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Nutritional modulation of environmental credentials of slow growing broiler chickens featuring data from a controlled replicated feeding study

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Abstract

Of all livestock systems, broiler chicken production has a relatively low environmental impact. However, the recent increase in the use of slow growing broiler chickens (SGB) in place of fast growing broilers (FGB), is predicted to increase environmental indicators. Nutritional interventions have been suggested. This study determines the impact of dietary nutrient density on environmental credentials per kg liveweight (LW) of FGB and SGB reared over the same period. A higher protein and energy diet, designed for FGB, or a lower protein and energy diet, designed for SGB, were fed to the commercial FGB breed, Ross 308, and the commercial SGB breed, Hubbard Redbro. Soybean meal (SBM) associated with low incidence of land conversion (LC) was the baseline scenario. A scenario using SBM from a region with greater LC (LC+) was modelled. Uncertainty was tested using Monte Carlo simulations. Statistical differences were assessed using generalised linear models, with the distribution family chosen based on characteristics of the response variable. In the baseline scenario, feeding the HS diet to SGB reduced the global warming impact per kg LW by 6.5%, eutrophication by 10%, and acidification by 8%. In the LC+ scenario, GW increased by 83–97%, FWEu by 55–62%, and TA and MEu by 16%. Manure emissions of Nitrogen and CH_4 per kg LW were not impacted by breed or diet. Feeding a HS diet reduced impact category results per kg broiler LW without impacting manure emissions and may be considered as a strategy to reduce the impact of SGB production.

Keywords Agriculture, Greenhouse gas, Manure, Nutrition, Lifecycle assessment

1 Introduction

Fast growing broiler (FGB) chickens efficiently produce meat that is eaten worldwide [1]. However, there is some concern that broilers with fast growth rates have greater mortality, contact dermatitis and difficulty walking compared to slower growing breeds (SGB) [2, 3, 4, 5, 6, 7, 8]. Market actors are driving animal welfare policy to encourage the transition from using FGB to SGB [https://betterchickencommitment.com/uk/]. The use of SGB is predicted to increase [9] and already occupies 100% of the Dutch fresh broiler meat market [10], 15% of slaughter volume in France [11], 11% of production in the UK [12], 7% of production in Denmark [13] [https://chr.fvst.dk/chri/faces/frontpage;jsessionid=5YmC6rfEeobheyJMNFpwA9Yd2-qewxhceLm7yTD4RysmDigh9eOH!1332607847] 8% of total EU production [14]. The economic cost of industry-wide conversion to indoor-based commercial SGB production may be up to $450 million for consumers and $3.1 billion for producers [15], and the policies may be subject to rapid change [16]. Environmentally, the use of SGB has been associated with greater impacts although this can vary greatly depending on the specific production system used [17, 18, 19]. Therefore, transitioning to SGB production presents financial and environmental challenges, and there is a need to investigate mitigation measures.

Nutritional mitigation measures are a focus as feed contributes approximately 75% to the cost of broiler production [20] and between 72% and 82% to their global warming impact [21, 22, 23]. Mitigation strategies include improving feed efficiency, incorporating feed materials that have lower environmental impacts, and reducing the excretion of nitrogen and phosphorus [23, 24, 25]. These strategies often focus on reducing the amount of soybean meal (SBM) fed to broilers. While SBM has a favourable amino acid profile [26, 27], it is a key contributor to economic and environmental costs of broiler production [28, 29, 30]. Few studies conducted in developed countries have employed nutritional interventions to lifecycle assessments of broiler chickens and validated changes using birds [31, 32, 33].

Growth performance of broilers is determined by genetic potential and nutrient intake [34]. Due to known differences in the growth performance of FGB and SGB [35, 36], diets for SGB are commercially formulated to a lower nutrient specification (LS) [18, 19, 33, 37]. These diets usually contain less energy and protein than the higher nutrient specification (HS) used to formulate diets for FGB. Increasing the levels of energy and nutrients in diets has been shown to improve the Feed Conversion Ratio (FCR) of FGB [38, 39], and of SGB, while maintaining a desired slower growth rate [36], which is an attraction to consumers and stakeholders [3, 4, 7]. However, higher nutrient density diets may require greater use of SBM, and an oversupply of nutrients may lead to greater excretion of N and P which could impact eutrophication and acidification metrics [40, 41]. This would inevitably impact the environmental footprint of broilers. The environmental impact of FGB and SGB is compared in this study. The impact of feeding diets based on a HS or LS to each breed is also compared to determine the influence of dietary formulation on the environmental impact.

It was hypothesised that SGB would have greater environmental impacts than FGB. However, it was hypothesised that this could be mitigated by reducing the FCR of SGB via feeding a higher nutrient specification diet. The aim of this study was to evaluate the use of HS and LS diets as a strategy to manipulate the environmental credentials of Ross 308 (FGB) and Redbro (SGB) broiler chickens per kg LW reared to the same age.

2 Methodology

The LCA method used in this study is based on guidance from BS EN ISO 14040:2006 and ISO 14044:2006 and includes four phases: (1) definition of the goal and scope, (2) life cycle inventory analysis (LCI), (3) life cycle impact assessment (LCIA), and (4) results and interpretation.

2.1 Goal, scope and functional unit

The primary goal of this study was to use LCA to evaluate feeding a HS or LS diet on environmental impact categories within FGB and SGB production. This was conducted using SBM from the USA, hence a secondary goal was to determine the impact of sourcing SBM from Brazil, which is also a leading soy producer [42], but some areas are associated with greater land conversion [43]. The impact categories used were global warming (GW), marine eutrophication (MEu), freshwater eutrophication (FWEu), terrestrial acidification (TA), land use (LU) and water consumption (WC), which are of significant interest in poultry production [44]. The system boundary was from the 'cradle', i.e. the production of input materials, to the 'farm gate' (Fig. 1). Activities involving the chickens after the farm stage (e.g. transport to slaughter, slaughter, processing of carcasses, packaging) were not considered, nor were the avoided emissions associated with using the manure to fertilise crops. The environmental impact of each diet (subsystem I) was determined with the functional unit of 1 kg of feed. The environmental impact of each breed fed each diet (subsystem II) was evaluated with the functional unit 1 kg bird LW in line with common methods [44].

2.2 Life cycle inventory analysis

Data from an in vivo feeding study was used to conduct the LCI. The experiment was designed as a 2 × 2 factorial where the two factors were diet and broiler breed as reported by [36].

2.2.1 Production of diets

There were two diets fed in this study, the detailed composition of which is reported by [36]. The first diet was a high nutrient specification diet (HS), formulated to meet

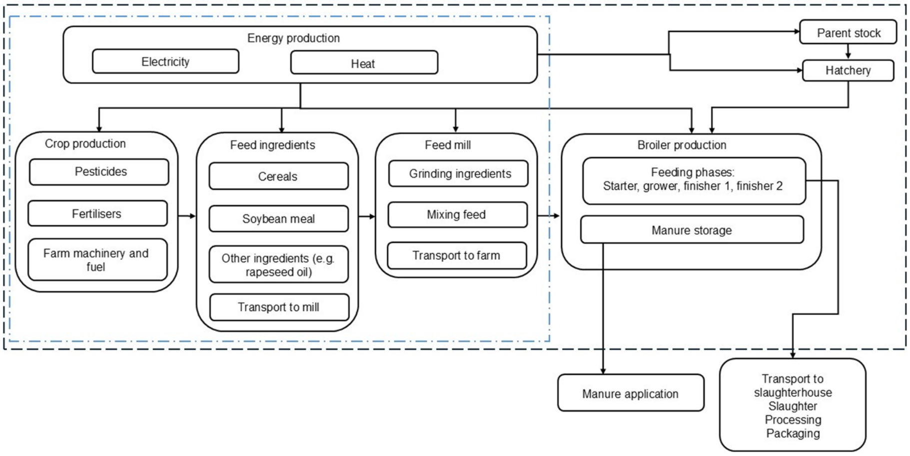

Fig. 1 System boundary of subsystem I (blue dashed line), for production of 1 kg of broiler chicken feed, and subsystem II (black dashed line), for production of 1 kg broiler chicken liveweight, under controlled housing conditions

a commercial specification designed for as-hatched Ross 308 broilers grown to 2.3 kg (Aviagen Ltd., Edinburgh, UK), which was expected to occur around 36 days of age [45], but can occur later when feeding mash diets [46, 47]. The second diet was a low nutrient specification diet (LS), formulated to meet a commercial specification designed for Hubbard Redbro broilers grown to 2.3 kg (Hubbard SAS, Le Fœil, France), which was expected to occur around 42 days of age (Hubbard SAS, Le Fœil, France). The major ingredients of both diets were wheat, soybean meal (SBM) and barley.

The geographical source of key feed ingredients was supplied by the feed manufacturer (Target Feeds, UK). It was estimated that SBM was shipped from the Port of New Orleans, USA [48] to Liverpool, UK. Barley and wheat were sourced from Shropshire, UK, whilst salt was sourced from Cheshire, UK. Rapeseed oil was also sourced from the UK. Nautical distances for sea-based transport were calculated using [http://ports.com/]. Distances travelled via truck were calculated using a geographical information system. According to the feed manufacturer, the electricity associated with grinding wheat and barley was 8 kWh/t and that associated with mixing feed was 4 kWh/t. This was in line with published figures for making and mixing poultry feed [49]. Data for environmental impacts associated with prairie meal, sodium bicarbonate, L-lysine, DL-methionine, L-threonine, limestone flour, dicalcium phosphorus flour and the premix were obtained from [30]. Small feed materials were substituted for sodium bicarbonate in the LCI as done by [50]. Background data for production and transport of feed ingredients were sourced from the Agri-footprint 5.0 database (version 5.0 [51]), and Ecoinvent database (version 3.11 [52]).

2.2.2 Rearing of broilers

Details of the environmental set up of the study, which was conducted at the National Institute of Poultry Husbandry at Harper Adams University in Shropshire, UK, are reported by [36]. Briefly, the study received ethical approval from the Harper Adams University Research Ethics Committee. A total of 420 day-old mixed sex broiler chicks were used, 210 of the Ross 308 breed (Aviagen Ltd., Edinburgh, UK) and 210 of the Hubbard Redbro breed (Hubbard SAS, Le Fœil, France). Birds were randomly allocated to twenty eight floor pens, and the pen was considered the experimental unit. Each pen contained fifteen birds and was fed one of the two diets over four feeding phases for 42 days. This gave seven pen replicates of four treatment groups: Ross 308 broiler fed HS; Redbro birds fed HS; Ross 308 birds fed LS; and Redbro birds fed LS. The four feeding phases were: starter, day 0–10; grower, day 10–24; finisher 1, day 24–36; and finisher 2, day 36–42. At the start and end of each feeding phase, feed intake and bird LW was recorded on a pen basis. The total LW of birds in each treatment group at 42 days of age was determined. Feed intake and the diet formulation were used to determine intake of each feed material per phase and total intake of each feed material from 0 to 42 days of age. Production performance variables were considered primary outcome measures with sample size determined a priori [53] to detect a commercially applicable 5% difference with 80% power at $P < 0.05$ [37]. estimated that the impact of production of day-old chicks, including the breeding, rearing and hatchery stages was 0.35 kg CO_2-eq per egg hatched, hence this figure was used in the present study. This was similar to other studies estimating chick production to be approximately 0.32 to 0.38 kg CO_2-eq per chick [54, 55]. On-farm electricity and gas use were assumed to be 0.24 kWh electricity and

18.2 kg LPG per bird for 42 days according to [56], who followed commercial temperature and climate recommendations (Aviagen Ltd., Edinburgh, UK), which was also done in the present study. Water intake was estimated to be 1.6 L:1 kg feed intake according to commercial guidance when using nipple drinkers without cups [57], as was done in the present study.

2.2.3 Emissions and losses

The emission factors used in this study are provided in Table S1. The emissions of CH_4, N_2O, NO_x and NH_3 from manure were calculated using IPCC guidelines [58], and were aligned to N in diet and excreta, following a Tier 2 method where possible. Nitrogen and gross energy of feed and the broiler chicken excreta were determined using previously reported methods [36].

Total inputs and outputs using primary data and data from literature are presented in Table 1.

2.3 Impact assessment and interpretation

SimaPro 9.1 [59] was used to model the impacts of each treatment group. This was done using the ReCiPe midpoint v1.03 hierarchist impact assessment method [60]. The outputs were expressed as kg CO_2-eq (GW), kg SO_2-eq (TA), kg N-eq (MEu), kg P-eq (FWEu), m^2a crop-eq (LU) and m^3 (WC). The contributions making up approximately 90% of each impact category were presented.

2.3.1 Scenario and uncertainty analyses

A scenario analysis was conducted to examine the impact of sourcing SBM from an area of greater land conversion (LC), called the LC+ scenario, compared to the baseline scenario. This was done using data for SBM from Brazil from the Agri-footprint 5.0 database (version 5.0 [51]). It was assumed that the nutrients supplied by SBM from the USA and Brazil were the same. In the dataset, soybean production was associated with LC in 11 regions of Brazil, compared to 7 regions in the USA [61]. Land conversion from primary forest was 316 times greater for the LC+ soybeans than for the baseline soybeans. Land conversion from grassland was 240 times greater for LC+ soya than for the baseline soya [61]. It was estimated that SBM was imported from the Port of Santos, Brazil [62] to Liverpool, UK. The effect of uncertainty related to on-farm emissions was evaluated by Monte Carlo analysis where the parameters were randomly drawn over 1000 iterations from the distributions summarised in Table S2.

2.3.2 Statistical analysis

Data for each impact category were tested for normality using the Shapiro-Wilk test in R (version 4.3.2 [63]), . For non-normally distributed data, a general linear model (GLM) with a gamma distribution and log link function was employed. Subsequently, using a pen of birds as the initial statistical unit, differences between treatment groups were tested with GLMs followed by a post-hoc Tukey's highest significant difference (HSD) test. Results were presented with standard errors and differences were reported as significant where $P < 0.05$.

The effect of breed and diet on manure emissions and losses were analysed by 2-way ANOVA with spatial blocks in GenStat® (version 23.1; VSN International Ltd). A pen of

Table 1 Inputs and outputs to produce fast growing broiler chickens (FGB; Ross 308) and slow growing broiler chickens (SGB; Redbro) fed a high nutrient specification (HS) or low nutrient specification (LS) diet

Item	Data source	Unit	FGB HS	FGB LS	SGB HS	SGB LS
FCR[1]	Primary	kg	1.677	1.798	1.748	1.903
Inputs						
On-farm						
Chicks	Primary	n	105	105	105	105
Barley	Primary	kg	39.2	46.9	34	40.2
Wheat	Primary	kg	231	215	199	186
Maize gluten meal	Primary	kg	0.560	0.584	0.482	0.533
Soybean meal	Primary	kg	119	99.1	103	86.2
L - lysine	Primary	kg	0.788	0.710	0.679	0.617
DL - methionine	Primary	kg	1.40	1.38	1.20	1.20
L - threonine	Primary	kg	0.420	0.040	0.362	0.034
Rapeseed oil	Primary	kg	18.8	15.9	16.2	13.7
Limestone flour	Primary	kg	3.47	4.89	2.99	4.25
Monocalcium phosphorus	Primary	kg	5.76	6.10	4.96	5.30
Salt	Primary	kg	1.49	1.57	1.29	1.36
Sodium bicarbonate	Primary	kg	2.81	2.47	2.38	2.23
Premix	Primary	kg	1.71	1.59	1.48	1.38
Electricity	[56]	kWh	25.2	25.2	25.2	25.2
LPG	[56]	L	35.7	35.7	35.7	35.7
Water	[57]	L	683	635	589	550
Feed production						
Electricity for grinding	Feed manufacturer	kWh	0.16	2.10	1.87	1.81
Electricity for mixing	Feed manufacturer	kWh	1.71	1.59	1.47	1.37
Total ship transport	Feed manufacturer	tkm	1014	841	873	732
Total lorry transport	Feed manufacturer	tkm	18.8	16.7	16.2	14.5
Outputs						
Chicken liveweight	Primary	kg	259	225	215	185
Emissions from chick production						
Carbon dioxide	[37]	kg	36.8	36.8	36.8	36.8
Emissions from manure						
Methane	[58]	kg	0.096	0.075	0.064	0.058
Nitrous oxide	[58]	kg	0.851	0.834	0.795	0.719
Ammonia and nitrogen oxides	[58]	kg	2.17	2.12	2.02	1.83

[1] FCR, Feed conversion ratio

birds was the statistical unit. Results were presented with standard errors of the means and differences were reported as significant where $P < 0.05$.

3 Results

3.1 Environmental impact of broiler chicken diets

The environmental impacts of the HS and LS diets themselves were similar overall (Table 2). In the starter phase, where the difference in dietary impact was greatest, the average GW of the HS diet ranged from 0.45 to 0.51 kg CO2-eq in the 95% confidence interval.

3.1.1 Contributions to the environmental impact of broiler diets

The percentage contribution of inputs to GW, LU and WC are displayed in Fig. 2, and contribution to acidification and eutrophication impact categories are displayed in

Table 2 Life cycle impact assessment results per kg of broiler chicken diet formulated to a high nutrient specification (HS) or low nutrient specification (LS) over four feeding phases

Impact category		GW[1] (kg CO_2-eq)	FWEu (kg *P*-eq)	MEu (kg *N*-eq)	TA (kg SO_2-eq)	LU (m^2a)	WC (m^3)
Starter	HS	0.47	0.0002	0.0018	0.0032	1.53	0.0049
	LS	0.46	0.0002	0.0017	0.0032	1.50	0.0056
Grower	HS	0.46	0.0002	0.0017	0.0033	1.56	0.005
	LS	0.45	0.0002	0.0017	0.0033	1.51	0.005
Finisher 1	HS	0.45	0.0002	0.0019	0.0035	1.49	0.0046
	LS	0.44	0.0002	0.0019	0.0034	1.41	0.0048
Finisher 2	HS	0.45	0.0002	0.002	0.0035	1.42	0.0044
	LS	0.44	0.0002	0.002	0.0035	1.37	0.0046

[1] GW, Global warming; FWEu, Freshwater eutrophication; MEu, Marine eutrophication; TA, Terrestrial acidification; LU, Land use; WC, Water consumption

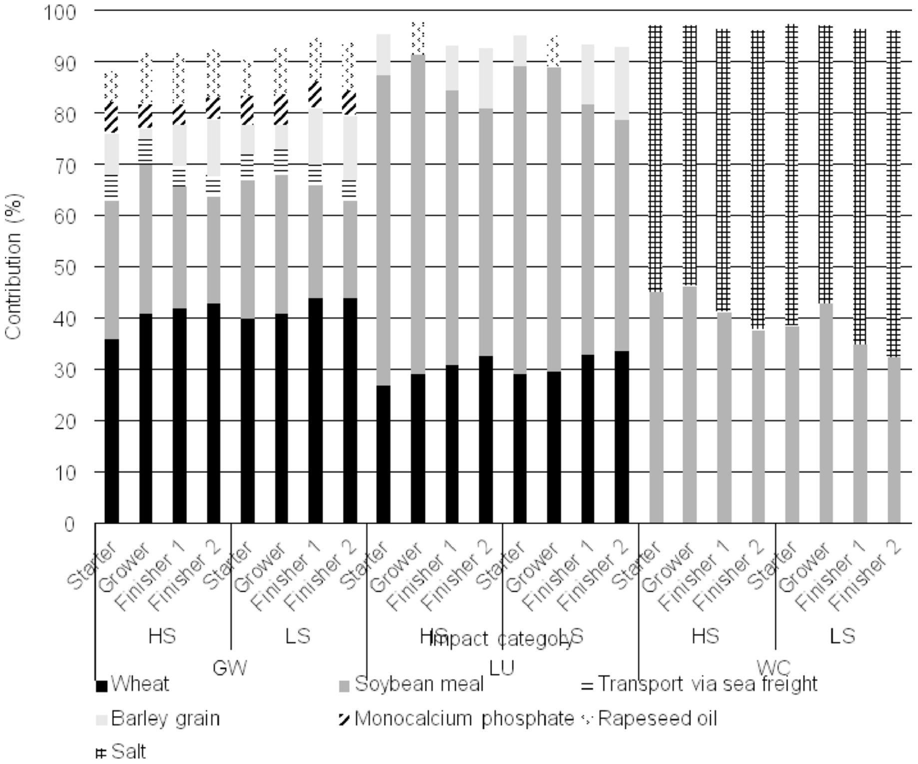

Fig. 2 Percentage contribution of major (~90%) inputs to global warming (GW), land use (LU) and water consumption (WC) per kg of broiler chicken diet (HS: high nutrient specification diet; LS: low nutrient specification diet)

Fig. 3. Soybean meal made up 19–29% of the GW emissions, 45–62% of LU impacts, and 32–46% of WC impacts. Wheat accounted for approximately 40% of GW and 30% of LU of impacts across all diets. This was driven by the major input of wheat, as well as diesel for cultivation and fertiliser inputs.

Transport via sea freight, rapeseed oil, monocalcium phosphate and barley accounted for the remainder of GW emissions, representing, on average, 5%, 9%, 5%, and 8%, respectively. A significant proportion of the WC impact was related to salt (51–64%) and the relevant production and processing, which is reported to be water and electricity intensive [64, 65].

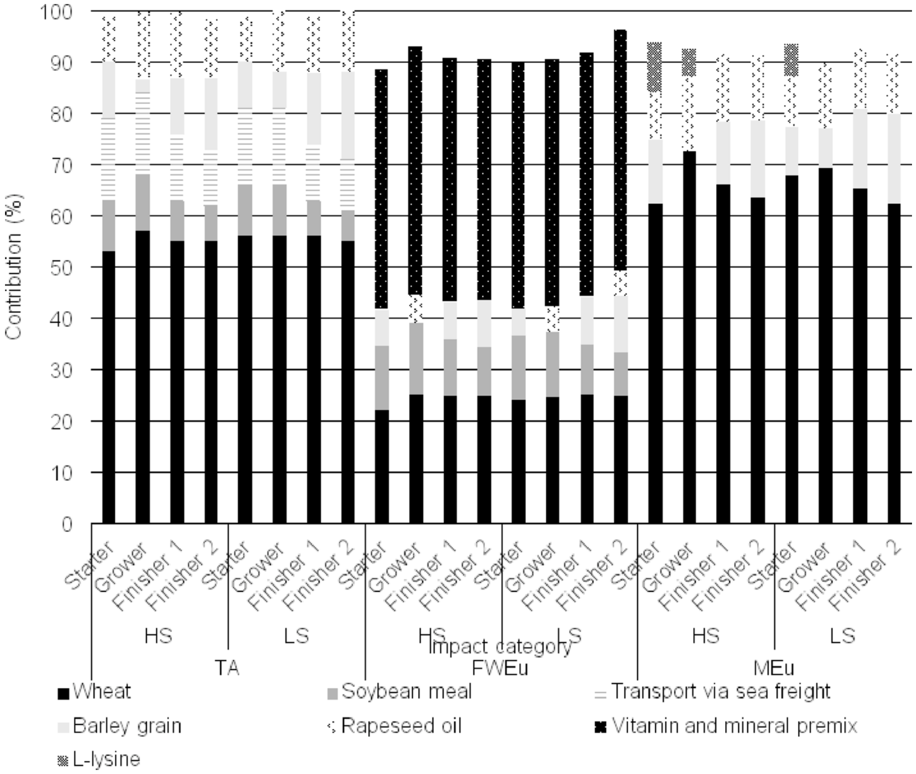

Fig. 3 Percentage contribution of major (~ 90%) inputs to terrestrial acidification (TA) and eutrophication of freshwater (FWEu) or marine water (MEu) per kg of broiler chicken diet (HS: high nutrient specification diet; LS: low nutrient specification diet)

Wheat was a significant contributor to the TA, MEu and FWEu impacts of each diet, accounting for around 55% of TA impact, 62–73% of MEu impact, and 22–25% of FWEu impact. This was driven by the major inputs for wheat cultivation, i.e. diesel and fertiliser. The vitamin and mineral premix that was used in the diets contributed to around 80% of FWEu impact in both diets. Other sources of emissions relating to TA came from sea freight transport (10–16%), SBM (around 9%), barley (3–17%), and rapeseed oil (around 11%). The impact of sea transport was linked to the production and use of petroleum and fuel oil, whilst crop-related impacts were due to fertiliser and machinery use during cultivation and harvesting. Barley also contributed to FWEu (around 8%) and MEu (8–17%). The remaining impacts on MEu were attributed to rapeseed oil (around 12%) and the synthetic amino acid L-lysine in some feeding phases (6% in LS starter, 10% in HS starter, 5% in HS grower).

3.2 Environmental impact of broiler chicken production

The environmental impacts of the four broiler treatment groups per kg LW at 42 d of age are displayed in Table 3. Compared to FGB, SGB had a 9% greater GW impact ($P < 0.0001$), 6% greater FWEu ($P < 0.0001$), 4% greater MEu ($P < 0.0001$), 5% greater TA ($P < 0.0001$), and 4% greater LU ($P < 0.0001$). When fed the HS diet, FGB had the lowest impacts ($P < 0.0001$) but feeding the LS diet increased GW by 10% ($P < 0.0001$), and FWEu, MEu, and TA impacts by 6% ($P < 0.0001$), 9% ($P < 0.0001$), and 7% ($P < 0.0001$) respectively, compared to feeding FGB the HS diet. Feeding the HS diet to SGB reduced GW by 6.5% ($P < 0.0001$), FWEu by 9% ($P < 0.0001$), MEu by 10% ($P < 0.0001$), TA by 8%

Table 3 Life cycle impact assessment results of fast growing broiler chickens (FGB; Ross 308) and slow growing broiler chickens (SGB; Redbro) fed a high nutrient specification (HS) or low nutrient specification (LS) diet using USA-sourced soybean meal, per kg liveweight

		GW[1] (kg CO_2-eq)	FWEu (kg *P*-eq)	MEu (kg *N*-eq)	TA (kg SO_2-eq)	LU (m^2a)	WC (m^3)
Breed	FGB	2.06	0.00034	0.00318	0.0063	2.50	0.0116
	SGB	2.24	0.00036	0.00332	0.0066	2.61	0.0114
SE		0.009	9E-07	2E-07	4.E-06	0.002	1.1E-03
Diet	HS	2.06	0.00034	0.00310	0.0062	2.51	0.0108
	LS	2.23	0.00036	0.00340	0.0067	2.60	0.0122
SE		0.010	9E-07	2E-07	4E-06	2E-03	1.1E-03
Interaction	FGB HS	1.97^a	0.00033^a	0.00304^a	0.0061^a	2.46^a	0.0108
	FGB LS	2.16^b	0.00035^c	0.00331^c	0.0065^c	2.53^b	0.0123
	SGB HS	2.16^b	0.00034^b	0.00316^b	0.0064^b	2.56^c	0.0108
	SGB LS	2.31^c	0.00037^d	0.00348^d	0.0069^d	2.66^d	0.0120
SE		0.013	1E-06	3E-07	6E-06	3E-03	1.5E-03
P value	Breed	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.984
	Diet	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.252
	Breed x diet	0.00634	< 0.001	< 0.001	< 0.001	< 0.001	0.849

[1] GW, Global warming; FWEu, Freshwater eutrophication; MEu, Marine eutrophication; TA, Terrestrial acidification; LU, Land use; WC, Water consumption

[2] SE, Standard error

[a, b, c] Means in the same column with a different superscript letter are significantly different at ($P < 0.0001$).

($P < 0.0001$), and LU by 4% ($P < 0.0001$) compared to feeding the LS diet. This resulted in the FWEu, MEu and TA impacts of SGB fed the HS diet being 3% ($P < 0.0001$), 5% ($P < 0.0001$), and 2% ($P < 0.0001$) lower respectively than those of FGB fed the LS diet.

3.2.1 Contributions to the environmental impact of broiler chicken production

Contributions to the GW, LU and WC per kg broiler LW are displayed in Fig. 4, and to TA, FWEu and MEu are displayed in Fig. 5. Emissions from manure accounted for around 50% of GW impact of each treatment group. Feed-related inputs contributed around 32% to GW, specifically attributed to wheat (approximately 15%), SBM (approximately 9%), rapeseed oil, barley (each 3%), and transport via sea freight (2%). The emissions associated with rearing of parent stock and hatching of chicks accounted for 7% of GW impact of FGB fed HS, 8% in SGB fed HS and FGB fed LS, and 9% in SGB fed LS.

Contributions to LU were driven by feed-related inputs. Regardless of broiler breed, SBM accounted for 55% of the LU in broiler treatment groups fed the HS diet and 51% in groups fed the LS diet. Wheat was responsible for 31% of LU in the HS groups and 32% in the LS groups whilst barley accounted for 8% and 10% of GW in the treatment groups fed HS and LS respectively. Rapeseed oil accounted for 7% of LU in the HS groups and 6% in the LS groups.

Around 70% of WC impact was attributed to feed-related inputs, mainly dietary salt, which accounted for 40% of WC in the HS groups and 44% in the LS groups, irrespective of broiler breed. Following this was SBM, which accounted for around 30% of WC in groups fed HS, and around 27% in groups fed LS. The remaining approximately 25% was attributed to water consumption of the birds on-farm.

The contributions to acidification and eutrophication categories were driven by inputs relating to the production of the diets. Other inputs such as electricity, some of which was used on farm, contributed less than 2% towards TA impact, 3% or less to FWEu, and

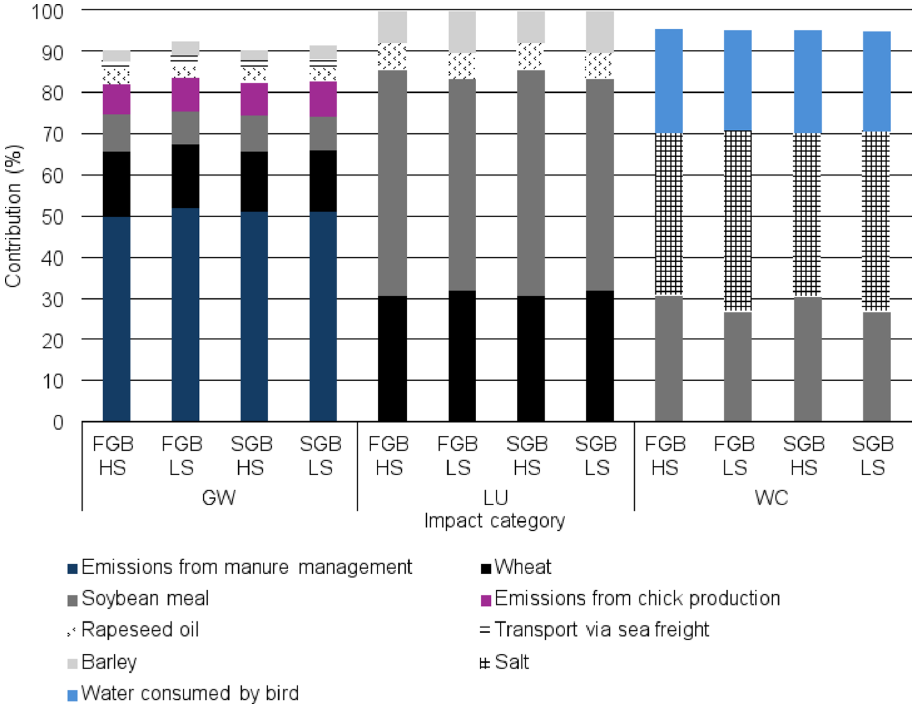

Fig. 4 Percentage contribution of major (~90%) inputs to global warming (GW), land use (LU) and water consumption (WC) of fast growing broiler chickens (FGB; Ross 308) and slow growing broiler chickens (SGB; Redbro) fed a high nutrient specification (HS) or low nutrient specification (LS) diet

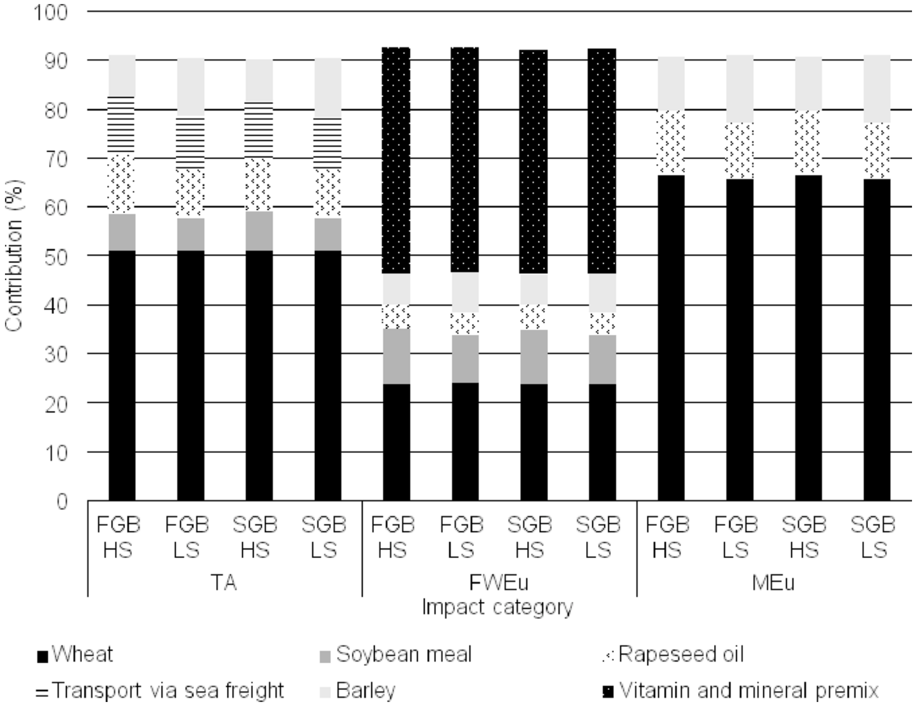

Fig. 5 Percentage contribution of major (~90%) inputs to terrestrial acidification (TA), freshwater eutrophication (FWEu), and marine eutrophication (MEu) per kg of fast growing broiler chickens (FGB; Ross 308) and slow growing broiler chickens (SGB; Redbro) fed a high nutrient specification (HS) or low nutrient specification (LS) diet

less than 1% to MEu. Other on-farm inputs such as water and propane gas for heating, each contributed less than 1% to TA, FWEu and MEu impacts.

Wheat was a significant contributor to TA, MEu, and to some extent FWEu. Wheat contributed 51% to TA in each treatment group while transport via sea freight contributed 12% to TA in the HS groups and 11% in the LS groups, irrespective of breed. Similarly, rapeseed oil produced 11–12% of TA impact in the HS treatment groups and 10% in the LS groups. Barley produced 9% of TA impacts in the HS groups and 12% in the LS groups and SBM was attributed to around 7% of TA impacts.

The premix produced 46% of FWEu impacts in all treatment groups, followed by 24% from wheat. Soybean meal contributed to 11% of the FWEu impacts in the HS groups and 10% in the LS groups. Similarly, barley accounted for 6% of FWEu impacts in the HS groups and 8% in the LS groups.

Wheat was the greatest contributor to MEu, accounting for 67% of MEu impacts in the HS treatment groups and 66% in the LS treatment groups. Similarly, rapeseed oil contributed 13% in the HS groups and 12% in the LS groups. Barley contributed more to the LS groups (14% each) than in the HS groups (11%). Lysine produced 6% of MEu impcats in the HS groups and 5% in the LS groups.

3.2.2 Manure emissions and losses

Total N intake over the 42 day production period (Table 4) was 16% greater ($P<0.001$) for FGB than SGB. The total N intake was also 10% greater ($P<0.001$) for groups fed HS than groups fed LS. The amount of N retained was 18% greater ($P<0.001$) for FGB birds than SGB birds and 13% greater ($P=0.004$) for groups fed HS than LS. There was a tendency for a breed x diet interaction for the amount of N retained ($P=0.073$), specifically that all groups retained a similar amount, except FGB birds fed HS tended to retain more N. Despite this, N excretion (NEX) per bird was 11% greater ($P=0.019$) for FGB than SGB. When NEX was calculated on a per kg LW basis, the differences between treatment groups were not significant, although there was a tendency ($P=0.068$) for SGB to have greater NEX/kg LW. A similar effect was observed for CH_4 as FGB had 17% greater ($P=0.007$) CH_4 emissions per bird but differences were not evident on a per kg LW basis. Diet did not impact NEX and CH_4 emissions.

3.3 Scenario analysis

The LCIA results of the LC+ scenario are presented in Table 5. Feeding the HS diet reduced the GW of FGB by 3% ($P<0.0001$), FWEu by 4% ($P<0.0001$), MEu by 7% ($P<0.0001$), TA by 5% ($P<0.0001$), and LU by 3% ($P<0.0001$). Feeding HS to SGB reduced GW by 2% ($P<0.0001$), FWEu by 3% ($P<0.0001$), MEu by 8% ($P<0.0001$), TA by 7% ($P<0.0001$), and LU by 4% ($P<0.0001$). No differences were observed for WC between breeds ($P=0.411$) or diets ($P=0.865$).

$^{a, b, c}$ Means in the same column with a different superscript letter are significantly different at ($P<0.0001$).

Figure 6 summarises the impact of the LC+ scenario for each broiler treatment group. Values are reported as percentage change from each treatment groups' own baseline reported in Table 3. The LC+ scenario increased the GW impact of all four treatment groups compared to the baseline. The effect was greatest for FGB fed the HS diet where GW was increased by 97%. The effect was least pronounced for SGB fed the LS diet,

Table 4 Environmental emission precursors of fast growing broiler chickens (FGB; Ross 308) and slow growing broiler chickens (SGB; Redbro) fed a high nutrient specification (HS) or low nutrient specification (LS) diet

		Total *N*[1] intake (kg/bird)	***N* retained (kg/bird)**	**NEX (kg/bird)**	**NEX (kg/kg LW)**	**Total GE intake (MJ/bird)**	**VS (kg/day)**	**CH_4 (kg/bird)**	**CH_4 (kg/kg LW)**
Breed	FGB	0.122	0.071	0.051	0.022	66.05	0.023	0.35	0.15
	SGB	0.105	0.060	0.046	0.024	57.09	0.020	0.30	0.16
SEM		0.0013	0.0017	0.0013	0.0007	0.682	0.0008	0.012	0.005
Diet	HS	0.119	0.069	0.050	0.022	63.66	0.022	0.34	0.15
	LS	0.108	0.061	0.047	0.023	59.48	0.021	0.32	0.16
SEM		0.0013	0.0017	0.0013	0.0007	0.682	0.0008	0.012	0.005
Interaction	FGB HS	0.129	0.077	0.051	0.020	68.85	0.025	0.37	0.15
	FGB LS	0.115	0.065	0.050	0.023	63.26	0.022	0.34	0.15
	SGB HS	0.109	0.061	0.048	0.024	58.48	0.020	0.31	0.15
	SGB LS	0.101	0.058	0.043	0.024	55.71	0.019	0.30	0.16
SEM		0.0018	0.0024	0.0019	0.0010	0.964	0.0012	0.018	0.008
P value	Breed	< 0.001	< 0.001	0.019	0.068	< 0.001	0.007	0.007	0.534
	Diet	< 0.001	0.004	0.112	0.216	< 0.001	0.167	0.167	0.302
	Breed x diet	0.115	0.073	0.399	0.243	0.161	0.447	0.447	0.658

[1] N, Nitrogen. Intake calculated according to elemental N in diets determined using methods reported by [36]

NEX, Nitrogen excretion. Calculated according to Eq. 10.31 A [58]

GE, Gross energy. Intake calculated according to methods reported by [36]

VS, Volatile solids. Calculated according to Eq. 10.24 [58]

CH_4, Emission factor of methane from manure management. Calculated according to Eq. 10.23 [58]

SEM, Standard error of means

Table 5 Life cycle impact assessment results of fast growing broiler chickens (FGB; Ross 308) and slow growing broiler chickens (SGB; Redbro) fed a high nutrient specification (HS) or low nutrient specification (LS) diet using soybean meal associated with greater land conversion, per kg liveweight

		GW[1] (kg CO_2-eq)	**FWEu (kg *P*-eq)**	**MEu (kg *N*-eq)**	**TA (kg SO_2-eq)**	**LU (m^2a)**	**WC (m^3)**
Breed	FGB	3.93	0.00054	0.00365	0.00728	2.31	0.0087
	SGB	4.19	0.00057	0.00382	0.00768	2.42	0.0087
SE							
Diet	HS	4.01	0.00055	0.00359	0.00725	2.32	0.0084
	LS	4.11	0.00056	0.00388	0.00771	2.41	0.0090
SE							
Interaction	FGB HS	3.87^{a}	0.00053^{a}	0.00352^{a}	0.00709^{a}	2.28^{a}	0.0080
	FGB LS	3.99^{b}	0.00055^{b}	0.00378^{c}	0.00747^{c}	2.35^{b}	0.0094
	SGB HS	4.14^{c}	0.00056^{c}	0.00366^{b}	0.00742^{b}	2.36^{c}	0.0087
	SGB LS	4.23^{d}	0.00058^{d}	0.00397^{d}	0.00795^{d}	2.47^{d}	0.0086
SE							
P value	Breed	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.411
	Diet	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.865
	Breed x diet	0.0321	< 0.001	< 0.001	< 0.001	< 0.001	0.202

[1] GW, Global warming; FWEu, Freshwater eutrophication; MEu, Marine eutrophication; TA, Terrestrial acidification; LU, Land use; WC, Water consumption

[2] SE, Standard error

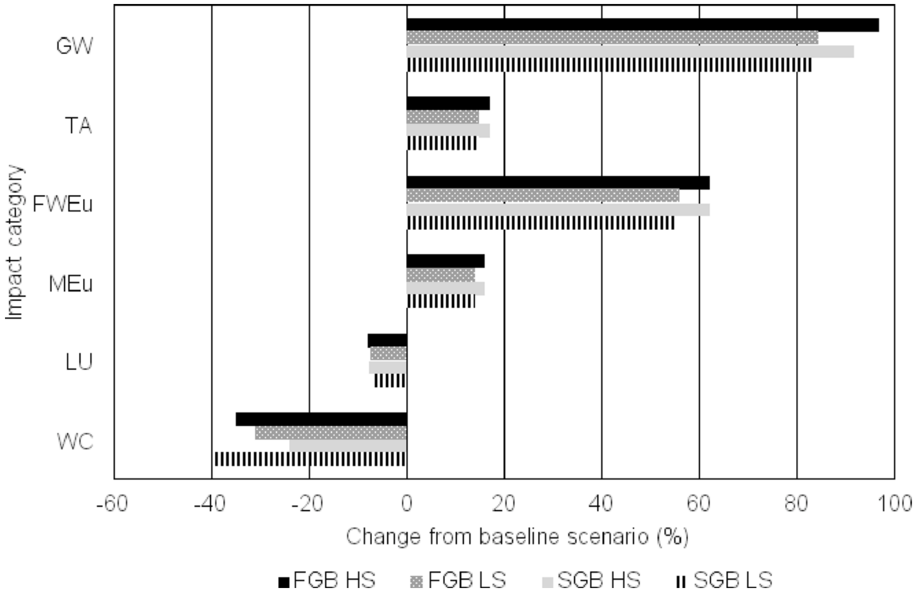

Fig. 6 The effect of feeding SBM associated with greater land conversion on baseline LCIA results of fast growing broiler chickens (FGB; Ross 308) and slow growing broiler chickens (SGB; Redbro) fed a high nutrient specification (HS) or low nutrient specification (LS) diet, presented as percentage change. GW, global warming; TA, terrestrial acidification; FWEu, freshwater eutrophication; MEu, marine eutrophication; LU, land use; WC, water consumption

where GW increased by 83%. In the LC+ scenario, TA and MEu increased by around 16% across all treatment groups. Furthermore, for both FGB and SGB fed the HS diet, FWEu increased by 62% compared to their baseline scenario. The FWEu of both FGB and SGB fed the LS diet increased by 56% in the LC+ scenario compared to their baselines. The LU of all treatment groups was reduced by around 7% in the LC+ scenario. The WC of each treatment group was reduced by 32% on average.

In the LC+ scenario SBM contributed around 50% to the GW impact of each treatment group, manure emissions contributed around 27%, and wheat contributed around 8%. Soybean meal contributed around 19% to TA impacts, wheat contributed around 44%, and transport via sea freight contributed 12% on average. Soybean meal contributed around 44% to FWEu impacts, the premix contributed around 29%, and wheat contributed 15%. The contribution of wheat to MEu was approximately 57%, SBM contributed approximately 14%, and barley and rapeseed meal contributed approximately 12% each.

4 Discussion

This study hypothesised that dietary nutrient density could be used to manipulate the environmental impacts of broiler chickens due to the interactions between diet, growth performance and manure emissions. Therefore, the ability of HS and LS diets to influence environmental impact of broilers was tested by applying LCA to an in vivo replicated broiler study. To our knowledge this is the first study to combine a nutritional broiler experiment with LCA in this way [66]. The results of this study agreed with previous LCA of broiler production [18, 21, 30, 41, 44, 67, 68, 69].

Transitioning to production using SGB would inevitably increase environmental outcomes [18, 19] due to their reduced growth performance compared to FGB [35, 36]. In agreement, this study found that SGB generally had greater impacts in all categories than

FGB. A FU of 1 kg carcass weight may further emphasise differences as SGB are reported to have around 3% lower carcass yield than FGB [70, 71]. Differences between breeds in this study were also smaller than other studies likely due to growing birds to the same age, and differences in feed efficiency and production environment [36]. reported a difference in FCR of 0.088 (8.8 points commercially) between Ross 308 and Redbro broilers. In contrast, the FGB and SGB breeds evaluated by [18] had a 122-point difference in FCR (1.87 vs. 3.09), because the model simulated SGB in an extensive French production system (Label Rouge), which requires a growing period of at least 81 days at low stocking density, with outdoor access and a diet containing at least 75% cereals. Birds in the present study were reared in an indoor environment for a shorter period (42 days), with relatively similar dietary feed materials to that of FGB. Growing SGB in this way resulted in smaller differences between the environmental credentials of each breed than other reports, suggesting that using SGB in an indoor production system is a middle ground between the environmental impacts of conventional FGB production and extensive SGB production. It is reported that middle segment SGB production systems are relatively cost-effective [10] and still offer potential improvements in welfare [72] compared to FGB production.

Feed contributes 72 to 82% to the environmental impact of broilers [21, 22], so nutritional interventions to improve feed efficiency have been suggested as a strategy to reduce the environmental footprint [24]. Previous studies have reported that diets containing more energy and crude protein reduce the FCR of SGB [73, 74] without impacting meat quality characteristics which are desirable to consumers [75]. However [19], also reported that feeding a higher protein diet may increase GHG emissions and LU of SGB production. Thus, it is important to assess the environmental impact of modulating dietary macronutrients for SGB to ensure the changes do not have negative environmental effects. In this study, feeding the HS diet to SGB reduced most impact categories. Feeding the HS diet to SGB reduced GW to be in line with that of FGB fed the LS diet, and reduced FWEu, MEu, and TA to be lower than FGB fed the LS diet. This study tested two commercial nutrient specifications, but more research can be done to determine exact broiler requirements, for example using a dose response study. It is recognised that birds were reared for the same amount of time in the present study, whereas commercially SGB would take longer than FGB to reach market weight and therefore their impacts may be greater [40, 41]. Furthermore, the use of a different FU, such as carcass weight, may increase the impact results of SGB production as SGB have lower carcass yield than FGB [70, 71]. Using the FU of 1 kg LW does not account for differences in the proportion of meat that is valuable to the consumer, which can vary between breeds [76, 77]. Therefore, future research should assess slaughter characteristics when modulating dietary macronutrients for SGB so that these parameters can be included in future LCA studies.

The area harvested for soybeans in South America has increased by more than 250 times from 0.26 Mha in 1961 to 65.35 Mha in 2023 [78]. [https://www.fao.org/faostat/en/#data/QC/visualize]. Hence, attention has been paid to the loss of native vegetation associated with the expansion of soy [42]. In a direct sense, soy expansion in South America is responsible for only a part of the total loss of native vegetation [79, 80, 81] but ongoing indirect effects are evident [43]. Soybean meal has been highlighted as a key contributor to GW impact in LCA studies, mainly due to associations with land use change [28, 30]. Hence, using diets with lower levels of SBM may help to reduce impacts. In the present study in the LC+ scenario, GW of FGB fed HS increased by 97% and GW of SGB fed LS increased by 83% compared to the Baseline scenario. The LS diet contained less SBM than the HS diet due to specifying a lower requirement for amino acids that are supplied by SBM [26, 27]. Therefore, the LC+ scenario had a lower impact on the LS diet than the HS diet. In the LC+ scenario, FWEu of treatment groups increased by 56 to 62%, and TA and MEu increased by around 16%, but increases were less prominent for groups fed the LS diet. The GW and FWEu impacts of the four broiler treatment groups became distinctly different and were greater for SGB than FGB. In this study, it was assumed that the nutritional content of SBM in both scenarios was the same. Some reports suggest that there is greater amino acid digestibility in SBM from the USA compared to Brazil [82] so accounting for this in future studies may increase differences between scenarios. The greater gap between the treatment groups in the LC+ scenario relates to the increased distance of transportation, the greater association with land use change [83], and the increased application of N and P in Brazilian soybean production [84]. Considering that alternatives to SBM may have lower environmental footprints [24], the feasibility of replacing SBM with different protein feed materials to further reduce the environmental impacts of broiler chicken production should be investigated.

Identifying inputs that contribute the most to the environmental footprint of broiler production focuses areas for further reduction [85]. In the baseline scenario, wheat was a significant input, contributing 67% to MEu, 51% to TA, 31–32% to LU, 24% to FWEu, and 15% to GW. This was driven by fertiliser inputs and diesel used for cultivation which have been highlighted as hotspots in wheat production systems [86]. In the LC+ scenario, total emissions and the contribution of feed-related inputs increased, in agreement with other findings [87, 21]. However, this was largely driven by inputs to SBM production rather than wheat. Therefore, alongside using alternatives to SBM, strategies to reduce the impact of wheat production may further reduce key impact categories.

5 Conclusion

This study used LCA to evaluate the use of high and low nutrient density diets to manipulate the environmental credentials of fast growing Ross 308, and slow growing Hubbard Redbro broiler chickens reared to the same age. Diets were based on soybean meal (SBM) from the USA so the impacts of using SBM associated with greater land conversion (LC+) was determined using scenario analysis. Results showed breed x diet interactions for environmental credentials per kg LW. Feeding the HS diet to SGB reduced GW by 6.5%, FWEu by 9%, MEu by 10%, TA by 8%, and LU by 4% compared to feeding SGB the LS diet. This resulted in the FWEu, MEu and TA impacts of SGB fed the HS diet being 3%, 5%, and 2% lower respectively than those of FGB fed the LS diet. In the LC+ scenario GW impact per kg LW increased by 83% to 97%, FWEu increased by 55% to 62%, and TA and MEu increased by approximately 16% compared to the baseline scenario. Nitrogen and CH_4 excretion per kg LW were not impacted by breed or diet. Wheat was a key contributor to GW, FWEu, MEu, TA, and LU in the baseline scenario. Therefore, if dietary SBM is sourced from a region with lower LC, further reducing the impact of wheat production should be investigated. In the LC+ scenario, the contribution of SBM to GW, FWEu, MEu, and TA increased while the contribution of wheat decreased. The efficacy of replacing SBM with different feed materials to further reduce the environmental impacts of broiler chicken production should be investigated. This should be considered alongside practicalities of using alternatives to SBM such as geographical availability, economic feasibility and potential trade-offs with animal performance. In conclusion, in the baseline and LC+ scenarios, feeding a HS diet reduced impact category results per kg broiler LW without impacting manure emissions.

Supplementary Information

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Supplementary Material 1.

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Author contributions

V.R.P. acquired project funding. H.S.C, E.J.S., S.C.M., A.M.M., and V.R.P. conceived and designed the manuscript. H.S.C. collected the data. H.S.C. and E.J.S. synthesised, analysed, and presented the data. H.S.C. drafted the manuscript, it was reviewed by E.J.S., S.C.M., A.M.M., J.S.B., M.R.F. L. and V.R.P. H.S.C. edited and revised the manuscript's final version. All authors read and approved the final manuscript.

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Data availability

The underlying data and code for this study is not publicly available but may be made available to qualified researchers on reasonable request from the corresponding author.

Declarations

Ethics approval and consent to participate

This study was approved by Harper Adams University Research Ethics Committee (reference number: 0220-202303-PGMPHD) and was conducted in accordance with the ARRIVE 2.0 guidelines.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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