warming potential of a wide range of modern fast–growing and slow–growing broiler genotypes under conditions where they are expected to meet their performance objectives set by breeding companies. The global warming potential was estimated for scenarios where the birds were fed on conventional and soy–free diets with different levels of balanced protein. Life cycle assessment approach based on the ISO 14040 standards was used to quantify the greenhouse gas emissions arising from the production. The results show that the fastest–growing genotypes have the lowest global warming potential when achieving their performance objectives, the difference being over 1 kg CO_2e per kg eviscerated carcass, compared to the slowest–growing genotypes. As the faster growth rate reduces the time to reach the slaughter weight (ranging from 38 days to 61 days between the genotypes), up to 13 MJ less energy per bird is lost as heat during the whole growth cycle and therefore less feed is needed. The improvement of feed efficiency is important because the feed-related emissions have a high contribution to the overall greenhouse gas emissions of broilers, ranging from 88 – 92%, when fed with the traditional soya-based diet. Additionally, differences in the body composition also have an effect on the energy consumption of the birds and on the corresponding greenhouse gas emissions. The protein sources in diets have generally high greenhouse gas intensity, and therefore reducing the protein concentration of the diet may, in some cases, reduce the global warming potential. On the other hand, this effect is limited by the adverse effect on the growth rate of the birds. In cases where protein sources with lower emission intensity can be used, the reduction of the protein concentration in the diet does not bring any further improvement to the climate performance of broiler production. In contrast, in such cases, low protein diets increase the emissions as a result of the longer growth cycle. In conclusion, the differences in Global Warming Potential of modern broiler genotypes are related to the differences in their efficiency of the use of feed energy. This efficiency is dependent on the growth rate of the birds, although the differences in body composition also have some effect.

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Implications

There is a need to identify the potential to improve the environmental performance of livestock through genetic selection. The climate impact of modern broiler genotypes is strongly dependent on their efficiency of the use of feed energy, and this depends on the growth rate of the birds, as fast growth rate reduces the time until the slaughter weight is reached. In slow–growing genotypes, alternative measures, mainly related to the composition of feed, are needed to reduce the climate impact. Breeding industry can improve the feed efficiency of broilers by simply focusing on growth rate and body composition.

Introduction

The environmental impacts related to poultry production are mainly arising from the production, processing and transport of feed, emissions from housing and manure management (which are largely affected by the consumption and composition of feed) and from the use of farm energy (e.g. for heating and ventilation) (Leinonen et al., 2012). Much of the energy-related greenhouse gas emissions are a result of using fossil fuels in heating, ventilation, transport and feed production (e.g. Payandeh et al., 2017, Ramedani et al., 2019, Kheiralipour and Sheikhi, 2021, Pourmehdi and Kheiralipour, 2024). However, the energy systems are now becoming more efficient, and the decarbonisation of energy generation is also progressing. Therefore, it can be expected that the role of other feed–related environmental impacts, arising mainly from

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https://doi.org/10.1016/j.animal.2025.101499
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land use changes and nitrogen emissions, will be even more dominant in poultry production in the future. Improving the feed efficiency of birds is one option to reduce those emissions.

Genetic selection aiming to improve the feed efficiency is believed to have a significant role in reducing the environmental impacts of livestock production (Neeteson-van Nieuwenhoven et al., 2013, Leinonen et al., 2016, Richardson et al., 2022). In broiler production, one of the most notable genetic trends during the last decades has been an increase in growth rate and reduction of the amount of feed needed to reach the slaughter weight, i.e. a phenomenon that within the poultry sector is known as "improved feed conversion ratio" (**FCR**), or "improved feed efficiency" (Laughlin, 2007, Zuidhof et al., 2014). It has also been found that the genetic changes during the last decades, and especially the reduced feed consumption over the production cycle and also higher carcass yield, have considerably reduced the greenhouse gas, ammonia and nitrate emissions per kg of saleable product (Defra, 2008, Pelletier, 2008, Prudencio da Silva et al., 2014). This observed trend has been used in studies based on mathematical modelling aiming to predict the potential to improve the environmental performance of broiler production through genetic selection (Leinonen et al., 2016). However, it should be noted that such predictions are often based on rather simplified assumptions, for example, expecting that the observed or predicted reduction in the feed intake per unit of product would be directly proportional to the changes in the environmental impacts arising from feed production. For more accurate predictions, it might be necessary to apply more comprehensive analyses, in order to understand the overall consequences of continuing genetic changes. For example, it would be necessary to take into account possible changes that could be required in feed composition as a result of the changes in bird performance (Leinonen, 2016).

To fully understand the overall effects of the past and future genetic changes on environmental sustainability of broiler production, more research is needed, including both theoretical modelling studies, and feeding experiments providing empirical evidence. One example of such studies was theoretical assessments carried out by Tallentire et al. (2016, 2018), where a model describing the full energy balance of the broiler bird was used to estimate the energy efficiency of the past, present and potential future broiler genotypes, and the consequences of the efficiency on the environmental performance of the birds.

It should also be emphasised that although there are breeding opportunities to keep reducing the environmental impacts of broiler meat production through continuous improvement in the feed efficiency, the modern broiler selection strategy is based on broad and balanced breeding goals including a strong focus on health and welfare, reproductive fitness and environmental adaptability alongside biological efficiency, yield and meat quality (Hiemstra and Ten Napel, 2013, Neeteson et al., 2020).

Despite increasing knowledge on the environmental performance of poultry production, a comprehensive analysis of the climate impacts of the wide range of modern broiler genotypes is still missing, together with a full understanding of the mechanisms behind potential differences between the genotypes. Therefore, the aim of this study was to apply Life Cycle Assessment (**LCA**) modelling to compare a wide range of modern fast and slow–growing broiler genotypes to quantify their global warming potential (**GWP**). The assessment was targeted to conditions where each of the genotypes could reach their commercially optimal performance, following the Performance Objectives specified by breeding companies, when fed on diets with different levels of balanced protein concentration and with alternative, soya-free diets.

It was expected that the emissions arising from land use change related to the production of soya would be a major component of the carbon footprint of the production of all broiler genotypes. Therefore, the idea behind the use of the soya-free diets was to explore how the exclusion of the ingredients associated with land use changes would affect the differences in the carbon footprint of these genotypes. As the soya-free diets were formulated according to the same nutritional recommendations as the soya-based diets, the performance objectives set by the breeding companies would be similar as with the baseline diets (Havilei et al., 2020). As a result, four different dietary scenarios were formulated: (1) High protein (**BP100s**) soya-based diet, (2) Low protein (**BP85s**) soya-based diet, (3) High protein soya-free diet (**BP100sf**) and (4) Low protein soya-free diet (**BP85sf**). The GWP was estimated for optimal conditions where the performance objectives set for these specific diets are expected to be met.

It would be essential for the breeding companies to identify specific traits that could be crucial for improving the environmental performance of different genotypes. Therefore, an additional aim of this study was to explore the relationship between different performance traits in order to understand the biological drivers behind the genotype differences in the environmental performance.

Material and methods

Breeds

The genotypes evaluated originate from two breeding companies Aviagen (https://www.Aviagen.com) and Hubbard Breeders (https://www.hubbardbreeders.com). The data on the expected biological performance of the genotypes were provided by the same companies and are based on the performance objectives of the genotypes set by the companies on the basis of experimental data (Table 1). The companies have produced the performance objectives for two different concentrations of balanced protein in the diet: the 100% balanced protein (BP100s) represents diets used commercially for the fastest growing genotypes while the 85% balanced protein (BP85s) diets represents diets used commercially for the slower growing genotypes (see the section Feed below).

Feed

Two different diets were provided by the breeding companies and applied in the analyses (Table 2): 1) 100% Balanced Protein (BP100s) diets and 2) 85% Balanced Protein diets (BP85s). The BP100 diets were formulated according to the published All Plant Protein nutritional recommendations (Aviagen, 2022). The BP85s diets were iso-caloric, while the level of all essential amino acids was reduced by 15%. All diets were based on least cost formulation. The BP100s represent diets optimising the performance (growth rate, feed conversion ratio, breast meat yield) for all genotypes while the BP85s diets could be more economical in certain European Welfare Schemes.

In addition to the baseline diets with 100 and 85% balanced protein concentration, an alternative scenario was also modelled where diets without any soybean meal or soy oil were formulated (BP100sf and BP85sf, Table 3). Soya was mainly replaced by ingredients that are less suitable for human consumption like sunflower meal and rapeseed meal (Bos et al., 2023).

Modelling

In order to quantify the greenhouse gas (**GHG**) emissions arising from the production cycle of each broiler genotype, an LCA approach following the ISO 14040 standards was applied (BSI, 2006). As an output of the assessment, the GWP with a 100-year timescale was determined for each genotype. The functional unit was set as 1 kg of eviscerated broiler carcass at a target slaughter

Table 1
The main performance indicators of different broiler genotypes at the point when reaching the final BW 2.5 kg, as provided by the breeding companies.

Breed	Feed	Days to 2.5 kg live weight	Average Daily Gain, g	Total feed consumption	Average daily feed intake, g	FCR 2.5 kg corrected for mortality	Eviscerated yield (%)	Livability (%)
Ross 308	BP100s	38.0	65.8	3 777	99.4	1.51	73.2	96.5
	BP85s	42.0	59.5	4 230	100.7	1.69	71.3	97.0
Ross 708	BP100s	39.8	62.8	3 752	94.3	1.50	74.5	96.5
	BP85s	44.0	56.8	4 203	95.5	1.68	72.6	97.0
Rustic Classic	BP100s	44.0	56.8	4 306	97.8	1.72	72.7	97.0
	BP85s	47.3	52.9	4 608	97.5	1.84	70.8	97.5
Redbro	BP100s	45.6	54.8	4 460	97.8	1.78	71.3	98.0
	BP85s	49.0	51.0	4 772	97.4	1.91	69.4	98.5
Rustic Gold	BP100s	48.2	51.8	4 486	93.0	1.79	71.9	98.0
	BP85s	51.8	48.2	4 800	92.6	1.92	70.0	98.5
Ranger Classic	BP100s	51.2	48.8	4 614	90.1	1.85	71.0	98.2
	BP85s	55.0	45.5	4 937	89.8	1.97	69.1	98.5
Hubbard JA787	BP100s	51.2	48.8	4 665	91.1	1.87	70.9	98.2
	BP85s	55.0	45.5	4 992	90.8	2.00	69.0	98.5
Ranger Gold	BP100s	57.0	43.8	4 801	84.2	1.92	70.5	98.5
	BP85s	61.3	40.8	5 041	82.3	2.02	69.0	98.7
Hubbard JA757	BP100s	57.0	43.8	4 854	85.2	1.94	70.0	98.5
	BP85s	61.3	40.8	5 097	83.1	2.04	68.5	98.7

Average Daily Gain = BW divided by production length (age).
Average Daily Feed intake = Total feed intake divided by the length of production cycle (age).
FCR 2.5 kg corrected for mortality = kg of feed/kg of live weight needed to achieve a 2.5 kg broiler, assuming livability is 100%.
Eviscerated yield: Eviscerated carcass (without neck, abdominal fat and internal organs) as percentage of live weight.
Abbreviations: FCR = Feed conversion ratio; BP100s = High-protein soya-based diet, BP85s = Low-protein soya-based diet.

weight of 2.5 kg. The emissions arising from the breeding generations (i.e., the reproductive birds that give rise to the broiler generation) were excluded from the comparison as the differences between the genotypes are very small and have only a small contribution to the overall differences in the GWP of broilers (Mostert et al., 2022). Therefore, the analysis carried out followed the "gate-to-gate" approach in terms of the system boundaries. A system-based LCA model for the broiler system was formulated in Microsoft Excel and parametrised based on the performance data made available for this study. The use of the systems model allowed exploring the differences in the bird performance and the effects of such differences on the GHG emissions arising from broiler production. In practice, this means that instead of using the "Tier 1" approach as described in the Intergovernmental Panel on Climate Change (**IPCC**) guidelines for national GHG inventories (IPCC, 2006), more detailed "Tier 2" or "Tier 3" calculation methods were applied where possible (IPCC, 2006).

The inputs of the model included all of the main resources (e.g. feed and inputs needed for feed production, and electricity and fuels needed in broiler housing) required to produce the functional unit. The model also took into account the differences in the performance objectives, including growth rate, feed intake, eviscerated yield and livability. The model also calculated all GHG emissions arising from the feed production and broiler housing. The direct and indirect N_2O emissions from housing and manure storage were calculated based on the IPCC Tier 2 methodology. These calculations were based on the amount of excreted nitrogen that was quantified according to the mass balance principle, i.e. the nitrogen retained in the animal body was subtracted from the total amount of nitrogen obtained from the feed (Leinonen et al., 2012, Usva et al., 2023). The CH_4 emissions from broiler housing were calculated following the IPCC Tier 1 approach. The emissions from feed production were quantified on the basis of the total feed consumption and the proportion of each feed ingredient in the diet. The global warming potential (GWP) of different feed ingredients was based on secondary data on the average global production of each ingredient, as obtained from the ecoinvent (2023) 3.6. database. For all the ingredients included in the diet, the component of GWP arising from the land use changes (**LUC**) was calculated separately from the other GHG emissions related to the production of the ingredient. For the emissions arising from the farm electricity consumption, the data on the average UK electricity generation were applied in combination with the data on electricity use provided by the breeding companies.

To explore the relationship between the energy intake of the birds and the length of the growth cycle, the following equation was formulated:

$$\text{ME intake} = \text{EB} + \text{DHL} \times \text{days} \qquad (1)$$

where ME intake is the total metabolisable energy intake during the production cycle, EB is the chemical energy stored in the bird body as protein and lipid, DHL is the average daily heat loss of the bird and days the length of the production cycle in days.

Results

Differences in the global warming potential

The GWP (excluding the breeding generations) per kg eviscerated carcass of different broiler genotypes is shown in Fig. 1. In this figure, the total GWP is divided into different components based on the sources of the GHG emissions, namely feed without LUC, the LUC emissions of feed production, methane (CH_4) emissions from housing, direct and indirect nitrous oxide (N_2O) emissions from housing, and the farm gas and electricity consumption. The two standout components of the total emissions were the feed production and the LUC related to feed, and the LUC emissions alone are of the same magnitude as all other emissions related to feed production. The total emissions related to feed production and LUC ranged from 88 to 92%, while the LUC emissions ranged from 41 to 50% of the total GHG emissions, depending on the genotype. The LUC emissions are mainly related to the production of soybean meal and soy oil, as they are a result of conversion of forest to cropland in certain parts of Southern America. Although the global average production data for soya was applied in this study, the proportion of soya originating from areas with land conversion was still big enough to produce these very high LUC emissions. The feed emissions other than those arising from LUC are mainly a result of crop farming activities, including the N_2O emissions from the application of the fertilisers, the fossil energy used in the production of fertilisers and the fuel consumption in field operations.

Table 2
The composition (%) and the nutritional properties of the broiler diets applied in the study.

	Starter		Grower		Grower 2		Finisher	
Item	BP100s	BP85s	BP100s	BP 85 s	BP100s	BP85s	BP100s	BP85s
Wheat EU	30.1	33.6	31.9	35.8	32.0	35.7	32.8	36.2
Corn	29	33	32	35	32	36	33	37
Soybean Meal - 48% Brazil	29.8	23.8	25.2	19.7	27.1	19.9	25.3	18.3
Potato Protein	2	1	2	1				
Canola Meal - 35%	1	1	1	1	1	1	1	1
Sunflower Meal 29%	0.9	1.1	1.2	1.4	0.9	1.3	1.0	1.4
Soy Crude Oil	2.9	2.2	3.2	2.6	3.8	3.0	3.9	3.1
Monocalcium Phosphate	1.12	1.16	0.78	0.81	0.64	0.67	0.51	0.54
Limestone 38%	1.27	1.29	0.92	0.94	0.85	0.87	0.78	0.80
Sodium Chloride 39%	0.20	0.19	0.20	0.19	0.21	0.20	0.21	0.20
Sodium bicarb 27%	0.24	0.25	0.24	0.26	0.23	0.25	0.23	0.25
Broiler Premix - 0.5%	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Lysine.SO4 55%	0.39	0.39	0.36	0.37	0.33	0.34	0.33	0.34
DL-Methionine - 99%	0.35	0.27	0.31	0.24	0.29	0.21	0.28	0.21
L-Threonine - 98.5%	0.12	0.11	0.10	0.09	0.10	0.09	0.10	0.08
L-Valine - 96%	0.01	0.00			0.01		0.01	
L- Arginine - 98%			0.01	0.01				
Choline Chloride 75%	0.06	0.08	0.06	0.08	0.04	0.06	0.04	0.06
Xylanase	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Phytase	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Moisture %	12.4	12.6	12.5	12.6	12.5	12.7	12.5	12.7
DM %	87.6	87.4	87.5	87.4	87.5	87.3	87.5	87.3
CP %	22.8	19.9	21.1	18.3	20.3	17.6	19.6	17.0
Crude Fat - Oil (A) %	4.9	4.3	5.3	4.7	5.9	5.1	6.0	5.2
Crude Fibre %	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Calcium incl Phytase contribution	0.95	0.95	0.75	0.75	0.7	0.7	0.65	0.65
Total Phosphorus	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.4
Available Phosphorus incl Phytase contribution	0.5	0.5	0.42	0.42	0.39	0.39	0.36	0.36
Ash %	5.7	5.4	4.8	4.6	4.7	4.4	4.4	4.1
Sugars %	4.6	4.2	4.3	3.9	4.5	3.9	4.3	3.8
Starches %	35.8	40.2	38.6	42.7	38.7	43.3	39.8	44.2
WPSA - AMEn kg kcal/k	2 948	2 945	3 022	3 018	3 046	3 043	3 070	3 067
WPSA - AMEn kcal enz kcal/k	2 975	2 975	3 050	3 050	3 075	3 075	3 100	3 100
Dig Lysine (SID) %	1.26	1.07	1.14	0.97	1.06	0.90	1.02	0.87
Sodium %	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Chloride %	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Potassium %	0.92	0.80	0.83	0.73	0.86	0.73	0.83	0.70
Na+K-Cl mEq/kg	253	225	232	205	239	205	230	198
Choline – Diet mg/kg	1 700	1 700	1 600	1 600	1 500	1 500	1 450	1 450
Phytase U/kg	500	500	500	500	500	500	500	500
Ratio to dig Lysine								
Dig Methionine	51.8	50.0	52.6	50.6	52.5	50.4	53.1	50.9
Dig Cystine	24.2	26.0	25.4	27.4	26.5	28.6	26.9	29.1
Dig Met+Cys	76	76	78	78	79	79	80	80
Dig Threonine	67	67	67	67	67	67	67	67
Dig Tryptophan	19.9	19.9	20.0	20.0	20.5	20.5	20.5	20.4
Dig Isoleucine	67.7	67.4	68.6	68	69	69	69	69
Dig Leucine	127.0	129.8	131.1	133.5	131.5	136.2	132.5	137.5
Dig Valine	76	76	77	77.4	78	78.3	78	78.8
Dig Arginine	104	104	105	105	109.8	107.8	109.4	107.4

Abbreviations: BP100s = High-protein soya-based diet; BP85s = Low-protein soya-based diet; EU = Origin: European Union; bicarb = bicarbonate; incl = including; WPSA = World Poultry Science Association; AMEn = Apparent Metabolisable Energy; enz = enzyme; Dig = digestible.

The differences in the GWP of different genotypes are directly related to the differences in the performance objectives shown earlier in Table 1. The results show that when fed with the BP100s diet, the expected length of the production cycle, i.e. the time to reach the slaughter weight of 2.5 kg varies from 38 days (Ross 308) to 57 days (Ranger Gold, Hubbard JA757). The use of the low-protein diet (BP85s) was expected to reduce the growth rate and increase the cycle length in all genotypes, and the biggest effect can be found in the fastest–growing genotypes. Clear differences can also be seen in the feed consumption between the genotypes. When fed with the high-protein diet (BP100s), the lowest feed consumptions for reaching the slaughter weight were found in the performance objectives for Ross 708 (3 752 g) and Ross 308 (3 777 g) and the highest in those for Ranger Gold (4 801 g) and Hubbard JA757 (4 857 g). In general, even if the expected daily feed intake is highest in the fast-growing genotypes, the feed consumption over the whole cycle is lowest in these genotypes, because of the shorter duration of the growth cycle. The use of the 85% balanced protein diet does not change the daily intake very much, but it would increase the total feed consumption due to the extension of the production cycle in all genotypes. Again, the biggest effect of the dietary change is expected in the fastest–growing genotypes.

Effect of feed composition

Although the feed composition has a major contribution to GWP, changing the protein concentration of the feed has two oppo-

Table 3
The composition (%) and the nutritional properties of the soya-free broiler diets applied in the study, as used in the alternative scenario.

	Starter		Grower		Grower 2		Finisher	
Item	BP100sf	BP85sf	BP100sf	BP85sf	BP100sf	BP 85sf	BP 100sf	BP85sf
Wheat EU	28.4	31.4	26.8	29.5	23.8	27.8	23.7	28.6
Corn	29	31	27	29	24	28	24	28
Peas	10	10	10	10	10	10	10	10
Potato Protein	5	4.4	4.9	3.1	2.7	1.0	1.8	
Corn Gluten 60% CP	7.8	4.1	2.4		0.6			
Canola Meal - 35%	5	5	8	8	10	10	12	12
Sunflower Meal Hipro - 36%	7.4	7.0	11.8	11.5	17.9	13.3	17.1	11.2
Sunflower oil	0.8	1.1	3.1	3.2	4.7	3.6	4.4	3.0
Poultry Fat	1	1	2	2	3	3	4	4
Monocalcium Phosphate	1.15	1.17	0.76	0.77	0.58	0.61	0.44	0.48
Limestone 38%	1.30	1.29	0.86	0.86	0.73	0.75	0.63	0.66
Sodium Chloride 39%	0.16	0.16	0.18	0.18	0.20	0.20	0.20	0.21
Sodium bicarb 27%	0.28	0.28	0.25	0.26	0.23	0.23	0.22	0.22
Broiler Premix - 0.5%	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Lysine.SO4 55%	0.92	0.67	0.64	0.52	0.58	0.53	0.58	0.55
DL-Methionine - 99%	0.27	0.21	0.25	0.20	0.21	0.17	0.22	0.18
L-Threonine - 98.5%	0.16	0.11	0.10	0.09	0.10	0.10	0.11	0.12
L-Tryptophan - 98%	0.02							
L-Valine - 96%	0.04					0.02	0.02	0.04
L-Arginine - 98%	0.32	0.19	0.14	0.06				0.02
L-Isoleucine - 99%	0.08	0.04	0.05	0.05	0.05	0.06	0.06	0.08
Choline Chloride 75%	0.12	0.11	0.06	0.06	0.01	0.02		
Xylanase -0.02%	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Phytase - 0.0025%	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Potasium Carbonate 56%	0.29	0.30	0.16	0.17	0.02	0.12	0.01	0.14
Moisture %	11.6	11.9	11.5	11.7	11.1	11.5	11.1	11.6
DM %	88.4	88.1	88.5	88.3	88.9	88.5	88.9	88.4
CP %	22.3	19.4	20.6	17.8	19.8	17.1	19.1	16.5
Crude Fat – Oil (A) %	3.9	4.1	6.9	7.0	9.4	8.4	10.1	8.8
Crude Fibre %	4.0	4.0	5.0	5.0	6.1	5.5	6.2	5.4
Calcium incl Phytase contribution	0.95	0.95	0.75	0.75	0.7	0.7	0.65	0.65
Total Phosphorus	0.61	0.60	0.56	0.56	0.58	0.55	0.56	0.52
Available Phosphorus incl Phytase contribution	0.5	0.5	0.42	0.42	0.39	0.39	0.36	0.36
Ash %	5.2	5.2	4.7	4.6	4.6	4.5	4.5	4.3
Sugars %	2.8	2.9	3.2	3.2	3.5	3.4	3.6	3.5
Starches %	39.7	42.2	36.9	39.3	33.1	37.8	33.0	38.3
WPSA – AMEn kg kcal/k	2.964	2.955	3.032	3.028	3.056	3.053	3.082	3.080
WPSA – AMEn kcal enz kcal/k	2.975	2.975	3.050	3.050	3.075	3.075	3.100	3.100
Dig Lysine (SID) %	1.26	1.07	1.14	0.97	1.06	0.90	1.02	0.87
Sodium %	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Chloride %	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Potassium %	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71
Na+K-Cl mEq/kg	200	200	200	200	200	200	200	200
Choline – Diet mg/kg	1.700	1.700	1.600	1.600	1.500	1.500	1.523	1.454
Phytase U/kg	500	500	500	500	500	500	500	500
Ratio to dig Lysine								
Dig Methionine	51.2	49.5	51.9	50.4	51.5	49.7	51.9	50.0
Dig Cystine	24.8	26.5	26.1	27.6	27.5	29.3	28.1	30.0
Dig Met+Cys	76	76	78	78	79	79	80	80
Dig Threonine	67	67	67	67	67	67	67	67
Dig Tryptophan	16	16.0	17.2	18.1	18.7	18.5	18.8	18.1
Dig Isoleucine	67	67	68	68	69	69	69	69
Dig Leucine	149.8	144.1	133.4	123.1	123.2	120.1	117.5	116.5
Dig Valine	76	76	77	77	78	78	78	78
Dig Arginine	104	104	105	105	106	106	107	107

Abbreviations: BP100sf = High-protein soya-free diet; BP85sf = Low-protein soya-free diet; EU = Origin: European Union; bicarb = bicarbonate; incl = including; WPSA = World Poultry Science Association; AMEn = Apparent Metabolisable Energy; enz = enzyme; Dig = digestible.

site effects on the emissions. When reducing the concentration of balanced protein, the total GWP per one kg of consumed feed was reduced considerably (Table 4). This is a result of the reduction of the high-emission feed ingredients, most notably the soybean meal. On the other hand, the reduction in protein concentration would reduce the growth rate of the birds, increasing the feed consumption until the slaughter weight is reached, and therefore also increased the feed-related emissions. This trade-off is also different in different genotypes. When fed with the low-protein diet (BP85s), the reduction of the growth rate would be biggest in the fast-growing genotypes, but still, no major differences in the GWP with different diets were observed in these genotypes. In contrast, in terms of reducing the GHG emissions, it would be more beneficial to feed the slow-growing genotypes with the 85% balanced protein diet. The reduction in growth in response to feeding lower balanced protein diets is smaller in these genotypes, and therefore, the reduction in the growth rate is moderate with the low-protein diet, and the composition of the diets would have a bigger effect on GWP than the differences in feed consumption.

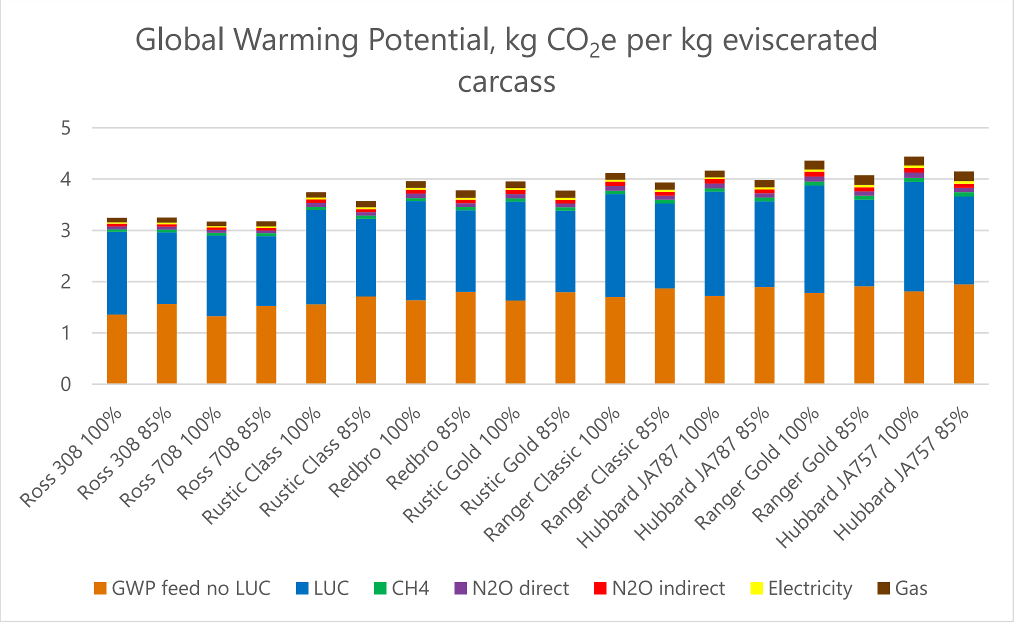

Fig. 1. Global Warming Potential (kg CO_2e, excluding the breeder generations) per kg eviscerated carcass of different broiler genotypes. 100% indicates a diet with 100% balanced protein concentration (BP100s) and 85% indicates a diet with 85% balanced protein (PB85s). Abbreviations: GWP = Global Warming Potential; LUC = Land Use Change.

Table 4
Global Warming Potential (GWP, kg CO2e/kg feed) of different broiler diets.

Phase	Starter		Grower		Grower 2		Finisher	
Diet	BP100s	BP85s	BP100s	BP85s	BP100s	BP85s	BP100s	BP85s
GWP, kg CO_2e/kg feed	1.44	1.28	1.36	1.21	1.44	1.24	1.41	1.21

Abbreviations: BP100s = High-protein soya-based diet; BP85s = Low-protein soya-based diet.

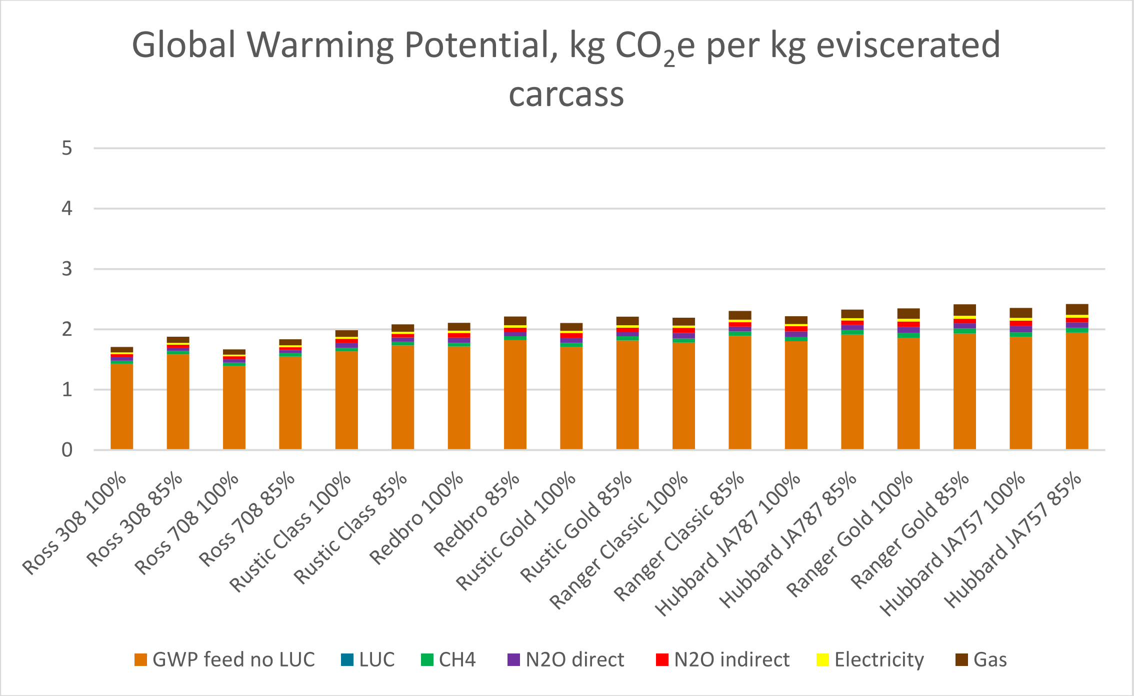

Fig. 2. Global Warming Potential (kg CO_2e, excluding the breeder generations) per kg eviscerated carcass of different broiler genotypes when fed with the soya-free diet. 100% indicates a diet with 100% balanced protein concentration (BP100sf) and 85% indicates a diet with 85% balanced protein (BP85sf). Abbreviations: GWP = Global Warming Potential; LUC = Land Use Change.

The results also show that the emissions per kg feed could be reduced by up to 47% when the soya-free diet was used in broiler production (Fig. 2). This results from the fact that the emissions arising from the land use changes related to the production of some of the soya included in the feed can be avoided (Table 5). The change in diet has also some effect on the differences in emissions between the genotypes. In general, when the soya-free diet is used, the GWP is more influenced by the feed intake increment effect of the low protein diet than the lower GWP of the low protein diet per se. Therefore, for each genotype, the low protein diets have higher GWP than the high protein diet.

Relationship between traits

There is a clear relationship between the expected length of the production cycle and the total metabolisable energy intake needed to reach the BW of 2.5 kg, as shown in Fig. 3. As the metabolisable energy intake determines the total feed consumption, it is also the main driving factor between the differences in the GHG emissions of different genotypes as observed in this study. A similar relationship exists also between the length of production cycle and the protein intake of the birds. As a result, the amount of nitrogen excretion and therefore also the direct and indirect N_2O emissions are higher in slow–growing birds than in fast–growing birds. However, the nitrogen emissions have only a small contribution to the total global warming potential, as is shown in Fig. 1.

Discussion

Growth rate and the energy balance

The relationship between the cycle length and the metabolisable energy intake clearly demonstrates the overall energy balance of the broiler chicken, as discussed by Tallentire et al. (2016, 2018). After the energy obtained from feed is metabolised, it can be only either stored in the chicken body as chemical energy, in the form of protein or lipid, or lost as heat. Therefore, if there are differences in the metabolisable energy intake between birds with the same BW and the same body composition, those differences can only be a result of differences in the metabolic heat loss. Further, if the average daily heat loss would be the same, then the length of the production cycle would directly determine the overall heat loss and also the proportion of the total metabolisable energy intake that would not be stored in the birds' body as protein or lipid (Tallentire et al., 2016). This relationship can be expressed by the simple Eq. (1). This linear relationship can be directly seen in Fig. 3, where the ME intake of the birds is expressed as a function of the length of the production cycle. As the final weight of the birds is the same for all genotypes, the fitted trendline can be expected to represent Eq. (1) so that the slope of the line is equal to the daily heat loss and the intercept is the energy content of the body of the bird at the end of the growth cycle. The relationship in Fig. 3 shows that amongst the genotypes included in this study,

Table 5
Global Warming Potential (GWP, kg CO2e/kg feed) of the soy-free broiler diets.

Phase	Starter		Grower		Grower 2		Finisher	
Diet	BP100sf	BP85sf	BP100sf	BP85sf	BP100sf	BP85sf	BP100sf	BP85sf
GWP, kg CO_2e/kg feed	0.72	0.68	0.69	0.67	0.68	0.66	0.67	0.65

Abbreviations: BP100sf = High-protein soya-free diet; BP85sf = Low-protein soya-free diet.

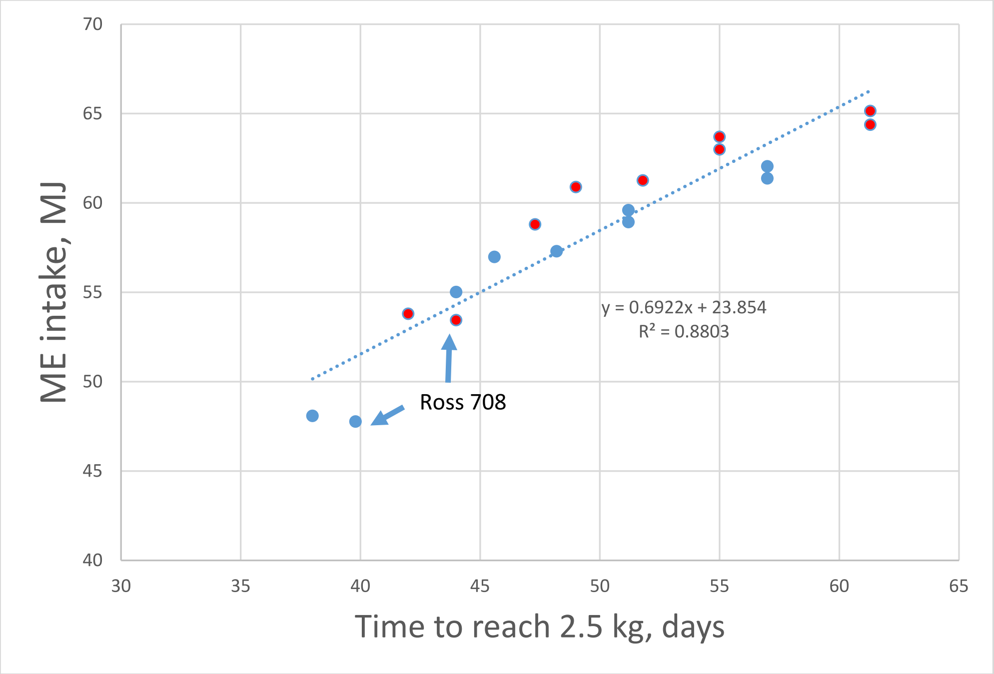

Fig. 3. The relationship between the time and the total metabolisable energy intake (MJ) needed to reach the broiler slaughter weight of 2.5 kg. Blue symbols indicate the 100% balanced protein diet (BP100s) and red symbols the 85% balanced protein diet (BP85s). The arrows indicate the genotype Ross 708 with high breast meat yield. Abbreviation: ME = Metabolisable energy.

each additional day in the length of the growth cycle would increase the metabolisable energy intake on average by about 0.7 MJ (as indicated by the slope of the fitted trendline). With the average metabolisable energy concentration of the feed (12.7 MJ/kg), the reduction of the length of the production cycle by one day would reduce the feed consumption by 55 g and reduce also the feed-related GHG emissions accordingly. Therefore, a fast growth rate can largely explain the improvement of the feed efficiency observed in broiler production (Havenstein et al., 2003a,b; Howie et al., 2011; Zuidhof et al., 2014; Tallentire et al., 2016).

The relationship shown in Fig. 3 has major consequences when considering the opportunities to reduce the environmental impacts of broiler production through breeding. The relationship between the growth rate and the energy efficiency is very strong and consistent within the whole range of genotypes and within different dietary options. This means that the faster growth rate obtained through genetic selection has been the main driver in improving the energy efficiency by reducing heat losses, in reducing the FCR and also in improving the environmental performance of broiler production. This result is also consistent with earlier theoretical modelling studies by Tallentire et al. (2016, 2018).

Other traits affecting the energy balance

As discussed above, the heat loss would be the only driver in the differences of metabolisable energy intake if the size of the bird and the content of the body would be equal. However, there can be differences in the protein and lipid content of the body (Caldas et al., 2019). For example, when comparing to birds with an equal total body mass, the bird with lower body fat content would have also less energy stored in the body, because of the lower energy concentration of protein compared to lipid and also because the higher protein content is associated with a higher water content of the body. In this study, it was not possible to assess such differences based on the available data, because the estimation of the protein and lipid contents of the whole body of the bird is not a very straightforward task methodologically. Nevertheless, it could be expected that there are some differences in the body composition. e.g. the fat content of the body, within the range of genotypes included in the assessment. On the basis of the trend shown in Fig. 3, it can be concluded that if such differences would affect the energy efficiency, the effect would be relatively small, as the differences in the growth rate alone can explain nearly all the variation occurring in the efficiency. However, there are some deviations from this common trend. Of all the genotypes included in the comparison, the highest energy efficiencies can be found in the genotypes Ross 308 and Ross 708. Especially the latter genotype, when fed with the BP100s diet, shows considerably lower metabolisable energy intake than what the common trend in Fig. 3 would indicate. This "unexpected" efficiency can be explained by the above-mentioned body composition (high muscle content, low fat content), as indicated by the high eviscerated yield (Table 1) and by the high breast meat yield, which is 26.6% of the live weight in Ross 708, while only 24.9% in Ross 308 (Aviagen, personal communication). Based on this high yield, it can be expected that the overall protein content of Ross 708 is higher than in other genotypes. This in turn leads to lower lipid content in Ross 708 when compared to other genotypes at the same weight. Therefore, the reduced allocation of energy to lipid, together with the relative fast growth rate, can explain the high energy efficiency of Ross 708. More detailed measurements of the body composition of both genotypes would be needed to confirm this hypothesis.

Differences in metabolic activity, i.e. the rate of metabolic heat production per unit of BW, have been sometimes suggested as a reason for the genetic differences in energy efficiency (e.g. Pym et al., 2004, Bottje and Carstens, 2009). However, no evidence of such differences in broiler chicken has been shown. In contrast, Tallentire et al. (2016) demonstrated that the historic trend in energy efficiency can be explained without any differences in metabolic activity. The comparison of the modern broiler genotypes in this study confirms this. The strong relationship between the length of the production cycle and the energy efficiency, together with the additional effect of body composition, can fully explain the differences in efficiency, without any possible differences in metabolic activity.

Overall global warming potential of different genotypes

In addition to the feed intake and the composition of the feed, there are also other factors that contribute to the differences in the climate performances between the genotypes, as observed in this study. As a result of the differences in feed efficiency, the emissions related to nitrogen excretion were as much as 80% higher in the slowest–growing genotypes compared to the fast–growing birds. Further, as the expected length of the growth cycle is greater, the methane emissions as well as the emissions arising from gas and electricity consumption would also be the highest in the slow–growing birds. However, these emissions not related to the production of the feed and associated land use changes had only a minor contribution to the overall GWP of the birds (Figs. 1 and 2). Similar results have also been observed in other recent environmental impact assessments of poultry production (e.g. Mostert et al., 2022, Usva et al., 2023).

As a general trend, the eviscerated carcass yield increased together with a faster growth rate amongst the genotypes included in this study. As the GWP is expressed per kg of the eviscerated carcass, the higher yield has a direct effect on the calculated climate performance. With the variation in carcass yield from 68.5% (Hubbard JA757 with BP85s diet) to 74.5% (Ross 708 with BP100s diet), the GWP of the lowest-yield genotype would be about 9% higher compared highest-yield genotype even if the emissions per unit of live weight would remain the same.

As growth rate has a direct impact on the carbon footprint of broiler meat production, the choice of genotypes for production has a big effect on the climate impact of the whole poultry sector (e.g. Mostert et al., 2022). However, one of the recommendations of the recent European Food Standard Agency scientific opinion on the welfare of broilers on farm is to limit the broiler growth rate to a maximum of 50 g/day (EFSA, 2023). Such a change would have a major impact on the overall GHG emissions of the poultry sector in Europe.

It should also be noted that this study was based on the performance objectives of the genotypes, i.e. performance under optimal conditions. However, the performance of the animal is also affected by environmental conditions, and the resistance to environmental stress is strongly affected by genotype/environmental interactions. This can also have effect on environmental impacts such as GWP. For example, Menchetti et al. (2024) found that under certain conditions, low–protein diets could give the same or even better productive results than full–protein ones in some slow-growing birds. Therefore, more experimental data are needed to confirm the environmental performance of different genotypes in different conditions.

In conclusion, it can be stated that the differences in the Global Warming Potential of modern broiler genotypes are strongly related to the differences in their efficiency of the use of feed energy. This efficiency is very much dependent on the growth rate of the birds, although the differences in body composition also have some effect. More specifically, the fast growth rate reduces the time until the slaughter weight is reached, and therefore, even if the rate of metabolic heat production would remain the same, less energy is lost as heat during the whole growth cycle. This was demonstrated by the very close relationship between the time required to reach the slaughter weight and the total energy consumption during the growth cycle.

Overall, at the same slaughter weight when fed with conventional, soya-based diets, fast–growing broiler genotypes have over 25% lower GWP than the slow–growing genotypes, due to their lower feed consumption required to reach the target slaughter weight. Reducing the protein concentration of the diet can reduce the GWP of slow–growing genotypes, even if that would also reduce the growth rate and increase the length of the production cycle. However, this is not the case for the fastest–growing genotypes. Reduced GWP can be achieved in slow–growing genotypes because the protein sources in the diet can themselves have very high GHG emission intensity, mainly as a result of land use changes. These emissions can be reduced through using more sustainable protein sources. In this study, this was demonstrated through the use of the soya-free diet, but there are also other options in feed formulation that can help reduce the environmental impacts of feed (e.g. Leinonen et al., 2014). In the case when the emission intensity of the protein sources remains low, the reduction of the protein content in the diet does not necessarily bring any further improvement in the environmental performance of broiler production, but in contrast, may increase the emissions as a result of the longer growth cycle.

Ethics approval

This research did not involve any animal experimentation.

Data and model availability statement

The data/models were not deposited in an official repository. The analysis was based on animal performance objectives that are available from the breeding companies. Details of the model are available from the author. Secondary data are available in publications and databases as indicated in the text.

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

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

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CRediT authorship contribution statement

I. Leinonen: Writing – review & editing, Writing – original draft, Visualisation, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualisation.

Declaration of interest

None.

Acknowledgements

None.

Financial support statement

This work was supported by Aviagen. This research received no specific grant from any other funding agency, commercial or not-for-profit section.

References

Aviagen, 2022. Nutrient Specifications. All Plant Protein-Based Feeds. https://aviagen.com/assets/Tech_Center/Ross_Broiler/Ross-PlantProteinBasedBroilerNutritionSpecifications2022-EN.pdf. Accessed 21 March 2025.

Bos, B., van Kernebeek, H., Mostert, P., van Harn, J., van Horne, P., de Jong, I., 2023. Welfare, environmental impact and economy of broiler chicken production. An overview of the lessons learned from the Greenwell project. Wageningen University and Research. https://edepot.wur.nl/629412. Accessed 21 March 2025.

Bottje, W., Carstens, G., 2009. Association of mitochondrial function and feed efficiency in poultry and livestock species. Journal of Animal Science 87, E48–E63. https://doi.org/10.2527/jas.2008-1379.

BSI, 2006. Environmental management: Life cycle assessment – Principles and framework. http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=37456. Accessed 21 March 2025.

Caldas, J.V., Boonsinchai, N., Wang, J., England, J.A., Coon, C.N., 2019. The dynamics of body composition and body energy content in broilers. Poultry Science 98, 866–877. https://doi.org/10.3382/ps/pey422.

Defra, 2008. A study of the scope for the application of research in animal genomics and breeding to reduce nitrogen and methane emissions from livestock based food chains. Defra project AC0204. Defra, London, UK.

ecoinvent, 2023. ecoinvent Database. https://ecoinvent.org/ Accessed 21 March 2025.

EFSA, 2023. Welfare of broilers on farm. https://efsa.onlinelibrary.wiley.com/action/downloadSupplement?doi=10.2903/j.efsa.2023.7788&file=efs27788-sup-0001-PLS.pdf. Accessed 21 March 2025.

Havenstein, G.B., Ferket, P.R., Qureshi, M.A., 2003a. Carcass composition and yield of 1957 versus 2001 broilers when fed representative 1957 and 2001 broiler diets. Poultry Science 82, 1509–1518. https://doi.org/10.1093/ps/82.10.1509.

Havenstein, G.B., Ferket, P.R., Qureshi, M.A., 2003b. Growth, livability, and feed conversion of 1957 versus 2001 broilers when fed representative 1957 and 2001 broiler diets. Poultry Science 82, 1500–1508. https://doi.org/10.1093/ps/82.10.1500.

Havilei, O., Pankova, S., Katerynych, O., Poliakova, L., 2020. Replacement of soybean meal with sunflower one in the diet of broiler chickens and its influence on their growth and development. Bulletin of Agricultural Science 98, 32–40.

Hiemstra, S.J., Ten Napel, J., 2013. Study of the impact of genetic selection on the welfare of chickens bred and kept for meat production. Publisher: DG SANCO 2011/12254. IBF International Consulting, Brussels, Belgium, pp. 118. https://food.ec.europa.eu/system/files/2016-10/aw_practice_farm_broilers_653020_final-report_en.pdf. Accessed 21 March 2025.

Howie, J.A., Avendano, S., Tolkamp, B.J., Kyriazakis, I., 2011. Genetic parameters of feeding behavior traits and their relationship with live performance traits in modern broiler lines. Poultry Science 90, 1197–1205. https://doi.org/10.3382/ps.2010-01313.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. (2006 Guidelines) http://www.ipcc-nggip.iges.or.jp/. Accessed 21 March 2025.

Kheiralipour, K., Sheikhi, N., 2021. Material and energy flow in different bread baking types. Environment, Development and Sustainability 23, 10512–10527. https://doi.org/10.1007/s10668-020-01069-2.

Laughlin, K., 2007. The evolution of genetics, breeding and production. Temperton Fellowship Report No.15. Harper Adams University College, Newport, Shropshire, UK.

Leinonen, I., 2016. Life cycle assessment (LCA) of intensive poultry production systems. In: Ricke, S. (ed.) Achieving Sustainable Production of Poultry Meat Vol 1: Safety, Quality and Sustainability. Burleigh Dodds Science Publishing. Cambridge, UK, pp. 339-355.

Leinonen, I., Williams, A.G., Wiseman, J., Guy, J., Kyriazakis, I., 2012. Predicting the environmental impacts of chicken systems in the UK through a Life Cycle Assessment: broiler production systems. Poultry Science 91, 8–25.

Leinonen, I., Williams, A.G., Wiseman, J., Kyriazakis, I., 2014. The potential to mitigate the environmental impacts of broiler production systems through changes in their diets. In: Garnsworthy, P.G., Wiseman, J. (Eds.), Recent Advances in Animal Nutrition – 2013. Context Products Ltd., Packington, England, pp. 123–144.

Leinonen, I., Williams, A.G., Kyriazakis, I., 2016. Potential environmental benefits of prospective genetic changes in broiler traits. Poultry Science 95, 228–236.

Menchetti, L., Birolo, M., Mugnai, C., Mancinelli, A.C., Xiccato, G., Trocino, A., Castellini, C., 2024. Effect of genotype and nutritional and environmental challenges on growth curve dynamics of broiler chickens. Poultry Science 103, 104095.

Mostert, P.F., Bos., A.P., van Harn, J., de Jong I.C., 2022. The impact of changing toward higher welfare broiler production systems on greenhouse gas emissions: a Dutch case study using life cycle assessment. Poultry Science 101, 102151.

Neeteson, A.-M., Avendaño, S., Koerhuis, A., 2020. Poultry Breeding for Sustainability and Welfare. In: Vosough Ahmadi, B., Moran, D., D'Eath, R. (Eds.), The Economics of Farm Animal Welfare. Theory, Evidence and Policy. CABI International, Wallingford, UK, pp. 117–146.

Neeteson-van Nieuwenhoven, A.-M., Knap, P., Avendaño, S., 2013. The role of sustainable commercial pig and poultry breeding for food security. Animal Frontiers 3, 52–57.

Payandeh, P., Kheiralipour, K., Karimi, M., Khoshnevisan, B., 2017. Joint data envelopment analysis and life cycle assessment for environmental impact reduction in broiler production systems. Energy 127, 768–774. https://doi.org/10.1016/j.energy.2017.03.112.

Pelletier, N., 2008. Environmental performance in the US broiler poultry sector: life cycle energy use and greenhouse gas, ozone depleting, acidifying and eutrophying emissions. Agricultural Systems 98, 67–73.

Pourmehdi, K., Kheiralipour, K., 2024. Net energy gain efficiency, a new indicator to analyze energy systems, case study: Comparing wheat production systems. Results in Engineering 22, 102211. https://doi.org/10.1016/j.rineng.2024.102211.

Prudencio da Silva, V., van der Werf, Hayo, M.G., Soares, S.R., Corson, M.S., 2014. Environmental impacts of French and Brazilian broiler chicken production scenarios: an LCA approach. Journal of Environmental Management 133, 222–231.

Pym, R., Leclercq, B., Tomas, F., Tesseraud, S., 2004. Protein utilisation and turnover in lines of chickens selected for different aspects of body composition. British Poultry Science 45, 775–786. https://doi.org/10.1080/00071660400012774.

Ramedani, Z., Alimohammadian, L., Kheialipour, K., Delpisheh, P., Abbasi, Z., 2019. Comparing energy state and environmental impacts in ostrich and chicken production systems. Environmental Science and Pollution Research 26, 28284–28293. https://doi.org/10.1007/s11356-019-05972-8.

Richardson, C.M., Amer, P.R., Quinton, C., Crowley, J., Hely, F.S., van den Berg, I., Pryce, J.E., 2022. Reducing greenhouse gas emissions through genetic selection in the Australian dairy industry. Journal of Dairy Science 105, 4272–4288. https://doi.org/10.3168/jds.2021-21277.

Tallentire, C.W., Leinonen, I., Kyriazakis, I., 2016. Breeding for efficiency in the broiler chicken. A review. Agronomy for Sustainable Development 36, 66. https://doi.org/10.1007/s13593-016-0398-2.

Tallentire, C.W., Leinonen, I., Kyriazakis, I., 2018. Artificial selection for improved energy efficiency is reaching its limits in broiler chickens. Scientific Reports 8, 1168. https://doi.org/10.1038/s41598-018-19231-2.

Usva, K., Hietala, S., Nousiainen, J., Vorne, V., Vieraankivi, M.-L., Jallinoja, M., Leinonen, I., 2023. Environmental life cycle assessment of Finnish broiler chicken production – Focus on climate change and water scarcity impacts. Journal of Cleaner Production 410, 137097.

Zuidhof, M.J., Schneider, B.L., Carney, V.L., Korver, D.R., Robinson, F.E., 2014. Growth, efficiency, and yield of commercial broilers from 1957, 1978, and 2005. Poultry Science 12, 2970–2982.