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ASSESSMENT OF THE CARBON FOOTPRINT ASSOCIATED WITH RYE GRAIN INCLUSION IN COMPOUND FEED FOR BROILER CHICKENS

SUMMARY

The carbon footprint of compound feed containing different levels of rye grain during the rearing of broiler chickens was calculated. The study was conducted on five groups of ROSS-308 broiler chickens, each consisting of 120 birds. The control group was fed compound feed based on corn grain and soybean meal without the inclusion of rye grain. Birds in the experimental groups received compound feed containing graded levels of rye. Rye grain was introduced into the compound feed of broiler chickens at inclusion levels of 2–5% between days 11 and 20, 4–10% between days 21 and 30, and 10–25% between days 31 and 42 of age. The carbon footprint of feed ingredients and compound feed was calculated using the FeedPrintNL software (version 2022.00, December 9, 2022) developed by Wageningen University. Greenhouse gas emission values for soybean meal were used according to the Life Cycle Assessment conducted by the Research Institute of Organic Agriculture FiBL and hybrid rye – according to the GFLI database, developed by the independent Blonk consultancy. The calculated greenhouse gas emission values consider only the emissions from raw materials and illustrate the potential for their reduction through the selection of different feed ingredients. The study revealed that the inclusion of rye grain in the compound feed for broiler chicken contributed to a 3.1% to 7.8% decrease in CO_2-eq emissions per tonne of feed.

Keywords: carbon footprint, rye, feeding, poultry

INTRODUCTION

According to the FAO (2013), livestock supply chains emit approximately seven gigatonnes of CO_2-eq/year, with feed production being the primary driver (45%). While poultry accounts for 8% of these emissions (Liu *et al*., 2015; Attia *et al.,* 2024) and exhibits a lower carbon footprint per unit of mass compared to other species (Williams, Audsley and Sandars, 2006; Peters *et al.,* 2014), the projected demand growth described by Attia *et al.* (2024) necessitates the

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development of sustainable systems (Peter John and Mishra, 2024). Consequently, reducing the "carbon footprint"—defined by Pertsova (2007) as cumulative CO_2, CH_4, and N_2O emissions—through feed optimization remains a priority. Moungsree *et al.* (2024) identify feed production, energy consumption, and manure management as the three primary drivers of GHG emissions in the poultry industry. Feed production, which includes cultivation technology, transport, fertilizer application, and land use change (LUC), exerts a direct influence on the carbon footprint of broiler production. Attia *et al*. (2024) specify that GHG emissions in the broiler industry are distributed as follows: 78% from feed production, 8% from direct on-farm energy consumption, 7% from post-farm processing and meat transport, and 6% from manure storage and processing.

Research by Leinonen *et al*. (2012) demonstrated that feed caused a greater overall environmental impact than any other materials utilized in broiler meat production. Furthermore, Martinelli *et al*. (2020) identified maize and soybean production as the major sources of GHG emissions. Significant interest in the utilization of low-emission feed components through diet modification is noted by Giannenas *et al.* (2017). GHG emissions from various raw materials used in compound feed production can vary substantially, occasionally by factors of tens or even hundreds. For instance, Ershadi *et al.* (2021) estimated GHG emissions from maize grain at 347 kg CO_2-eq/t. In contrast, for maize grown in Ukraine, GHG emissions amount to 481 kg CO_2-eq/t according to the FeedPrintNL software (version 2022.00, December 9, 2022, Wageningen University), which allows for the calculation of GHG emissions for specific cultivation technologies, accounting for actual yield and transport to the processing site.

Protein feeds occupy a significant proportion of poultry diets. An ideal scenario involves meeting the growing demand for protein feeds by increasing the productivity of agricultural lands (Bennetzen *et al*., 2016). However, as emphasized by Riedesel *et al.* (2022), increased productivity may also be accompanied by a rise in GHG emissions per unit area and, consequently, does not always lead to a reduction in GHG emissions per unit of product. A promising avenue lies in the investigation of various feeding strategies, including alternative protein sources that contribute to improved nutrient utilization, thereby reducing nitrogen and carbon emissions. The use of locally produced protein feeds holds significant potential for this purpose (Sychov *et al.,* 2025; Sychov *et al.,* 2022; Plyska *et al.,* 2021).

The utilization of locally sourced ingredients for compound feed manufacturing plays a significant role in mitigating GHG emissions. Thus, when assessing GHG emissions associated with soy-derived products, their provenance is a critical factor, as transport can substantially increase total emissions. GHG emissions also rise significantly when soy is cultivated on land that has undergone a change in land use purpose. Prudêncio da Silva *et al*. (2014) linked the carbon footprint of broilers raised in Brazil to high energy consumption and GHG emissions associated with maize and soybean cultivation, as well as emissions resulting from deforestation (0.39–0.81 kg CO_2-eq/kg maize and 0.39–1.7 kg CO_2-eq/kg soybean). Finnish researchers Usva *et al*. (2023) reported that land use change accounted for 0.55 kg CO_2-eq/kg carcass weight (23%), primarily due to soybean production for feed purposes in Brazil. This view is supported by other researchers (Lopes, Zepka and Deprá, 2024), who assert that increased GHG emissions are associated with higher protein content in broiler feed, which often includes a larger proportion of soy obtained from lands cultivated following deforestation.

Although Arrieta and González (2019) noted that the choice between extruded full-fat soybeans or soybean meal and oil as feed ingredients results in only minor differences in carbon emissions, provenance remains crucial. According to FeedPrintNL software, GHG emissions associated with soybean meal imported into the European Union can amount to 5,728 kg CO_2-eq/t. Conversely, according to Ershadi *et al.* (2021), GHG emissions from soybean meal are 204 kg CO_2-eq/t. For comparison, GHG emissions from locally produced rapeseed meal amount to 607 kg CO_2-eq/t. It is worth noting that, according to the Danube Soya Association, the average carbon footprint of soybean meal produced in Europe from imported soybeans is 1,990 kg CO_2-eq/t, highlighting the significant environmental advantage of using local raw materials and ingredients (Life Cycle Assessment/Carbon Footprint Project - Donau Soja).

The role of amino acids in animal nutrition is considered significant. Calculations by Sturm *et al.* (2022) showed that the use of free amino acids in animal feed has already contributed to avoiding the use of millions of hectares of arable land. In general, the positive effects of including free amino acids in animal feed are realized through two main pathways. First, they improve feed efficiency, thereby reducing the overall demand for feed and, consequently, the negative environmental impact associated with feed production. Second, free amino acids allow for a reduction in the crude protein content of feeds. The implementation of diets with reduced crude protein content is regarded as one strategy to reduce demand for soy in the European Union. This approach also contributes to lowering the overall negative environmental impact of feed production, particularly regarding land use change and deforestation (Sturm *et al.*, 2022).

Since amino acids enhance feed efficiency and reduce nitrogen losses, their usage is expected to increase if regulations aimed at reducing nitrogen emissions are implemented (Vijn *et al.,* 2020; Selle *et al.*, 2022; Sturm *et al.,* 2022). Alves *et al*. (2023) hypothesized that the inclusion of the amino acid lysine HCl in broiler diets would reduce environmental impact; however, their findings did not confirm this. Data modeling in their study did not demonstrate a significant reduction in environmental impact, possibly because lysine production involves the use of crude protein and energy-rich resources. Mosnier *et al.* (2011) emphasized that although amino acid production causes a significant environmental impact, their low inclusion rates result in a negligible contribution to impact categories for broiler and pig diets. Furthermore, diets with reduced crude protein content had higher amino acid inclusion rates. Ershadi *et al.* (2021) reported significantly lower levels of GHG emissions from L-threonine and L-lysine produced by the enzymatic method – 388 kg CO_2-eq/t, whereas emission levels from DL-methionine are estimated at 3010 kg CO_2-eq/t. Overall, Ershadi *et al.* (2021) highlighted that the production of amino acids, including DL-methionine, L-lysine, and L-threonine, requires a large amount of energy compared to other feeds. This may represent an additional source for GHG emission reduction in the production of compound feeds for livestock.

The use of local alternative cereal feeds with minimal GHG emissions is a highly promising direction. One promising cereal crop is rye. Riedesel *et al.* (2022) emphasize that rye has approximately 20% lower GHG emissions per unit area and an 8% smaller carbon footprint compared to wheat. This difference is primarily due to the fact that rye requires approximately 25% less nitrogen than wheat. Expanding rye cultivation in cereal crop rotations offers additional opportunities for feeding and climate change mitigation. Moreover, Macholdt and Honermeier (2017) and Miedaner and Laidig (2019) assert that hybrid breeding increases yield due to the benefits of the heterosis effect. Research by Riedesel *et al.* (2022) showed that the higher yield of hybrid rye varieties (+13%) more than compensates for the resultant higher GHG emissions per unit area (+4%), leading to a lower carbon footprint (-9%) and, accordingly, a reduced climatic impact of hybrids compared to pure lines. The main reason for this is that rye is better adapted for cultivation in extreme conditions, particularly due to its highly developed root system and greater specific root length (Ryser, 2006). Consequently, rye demonstrates higher nitrogen use efficiency and a lower risk of leaching compared to other cereals, including wheat. These findings corroborate previous studies by Wojcik-Gront and Bloch-Michalik (2016), who also identified rye as the crop with the lowest GHG emissions due to the lowest nitrogen requirement among all cereals studied. This can serve as a basis for its use in animal feed to achieve significant reductions in GHG emissions.

The study by Moungsree *et al.* (2024) was based on a "cradle-to-gate" approach, where total GHG emissions from feed production for broilers, laying hens, and pigs were estimated at 650 ± 20, 706 ± 20, and 466 ± 20 kg CO_2-eq/t of feed, respectively. Feed production for laying hens resulted in the highest GHG emissions, being 1.09 and 1.52 times higher than for broilers and pigs, respectively. This is primarily explained by the inclusion of fish meal in diets formulated for laying hens. However, in studies by Usva *et al*. (2023), the climate change impact of the average industrial feed mixture was estimated at 0.96 kg CO_2-eq/kg feed, or 960 kg CO_2-eq/t. A significant portion of the impact (23%) was attributed to land use change, mainly associated with soybean production in Brazil for feed requirements.

For assessing the impact of technological interventions, the study by Leinonen *et al.* (2012) is particularly relevant as it accounted for key parameters such as feed consumption, animal growth, and nutrient assimilation. Simultaneously, Tallentire *et al.* (2017) highlighted that both slaughter age and growth rate significantly influence the feed conversion ratio (FCR). As the production cycle duration increases, energy expenditure for metabolic heat production also increases, thereby reducing feed conversion efficiency. Nacimento *et al.* (2022) reported that reducing the final live weight of broiler chickens from 2.6 to 1.6 kg could reduce the total global warming potential in the Italian poultry sector by approximately 12%.

The application of enzymes in animal feed is a promising strategy for mitigating GHG emissions. For example, a study by Bundgaard *et al.* (2014) demonstrated that the use of an enzyme product based on xylanase, amylase, and protease has the potential to reduce GHG emissions from broiler chicken production by approximately 90 g CO_2-eq per head. Similarly, these findings are supported by Wiedemann *et al*. (2017), who demonstrated that an improvement in the feed conversion ratio by 0.1 led to a reduction in GHG emissions by 3–4.5%. According to Alves *et al*. (2023) and Prudêncio da Silva *et al*. (2014), the assessment of GHG emissions per animal plays a key role in identifying effective emission reduction strategies. The authors suggest that shortening the production cycle and reducing the final live weight of broilers could potentially lower energy consumption and reduce GHG emissions in the Argentine broiler industry. This strategy may contribute to optimizing production efficiency with improvements in feed conversion ratios. Leinonen *et al.* (2012) also emphasized that modifications in feed consumption and composition influence GHG emissions.

In a review by Cesari *et al*. (2017) on the efficiency of broiler production in Italy, emissions ranged from 1.1 to 3.84 tonnes CO_2-eq/kg live weight under identical system parameters and rearing conditions. The average slaughter weight ranged from 1.9 to 2.5 kg, and the fattening cycle lasted from 31 to 42 days. Simultaneously, citing van Horne (2017), Cesari *et al.* (2017) presented results from reports in France indicating a slightly lower weight of 1.9 kg, and from Spain – 2.7 kg. Conversely, the average Argentine chicken weighed 2.88 kg at 49–50 days. On the other hand, although Brazil shares similar production profiles with Argentina, the higher energy usage and carbon footprint of chickens raised in Brazil, estimated by Prudêncio da Silva *et al*. (2014), can be explained by higher energy consumption and GHG emissions throughout the entire production cycle. According to Usva *et al.* (2023), GHG emissions from broiler meat production in Finland were estimated at 2.37 kg CO_2-eq per kg of carcass weight. A study conducted by Duarte da Silva Lima *et al*. (2019) reported a carbon footprint of 2.70 kg CO_2-eq/kg live weight in broiler meat production. The overall results of three review studies by Usva *et al.* (2023) in Finland indicated a carbon footprint in the range of 2.1 to 8.5 kg CO_2-eq/kg carcass weight, with the highest values associated with free-range and alternative production systems.

Pelletier *et al.* (2013) analyzed the carbon footprint of modern intensive production and concluded that further optimization of feed efficiency and the sourcing of feed with the lowest ecological burden are key levers for reducing GHG emission intensity. The use of local crops for animal feeding, which are well-adapted to growing conditions and ensure high yields and low levels of GHG emissions per unit of feed, is highly promising. Such feeds do not have widely investigated optimal usage rates or assessments of their impact on GHG emissions. The utilization of local feeds, such as rye, allows for a reduction in GHG emissions associated with logistics. The search for alternative local diet components with the lowest greenhouse gas emissions is particularly effective.

MATERIAL AND METHODS

A study investigating the potential inclusion of standardized levels of KWS Tayo hybrid rye grain was conducted in 2024 at the Research Laboratory of Animal Nutrition and Feed Quality of the National University of Life and Environmental Sciences of Ukraine, utilizing 600 ROSS-308 broiler chickens. At the age of 10 days, the broilers were randomly allocated into five groups of 120 birds each: one control group and four experimental groups. The broilers in the experimental groups received diets including rye grain at inclusion rates ranging from 2% to 25%.

The study employed a two-step methodological approach integrating biological data with environmental modeling. First, the in vivo experiment determined the actual zootechnical performance of broilers, specifically feed intake and feed conversion ratio (FCR), across different rye inclusion levels. Second, these empirical performance data served as key input variables for the computational modeling using FeedPrintNL software. This integration allowed for a precise assessment of the carbon footprint, translating the physical consumption of specific feed formulations into environmental impact metrics expressed as CO_2-eq/kg per bird and per kilogram of live weight gain.

Within the framework of this study, an assessment of the carbon footprint associated with the inclusion of rye grain in broiler chicken nutrition was performed.

The carbon footprint for corn grain, soybean meal, hybrid rye grain, soybean oil, DL-methionine, L-threonine, L-lysine, L-valine, L-isoleucine, salt, monocalcium phosphate, calcium carbonate, sodium bicarbonate, mineral premix, and vitamin premix was calculated using the FeedPrintNL software (version 2022.00, December 9, 2022), developed by Wageningen University. For corn and rye grain, adjustments regarding cultivation technology were applied during the life cycle assessment (LCA). The greenhouse gas emission potential of the soybean meal used for compound feed preparation is certified in accordance with the LCA conducted by the Research Institute of Organic Agriculture (FiBL), while for hybrid rye, it aligns with the GFLI database developed by the independent consultancy Blonk.

According to FiBL data, greenhouse gas emissions associated with soybean meal produced in the Khmelnytskyi region (Ukraine) from AdamPolSoya soybeans grown under Danube Soya standards amount to 360 kg CO_2-eq/t. Under Ukrainian conditions, soybean meal emissions are estimated by the FeedPrintNL software at 821 kg CO_2-eq/t. In this study, soybean meal obtained from AdamPolSoya soybeans and processed at the enterprise's facilities was utilized; consequently, the emission value of 360 kg CO_2-eq/t provided by FiBL was applied for the calculations.

Greenhouse gas emissions from the hybrid winter rye KWS Tayo used in this study, calculated according to the GFLI database, amounted to 331 kg CO_2-eq/t. For comparison, greenhouse gas emissions from conventional rye varieties constitute 382 kg CO_2-eq/t (GFLI Database – The Global Feed LCA Institute). This emission value is based on a three-year study conducted on farms in Germany. According to the FeedPrintNL software, the range of greenhouse gas emissions from various hybrid rye cultivation technologies in Ukraine lies between 232 and 381 kg CO_2-eq/t of grain. The value of 331 kg CO_2-eq/t was selected based on the identical agronomic practices for hybrid rye in Ukraine and Germany. This figure is consistent with validated emission ranges derived from longitudinal research.

For corn grown in Ukraine using the most prevalent intensive cultivation technology with the application of organic fertilizers, greenhouse gas emissions amounted to 481 kg CO_2-eq/t. Depending on the specific cultivation technology applied, greenhouse gas emissions may range from 250 to 520 kg CO_2-eq/t.

The determination of the carbon footprint per broiler and per kilogram of live weight gain considered only the experimental period (11–42 days of life).

Each group was divided into 6 replicates with 20 birds in each (Table 1).

Table 1. The experimental design of the research and production trial

Group	Number of broilers	Broiler age, days		
		11–20	21–30	31–42
		Content of rye grain in the compound feed, %		
Control: 1	6 × 20	0	0	0
Experimental: 2	6 × 20	2	4	10
3	6 × 20	3	6	15
4	6 × 20	4	8	20
5	6 × 20	5	10	25

The experimental broiler chickens were housed in floor pens with a stocking density of 0.2 m² per bird and a feeder space of 3 cm per bird. The birds received a complete compound diet composed of corn grain, soybean meal, soybean oil, essential amino acid supplements (valine, isoleucine, lysine, methionine, and threonine), sodium and calcium additives, as well as a vitamin-mineral premix. The diet provided to the control group did not contain rye grain. Rye grain was incorporated into the diets of the experimental groups in accordance with the experimental design. The proportions of ingredients were adjusted to maintain adequate nutrient and energy levels.

RESULTS AND DISCUSSION

The calculated values are presented in Table 2. According to the FeedPrintNL software, synthetic amino acids and vitamins exhibit the highest levels of greenhouse gas emissions, with values ranging from 3,044 to 7,247 kg CO_2-eq/t. This is primarily attributed to their synthesis methods and the resource intensity of their production.

Greenhouse gas emission levels for table salt (NaCl), calcium carbonate, monocalcium phosphate, and sodium bicarbonate vary depending on their origin and processing methods. In Ukraine, the emission level for carbonates may be as low as 4 kg CO_2-eq/t, whereas emissions for monocalcium phosphate and sodium bicarbonate are significantly higher, at 485 and 486 kg CO_2-eq/t, respectively. A similar trend is observed for the mineral premix utilized in compound feed production, with an emission estimate of 1,176 kg CO_2-eq/t according to the FeedPrintNL software.

The results of greenhouse gas emission calculations for broiler chicken diets containing rye grain, based on the conducted studies, are presented in Table 3.

Table 2. Carbon emissions from input raw materials of feed mill, expressed as CO_2-eq/t

Ingredients	Emissions, kg CO2-eq/t
Corn grain	481
Hybrid rye grain	331
Soybean meal	360
Soybean oil	1010
DL-methionine, 99%	3044
L-threonine, 98%	6487
L-lysine, 96%	6487
L-valine, 96.5%	6397
L-isoleucine, 90%	7247
Salt	174
Monocalcium phosphate	485
Calcium carbonate	4
Sodium bicarbonate	486
Mineral premix	1176
Vitamin premix	6449

Table 3. Total greenhouse gas emissions from the production of compound feed for broiler chickens, kg CO2-eq/t compound feed

Broiler age, days	Group				
	1	2	3	4	5
11–20	468	467	467	466	466
21–30	481	477	475	473	471
31–42	477	467	462	456	451

The carbon footprint of the compound feed for broiler chickens in Group 1 (control, based on soybean meal and corn grain), excluding GHG emissions from feed manufacturing processes, amounted to 468 kg CO_2-eq/t during the first experimental period (11–20 days). This period coincided with the diet containing the highest crude protein content, corresponding to the maximum inclusion of soy products. Increasing the proportion of rye in the feed to 2% and 3% in experimental Groups 2 and 3 resulted in a GHG emission reduction of 1 kg CO_2-eq/t compared to the control group. Similarly, the inclusion of 4% and 5% rye in the diets of experimental Groups 4 and 5 yielded a reduction of 2 kg CO_2-eq/t. Overall, the incorporation of rye into broiler diets during the 11–20 day period provided a reduction in CO_2-eq emissions per tonne of feed of 0.2–0.4%.

During the 21–30 day period, the carbon footprint of the compound feed increased to 481 kg CO_2-eq/t in Group 1 (control) and to 477, 475, 473, and 471 kg CO_2-eq/t in Groups 2–5, respectively. This increase is attributed to a reduction in soybean meal content and a corresponding increase in corn grain levels, which has a higher carbon footprint by 121 kg CO_2-eq/t (compared to the soy source used). Emissions were also influenced by the inclusion of synthetic amino acids, where DL-methionine (99%) contributes 3044 kg CO_2-eq/t, and L-isoleucine (90%) contributes 7247 kg CO_2-eq/t. Nevertheless, the inclusion of 4–10% rye grain in broiler diets allowed for a reduction in CO_2-eq emissions per tonne of feed by approximately 0.8–2.0%.

The final experimental period, covering broiler rearing from 31 to 42 days of age, was the most indicative regarding GHG emissions. During this period, GHG emissions for Group 1 (control) amounted to 477 kg CO_2-eq/t. The inclusion of 10% rye in the compound feed resulted in a 2.1% reduction in GHG emissions, while the inclusion of 25% rye achieved a reduction of up to 5.4%.

Consequently, the inclusion of rye grain in broiler compound feed at levels of 2–5% during days 11–20, 4–10% during days 21–30, and 10–25% during days 31–42 led to a reduction in CO_2-eq emissions per tonne of compound feed in the range of 3.1% to 7.8%.

The quantity of soybean meal within a specific age group remained constant regardless of rye usage in the diet. Given the crude protein content of corn and rye, the diet did not require adjustments to crude protein levels using soybean meal. Thus, soybean meal did not contribute to changes in GHG emissions between groups. The use of rye in diets necessitated the additional use of amino acids, which possess significant GHG emission levels as per Table 1. In the structure of GHG emissions per tonne of feed, amino acids accounted for 1.66–2.01% in Control Group 1, while for the experimental groups, the range was 1.67–2.04%, indicating a negligible impact on overall GHG emission levels. At the same time, the introduction of rye into the diet according to the experimental design reduced emissions associated with corn usage by 4.8% to 17.19%.

Rye grain contains a lower amount of metabolizable energy than corn; consequently, additional soybean oil was used to balance the metabolizable energy levels in the diets. The GHG emission level of soybean oil is 1,010 kg carbon per tonne, which increased the total GHG quantity per tonne of feed. Soybean oil usage in the diet of Control Group 1 ranged from 0.35–0.60%, whereas in the experimental group diets, it increased to 3.1%. Accordingly, within the structure of GHG emissions, soybean oil had a substantial impact on their increase. For Control Group 1, the level of GHG emissions in the overall structure attributed to soybean oil usage was 0.75–1.27%, while in the experimental groups, it ranged from 1.19% to 6.94%. The additional inclusion of soybean oil increased GHG emissions per tonne of compound feed, thereby diminishing the positive effect of utilizing rye in the diet. The search for alternative energy sources and enzyme preparations that enhance energy availability in rye-based diets for broiler feeding, while maintaining low GHG emission levels, is highly promising.

The calculated greenhouse gas emissions for broiler feed preparation account only for emissions associated with raw materials and illustrate the potential for emission reduction through the selection of alternative feed ingredients. These calculations exclude emissions from raw material logistics, grinding, mixing, and pelleting of the finished feed. When considering these additional sources of GHG emissions, it can be assumed that the results align with the conclusions presented by Moungsree *et al*. (2024) during field studies.

Differences in broiler growth rates influence, among other factors, feed consumption per bird, manure output, energy usage, and housing requirements. Consequently, GHG emissions per broiler reflect not only emissions associated with various feed ingredients but also the efficiency of these feeds in terms of live weight at slaughter.

Calculations of greenhouse gas emissions per broiler are presented in Table 4.

Table 4. Total greenhouse gas emissions from broiler feed production, kg CO2-eq per broiler during the experimental period

Broiler age, days	Group				
	1	2	3	4	5
11–20	0.312	0.315	0.314	0.314	0.320
21–30	0.773	0.746	0.763	0.778	0.750
31–42	0.998	1.004	0.980	0.979	0.955
Total	2.083	2.065	2.057	2.071	2.025

Experimental Group 5 exhibited the lowest emission level in terms of kg CO_2-eq per bird. This is attributed to the utilization of compound feed with the lowest GHG emission intensity in this group. Furthermore, a marked reduction in feed consumption per bird was observed in this group.

The calculated emission value for Group 1, which served as the control in the experiment and whose diet was formulated based on corn grain and soybean meal, amounted to 2.083 kg CO_2-eq per broiler. Meanwhile, in Group 2, where the diet contained the lowest inclusion levels of rye throughout the experiment, greenhouse gas emissions decreased by 0.86% per bird. In Group 5, where the diet contained the highest rye inclusion levels, greenhouse gas emissions decreased by 2.78% per bird.

Similar conclusions were reported by Cesari *et al*. (2017), van Horne (2017), Prudêncio da Silva *et al.* (2014), Usva *et al*. (2023), and Duarte da Silva Lima *et al.* (2019).

Total greenhouse gas emissions from feed production per kilogram of live weight of broiler chickens are presented in Table 5.

In Group 1 (control), where broilers received a diet based on corn grain and soybean meal, greenhouse gas emissions averaged 0.836 kg CO_2-eq/kg live weight over the experimental period. In Group 2, the diet of which contained the lowest inclusion levels of rye, the GHG emission value decreased by 2.27%. In Group 5, characterized by the highest rye inclusion levels, the GHG emission value decreased by 1.91%. The most significant reduction was observed in Group 3, where emissions were on average 3.35% lower over the experimental period. In this group, rye inclusion levels were 3% during days 10–20, 6% during days 21–30, and 15% during the 31–42 day rearing period.

It is noteworthy that a progressive increase in greenhouse gas emissions per kg of live weight was observed throughout the entire experimental period. Thus, greenhouse gas emissions per absolute weight gain during the period from day 21 to 30 were 34–37% higher compared to emissions recorded between days 11 and 20 of growth. Furthermore, emissions recorded during the final rearing stage (days 31–42) were 15–29% higher than those observed in the preceding period (days 21–30).

Table 5. Total greenhouse gas emissions from feed production, kg CO_2-eq/kg weight gain during the experimental period

Broiler age, days	Group				
	1	2	3	4	5
11–20	0.596	0.595	0.590	0.589	0.595
21–30	0.810	0.815	0.791	0.816	0.809
31–42	0.986	1.052	0.935	0.942	0.958
Total	0.836	0.817	0.808	0.819	0.820

In addition to the level of feed intake, the Feed Conversion Ratio (FCR) exerts a significant influence on the level of GHG emissions per kg of live weight. Consequently, it is clearly observed that certain experimental groups exhibit higher GHG emission levels per bird—which depend on the kg CO_2-eq/t of feed and the level of feed consumption—yet demonstrate lower levels of kg CO_2-eq/kg live weight.

The obtained results are consistent with data from Leinonen *et al.* (2012), Tongpool *et al.* (2012), Skunca *et al.* (2018), Ershadi *et al.* (2020), Vijn *et al.* (2020), Wiedemann *et al.* (2017), and Ershadi *et al.* (2021), who reported that improving feed efficiency, including the quantity, composition, and nutritional density of consumed feed, holds potential for reducing the environmental impact of broiler meat production.

CONCLUSIONS

The study demonstrated that feed production constitutes the largest contribution to the environmental profile of the entire broiler chicken meat production chain. Inclusion of rye grain into broiler diets at 2–5% during days 11–20, 4–10% during days 21–30, and 10–25% during days 31–42 resulted in a reduction in CO_2-equivalent emissions per tonne of feed by 3.1% to 7.8%. In summary, the results of the calculations highlight the significant potential for reducing greenhouse gas emissions through careful selection of raw materials, taking into account the carbon footprint of each feed ingredient.

Future research should explore in greater detail the options for mitigating the environmental impact of broiler chicken meat production, with particular attention to greenhouse gas emissions per kg of product across different growth periods.

The potential for reducing the overall growing period should also be investigated. In addition, the use of enzyme products warrants further study, as they may enhance feed conversion efficiency and contribute to lower greenhouse gas emissions.

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