Effect of life cycle inventory choices and nutritional variation on carbon footprint of broiler meat production

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Abstract

The goal of the current study is to identify the effect of life cycle inventory (LCI) specifications on carbon footprint of feed used to produce one kg of broiler meat in multi-treatment trials. A total of 384 one-day Hubbard JA787 male checks were allocated equally to 48 pens. The pens were distributed randomly to three treatments (16 pens/treatment), high density (crude protein (ME): 23% (12.5 MJ/kg),20.4% (13 MJ/kg), 19.1% (13.7 MJ/kg) for starter grower and finisher diets, respectively), medium density (crude protein (ME): 22.3% (12.2 MJ/kg), 19.7 (12.6 MJ/kg),18.2% (13 MJ/kg) for starter grower and finisher diets, respectively) and low density (crude protein (ME): 21.6% (11.9MJ/kg), 19 (12.1 MJ/kg),17.3% (12.4 MJ/kg) for starter grower and finisher diets, respectively). The experimental birds had free access to water and feed throughout the trial. All experimental diets were in crumb form in starter phase and in pellet form in grower and finisher phase. Two birds/pen were euthanised at the end of the trial (day 42) to obtain meat yield. Feed consumption and bird weight of each pen were recorded weekly. The carbon footprint (CF) of feed consumed by each pen was calculated and normalised for one kg meat yield. The CF of the pens was calculated using 3 open access databases (Agribalyse (ReCiPe (H) impact assessment method and mass allocation), GLFI (ReCiPe 2016 midpoint (H), mass allocation) and ECO-ALIM (CLM impact assessment method and mass allocation). The three CF datasets were combined and analysed to determine the effect of treatment, LCI database and treatment*LCI database on CF of broilers. The CF of each pen was calculated using GLFI database according to three allocation methods, mass, energy and economic. Data of the three allocation methods were combined and analysed to identify the effect of treatment, allocation method and treatment*allocation method on CF. Agribalyse dataset was used to calculated CF of each pen according to 3 impact assessment methods, ReCiPe (i), IPCC 2013 and CLM (with AI as a baseline). The three datasets were combined and analysed to determine the effect of the treatment, impact assessment method of LCA and treatment*assessment method on CF. There was significant effect of treatment, database and treatment*database on CF (P<0.001). The CF was significantly affected by treatment, impact assessment method and the treatment*impact assessment method (P= 0.037). Treatment and treatment*allocation method significantly affected the CF (P<0.001).

In conclusion, the effect of the dietary treatment on CF depends on the LCI database, impact assessment method and method of allocation. Thus, LCI specifications should be presented in detail in broiler trials aiming at identifying of the effect dietary treatment on CF of broilers.

Keywords: Life cycle inventory; meat; GLFI; Agribalyse; ECO-ALIM; impact assessment method; allocation method

1. **Introduction**

Life cycle assessment (LCA) methodology is one of the key methods used to determine the environmental impacts of livestock products. Whilst the methodology is standardised through ISO standards 14040 (ISO, 2006a) and 14044 (2006) (ISO, 2006b), many methodological issues/options are left open for LCA practitioners (Svanes et al., 2011); (Ayer et al., 2006). This includes the selection of life cycle inventory (LCI) database, the impact assessment method and method of allocation (European Commission et al., 2012). Many methods of assessment have been developed to calculate the environmental impact of products (Frontera et al., 2020). The impact assessment method is defined as "A set of principle, model and characterization factors that allows the calculation of the characterization results for a certain impact category" (Frontera et al., 2020);(Akanuma et al., 2014). The choice of impact assessment methods for a reliable LCA is one of the main challenges that faces the LCA analysts (Frontera et al., 2020). The environmental impact of a given product/feed extracted from the same LCI database can differ according to the impact assessment method.

Allocation method is one of the choices that potentially has a high impact on LCA results (Svanes et al., 2011). Feed ingredients go through a long value chain before being consumed by livestock. Some steps in that value chain are multiple output processes. In these steps, the environmental impact is distributed (allocated) among the outputs based on mass, price or energy consumption (Svanes et al., 2011). The effect of allocation method on environmental impact of livestock was analysed in wild-caught fish (Svanes et al., 2011) and dairy cattle (March et al., 2021). However, none on these studies reported on the interaction between the dietary treatment and LCI specification of feed.

Nowadays there is a wide range of open access and paid LCA databases of feed stuffs which differ in number of LCIs, origin of the product, boundaries, method of impact assessment and method of allocation. For example, OpenLCA Nexus website offers 2176 LCA datasets. Agribalyse is a public LCI database (Colomb et al., 2014) with 139 LCIs of French agricultural products at the farm gate. A common methodology was defined in line with the International Organisation for Standardisation (ISO) and the International Reference Life Cycle Data System standards (Koch and Salou, 2014) to ensure database consistency. When Agribalyse is integrated with Open-LCA software, the impact assessment of feed ingredients in the database could be calculated by 43 impact assessment methods. However, the allocation method used in Agribalyse is based on mass.

Global LCA feed institute (GFLI) database contains LCIs of 962 raw materials from different regions in the world (GLFI, 2021). GFLI had a methodology which is compliant with FAO-LEAP and EU-PEF to the dataset to ensure the quality and standardization of the data (GLFI, 2021). The system boundary is cradle-to-farm gate, as well as feed mill operations and logistics (GLFI, 2021). LCA of feeds was calculated according to three allocations at co-production, which are economic, mass dry matter, and energy (GLFI, 2021). The GFLI's methodology is based on 4 reference documents, namely the FAO LEAP feed guidelines (2016), LEAP feed additives guidelines (2020), Feed PEF database methodology (2017), and Feed PEFCR (2018) (GLFI, 2021). ECO-ALIM database was built by INRA for French ingredients and LCA methodology was used to calculate the environmental impacts (INRA, 2017). The database was last updated in 2012 (INRA, 2017). The database contains 60 ingredients and 150 LCIs (INRA, 2017). Different scopes were used depending on the needs and the ingredients, cradle to field gate, cradle to storage agency, cradle to French port and cradle to mill gate (INRA, 2017). The impacts followed the ILCD recommendations and the usual practices of international scientific references (CML methodology). The emission models were identified to fit with French context (INRA, 2017).

Thus, it is clear that the environmental impact of a given feed would be different across LCI databases, method of assessment and method of allocations. However, the effect of LCI specification of feed on the treatment in multi-dietary treatment trials is still unknown.

The goal of the current study is to identify the effect of LCI specifications of feedstuffs on the carbon footprint (CF) of broiler meat in a multi-treatment trial.

2. Materials and methods

2.1. Animals and diets

Institutional and UK national NC3R ARRIVE guidelines for the care, use and reporting of animals in research (Kilkenny et al., 2010) were followed during the study and all experimental procedures were approved by Nottingham Trent University's animal ethics review committee. A total of 384 Hubbard JA787 male chicks at one day of age were distributed to 16 pens (0.64 m^2) with 8 birds each. The pens were distributed randomly to three treatment diets, high density (crude protein (ME): 23% (12.5 MJ/kg),20.4% (13 MJ/kg), 19.1% (13.7 MJ/kg) for starter grower and finisher diets, respectively), medium density (crude protein (ME): 22.3% (12.2 MJ/kg), 19.7 (12.6 MJ/kg),18.2% (13 MJ/kg) for starter grower and finisher diets, respectively) and low density (crude protein (ME): 21.6% (11.9MJ/kg), 19 (12.1 MJ/kg),17.3% (12.4 MJ/kg) for starter grower and finisher diets, respectively) (Table 1). The feeding phases were starter (d0-d14), grower (d15-d30) and finisher (d31-d45). The specification and nutritional composition of the diets used in the study is presented in Table 1 and Table 2, respectively. All experimental diets were in crumb (starter) or a pellet form (grower and finisher). The birds had free access to water and feed throughout the trial. The lighting regimen started with 23 h of light on d1 then decreased by one h/day to reach 18 h/day on day 6. After that, 6h/day of light was maintained till the end of the trial. Temperature was set at 32°C on day 1 and reduced by approximately 1°C per day until 21°C was reached. The temperature was then maintained at 21 ^{o}C until the end of the trial. The experimental birds were bedded on clean wood shavings. Two birds/pen were euthanised by cervical dislocation at the end of the trial to obtain the meat yield. Feed consumption and bird weight of each pen were recorded weekly. The experimental chicks were vaccinated against Marek`s disease, infectious bronchitis and Newcastle disease at the hatchery. The mortality was daily recorded and any birds culled or found dead were weighed.

2.2. Feed analysis

Representative samples of the experimental feeds were ground to pass through 1mm screen then analysed for dry matter, ash, ether extract and crude fibre according to standard (AOAC, 2006) (methods 930.15, 942.05, 2003.05 and 962.09 respectively). Total nitrogen content of the feed was determined using the Dumas combustion method (Dumatherm N Pro, Gerhardt Analytical Systems, Königswinter, Germany) and then crude protein was calculated as nitrogen ×6.25. Nitrogen free extract was calculated by subtracting ether extract, crude fibre and crude protein from organic matter. Metabolizable energy of the experimental feeds was calculated according to (Wiseman, 1987). All samples were analysed in poultry research unit at Nottingham Trent University.

2.3. Life cycle analysis inventory and carbon footprint calculation

Life cycle analysis specification of the experimental feed ingredients is presented in Table 3. The CF of each bird was calculated for each pen then normalised for one kg of meat. Three data sets were generated to determine the effect LCI database, LCI method of assessment and LCI method of allocation on CF of broilers.

Effect of database

The CF of each pen was calculated using LCIs of Agribalyse3.01 (ReCiPe (H) impact assessment method, mass allocation method), GLFI (ReCiPe 2016 midpoint (H), mass allocation) and ECO-ALIM (CLM impact assessment method, mass allocation method).

Effect of allocation method within the same LCI

The CF of each pen was calculated using GLFI LCIs using three different allocation methods, namely, energy, economic and mass.

Effect of impact assessment method within the same LCI

Agribalyse database file was downloaded in .zolca format then imported to Open LCA 1.10.3 (GreenDelta, 2017). Open LCA was used to calculate CF of feed ingredient using 3 methods of impact assessment, ReCiPe (i), IPCC 2013 and CLM (with AI as a baseline). Following this, CF of each pen was calculated according to the three methods before data analysis.

2.4. Data analysis

The growth performance and meat yield data was analysed according to the following model:

$$Y_{(ij)} = M + TRT_{(i)} + B_{(j)} + E_{(ij)}$$

Where Y is the response variable, M is the overall mean, TRT is the effect of treatment, B is the effect of block E is the residual.

The effect of treatment and database was analysed according to the following model:

$Y_{(ijk)} = M + TRT_{(i)} + DB_{(j)} + B_{(k)} + (TRT*DB)_{(ij)} + E_{(ijk)}$

Where Y is CF, M is the overall mean, TRT is the effect of treatment, DB is the effect of the database, B(k) is the effect of block, TRT*DB is the effect of the interaction between the treatment and the database and E is the residual.

The effect of method of allocation of CF of the broilers was analysed according to the following model:

$Y_{(ijk)} = M + TRT_{(i)} + MA_{(j)} + B_{(k)} + (TRT*MA)_{(ij)} + E_{(ijk)}$

Where Y is CF, M is the overall mean, TRT is the effect of diet, MA is the effect of the method of allocation, B is the effect of block, TRT*MA is the effect of the interaction between the diet and the method of allocation and E is the residual.

The effect of method of impact assessment on CF of the broilers was analysed according to the following model:

$Y_{(ijk)} = M + TRT_{(i)} + IAM_{(j)} + B_{(k)} + (TRT*)IAM_{(ij)} + E_{(ijk)}$

Where Y is CF of the broilers, M is the overall mean, TRT is the effect of the treatment, IAM is the effect of the impact assessment method, B is the effect of block, TRT*IAM is the effect of the interaction between the treatment and the impact assessment method and E is the residual. Least square means of the treatments were separated using least significant difference method of Fisher. R was used to conduct the statistical analyses (R core Team, 2017).

3. Results

3.1. Performance and meat yield data

The effect of dietary treatment on growth performance and meat yield of broilers is presented in Table 5. Bird weigh, final bird weight gain and meat yield were significantly reduced by decreasing nutrient density. Increasing diet density significantly increased feed conversion ratio of the broilers

3.2. Carbon footprint data

Table 6 shows that there was significant effect of treatment, database and treatment-database interaction on CF of broilers (P<0.001). The treatment and the treatment-allocation method interaction significantly affected CF of broilers (P<0.001). The Method of allocation did not significantly affect CF of broilers (P= 0.686). There was a significant effect of treatment (P<0.001), impact assessment method (P<0.001) and treatment*impact assessment method on CF of broilers (P= 0.037). The impact assessment method did not significantly affect CF of broilers (P= 0.164).

The effect of LCI database

When Agribalyse data was used to calculate CF, the treatment did not significantly affect CF. When ECO-ALIM was used for CF calculation, CF of MD was significantly higher than the HD and LD which did not significantly differ from each other. The broilers fed MD and LD diets did not significantly differ in CF when LCIs were obtained form GLFI. Birds of MD and LD had significantly higher CF compared to the high when GLFI database was used for the calculation.

Effect of allocation method

Table 6 shows that the effect of the treatment on CF of broilers depended on the method of allocation. Medium and low-density diets had significantly higher CF compared to HD diet when Economic and mass allocation method was used. Yet, the dietary treatment did not significantly affect CF when energy allocation method was used.

Effect of the impact assessment method

The impact assessment method interfered the effect of treatment on CF of broilers (Table 6). In IPCC, the low-density treatment had significantly the lower CF compared to HD and LD diets. However, the treatment did not significantly affect CF when CLM or ReCipe midpoint (H) method were used for CF calculations.

4. Discussion

There has recently been substantial interest in mediating the environmental impact of livestock production, with particular emphasis on achieving this through dietary alterations. This includes the use of corn gluten meal and protease (Giannenas et al., 2017). No studies have yet reported on the effect of nutritional options on CF of broilers. Yet, CO_2 footprint of feed ingredients and final product is becoming an important component in routine poultry ration formulation and it is likely to be the trend in poultry studies in the near-future [(OpteinicsTM, 2022)]. It is not clear that LCI choice when calculating CF would alter the final results and recommendation of studies targeting reduction the environmental impact of poultry. Thus, it is imperative to identify the effect of the LCI specifications on the results of broiler studies which include CF calculation.

The decrease in meat yield due to the decrease in diet density agrees with (Widyaratne and Drew, 2011) who found that high meat yield of broilers requires high protein levels in the diet. However, the main goal of the current study is to identify if the effect of the dietary treatment on CF of broilers depends on LCI choices.

Previous studies showed that there was an effect of different allocation methods on LCA results of products obtained from wild-caught fish (Svanes et al., 2011). Changing the allocation method (from mass to economic) and land use functional units resulted in changes in CF performance ranking of the dairy systems (March et al., 2021). However, these two studies did not investigate the impact of LCI choices on the effect of nutritional treatments aiming to decrease CF of livestock.

Recently, consumers have shown increasing concerns about the Impact of their daily activities on the environment (Liu et al., 2017). It has been reported that two-thirds of consumers mentioned that they think that labelling products with carbon footprint “is a good idea”(Carbon Trust, 2020). Therefore, over the last decade, several labelling systems were developed to help consumers to choose more sustainable options (Grunert et al., 2014).

The magnitude of CF was strongly affected by LCI choice, yet, that effect depended on the treatment. For example, the CF of MD diet increased by 81% when LCI database changed from Agribalyse to ECO-ALIM. Furthermore, the CP of LD increased by 21% when impact assessment method of Agribalyse LCI calculation was changed from CLM-AI baseline into IPCC 2013. Accordingly, the same product would be labelled differently according to the way CF is calculated. It is important to standardise the method used to calculate CF of broiler meat thus the consumer could make a valid comparison among different sources of broiler meat. It is notable that the products describes in each database do not align in detail, forcing modellers to select the nearest figure available, for example, where GFLI offers a figure for Brazilian soyabean crushed in the UK, other databases do not have a figure closer than Brazilian crushed soya delivered to a French port. All premix components, like enzymes and minerals, have the same CF.

The interaction between the treatment and LCI database pinpoints that effect of the treatment on CF of broilers depended on the inventory database. The relative ranking of the treatments differed across LCI databases. Furthermore, changing impact assessment method or allocation method of the same database changed the relative ranking of the dietary treatments based on CF. Therefore, a detailed description of LCIs datasets used for CF calculations should be presented to avoid misinterpretation of the results.

The current LCI databases are different in impact assessment method and allocation method. Since the effect of dietary treatment is affected by LCIs choices, level of bias in studies where LCIs of experimental feed are obtained from multiple sources would be high.

The application of the current study is based on broiler trial data.

5. Conclusions

The effect of the dietary treatment (diet density in the current study) on CF of broilers depends on LCIs database, allocation method and the method of impact assessment. Detailed information on LCIs database used for CF calculations should be clearly presented in multi-treatment studies.

CRediT authorship contribution statement

A. Alkhtib: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review. **E. Burton:** Conceptualization, Methodology, Investigation, Writing – review. **P. Wilson:** Conceptualization, Methodology, Writing – review. **D. Scholey:** Conceptualization, Methodology, Writing – review, **J. Bentley:** Conceptualization, Methodology, Writing – review.

Conflict of interest statement

The authors declare no conflict of interest related to the current study.

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Table 1. Ingredient composition of the experimental diets[a] (%)

	HD			MD			LD		
	Starter	Grower	Finisher	Starter	Grower	Finisher	Starter	Grower	Finisher
Barley grain	5	5	5	7.5	7.5	7.5	10	10	10
Wheat grain	56.6	62.7	63.9	52.67	59.6	62.9	48.7	56.5	61.9
Potato protein	0	0	0	1.25	1.25	1.25	2.5	2.5	2.5
Wheat feed	0	0	0	5	5	5	10	10	10
Sunflower extract	0	0	0	3	3	3	6	6	6
Soybean meal	34	27	24	26.2	19.3	15.3	19	11.5	6.5
Lysine HCl	0.25	0.28	0.25	0.329	0.361	0.345	0.408	0.442	0.44
DL-Methionine	0.32	0.29	0.27	0.325	0.295	0.26	0.33	0.3	0.25
Threonine	0.12	0.13	0.13	0.15	0.155	0.16	0.18	0.18	0.19
Soybean oil	0.5	1.6	3.8	0.25	0.8	1.9	0	0	0
Limestone	1.3	1.2	1	1.25	1.15	0.94	1.2	1.1	0.88
Monocalcium phosphate	1	0.92	0.8	0.91	0.785	0.615	0.82	0.65	0.43
Salt	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Sodium bicarbonate	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
BR.trial starter premix	0.4	0	0	0.4	0	0	0.4	0	0
BR.trial Grower premix	0	0.4	0.4	0	0.4	0.4	0	0.4	0.4
Monteban G100	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065
Ronozyme WXCT2000	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075
RONO.Hiphos m NUT	0	0	0	0.0005	0.0005	0.0005	0.001	0.001	0.001

a: HD= High density diet, MD= Medium density diet, LD= Low density diet.

Table 2. Nutritional composition of the experimental diets[a]

	Starter			Grower			Finisher		
Treatment	LD	MD[b]	HD	LD	MD	HD	LD	MD	HD
Ether extract (%)	1.83	2.39	2.94	1.85	2.95	4.04	1.88	4.05	6.22
Protein (%)	21.6	22.3	23	19	19.7	20.4	17.3	18.2	19.1
Fibre (%)	4.78	3.98	3.18	4.74	3.93	3.11	4.72	3.88	3.04
ME[c] (MJ/kg)	11.9	12.2	12.5	12.1	12.6	13	12.4	13	13.7
T-Lysine (%)	1.38	1.4	1.41	1.21	1.23	1.25	1.07	1.1	1.13
D-Lysine (%)	1.16	1.195	1.23	1.01	1.045	1.08	0.89	0.935	0.979
M+C[d] (%)	0.995	0.992	0.989	0.89	0.888	0.885	0.791	0.81	0.828
DM+C[e] (%)	0.863	0.888	0.913	0.777	0.802	0.826	0.691	0.734	0.777
Threonine (%)	0.97	0.953	0.936	0.851	0.832	0.813	0.782	0.78	0.777
D- Threonine (%)	0.749	0.767	0.784	0.655	0.679	0.703	0.603	0.632	0.66
Tryptophan (%)	0.261	0.267	0.272	0.224	0.23	0.236	0.2	0.21	0.219
D-Tryptophan (%)	0.193	0.211	0.228	0.162	0.181	0.199	0.142	0.163	0.184
Ca (%)	0.982	1.02	1.06	0.892	0.939	0.985	0.755	0.816	0.877
Available P (%)	0.477	0.485	0.492	0.429	0.446	0.463	0.372	0.401	0.43
Na (%)	0.181	0.179	0.177	0.181	0.179	0.177	0.181	0.178	0.176
Vitamin A (IU)	13.5	13.5	13.5	10	10	10	10	10	10
Vitamin D3 (IU)	5	5	5	5	5	5	5	5	5
Vitamin E (IU)	100	100	100	100	100	100	100	100	100

a: HD= High density diet, MD= Medium density diet, LD= Low density diet.

b: The mean of low-density diet and high-density diet.

c: ME: metabolizable energy.

d: M+C: methionine+ cysteine.

e: DM+C: D-methionine+ cysteine.

Table 3. Carbon footprint (kg CO_2 e/kg feed - land use change exclusive) of the experimental feed.

Database	GLFI			ECO-ALIM	Agribalyse		
	Allocation method				Impact assessment method		
	Economic	Energy	Mass		ReCiPe (i)	IPCC	CLM
Barley grain	0.403	0.322	0.325	0.391	0.224	0.23	0.22
Wheat grain	0.432	0.351	0.345	0.503	0.336	0.325	0.324
Potato protein	2.43	1.02	1.18	0.058	0.033[a]	0.031[a]	0.031[a]
Wheat feed	0.532	1.01	1.07	0.077	0.32	0.283	0.281
Sunflower extract	0.83	1.43	1.96	0.343	0.511	0.498	0.494

Soya ext hipro	0.647	0.675	0.819	0.859	0.498	0.464	0.462
Lysine HCl	1.18	1.17	1.17	3.87	3.35	3.07	3.06
DL-Methionine	1.18	1.17	1.17	2.93	4.81	3.13	3.05
Threonine	1.18	1.17	1.17	3.87	3.35	3.07	3.06
Soya oil	1.79	1.52	0.93	1.28	1.19	1.12	1.11
Limestone trucal 52	1.18	1.17	1.17	0.079	0.036	0.033	0.033
Monocalcium phosphate	1.18	1.17	1.17	1.24	1.34	1.18	1.18
Salt	1.18	1.17	1.17	0.058	0.302	0.195	0.276
Sodium bicarbonate	1.18	1.17	1.17	1.17[b]	1.17[b]	1.17[b]	1.17[b]
BR.trial starter premix	1.18	1.17	1.17	1.17[b]	1.17[b]	1.17[b]	1.17[b]
BR.trial Grower premix	1.18	1.17	1.17	1.17[b]	1.17[b]	1.17[b]	1.17[b]
Monteban G100	1.18	1.17	1.17	1.17[b]	1.17[b]	1.17[b]	1.17[b]
Ronozyme WXCT2000	1.18	1.17	1.17	1.17[b]	1.17[b]	1.17[b]	1.17[b]
RONO.Hiphos m NUT	1.18	1.17	1.17	1.17[b]	1.17[b]	1.17[b]	1.17[b]

a: Adopted from GLFI.

b: potato starch since Agribalyse does not have carbon footprint of potato protein.

Table 4. Carbon footprint (kg of CO_2 e/ kg - land use change exclusive) of the experimental diets.

Database		GLFI			ECO-ALIM	Agribalyse		
		Allocation method				Impact assessment method		
Diet[a]	Stage	Economic	Energy	Mass		ReCiPe (H)	IPCC	CLM
	Starter	0.555	0.503	0.56	0.469	0.385	0.356	0.365
LD	Grower	0.537	0.477	0.523	0.463	0.374	0.356	0.354
	Finisher	0.522	0.457	0.495	0.457	0.366	0.347	0.345
	Starter	0.544	0.497	0.547	0.814	0.398	0.374	0.378
MD	Grower	0.535	0.478	0.514	0.728	0.393	0.374	0.372
	Finisher	0.538	0.475	0.498	0.686	0.395	0.375	0.373
	Starter	0.534	0.491	0.534	0.548	0.412	0.392	0.392
HD	Grower	0.532	0.48	0.506	0.551	0.412	0.392	0.390
	Finisher	0.553	0.493	0.502	0.564	0.424	0.404	0.402

a: HD= High density diet, MD= Medium density diet, LD= Low density diet.

Table 5. Growth performance and meat yield of broilers as affected by the dietary treatment.[a]

	HD	MD	LD
Initial bird weight (g)	40.2(0.19)	40.3(0.19)	40.6(0.19)
D44 Bird weight (g)	2456 (25.4)a	2340 (23.0)b	2226 (24.13)c
D0-D44 Bird weight gain (g)	2415 (25.4)a	2300 (23.0)b	2186 (24.13)c
D0-D44 Feed intake (g)	4052 (44.2)	3989 (46.3)	3975 (51.27)
D0-D44 Feed conversion ratio	1.66 (0.01)a	1.73 (0.01)b	1.82 (0.01)c
Meat yield (kg)	0.985(0.019)a	0.899(0.017)b	0.84(0.018)c

Means within a row with different letters are significantly different (P≤ 0.05). a: HD= High density diet, MD= Medium density diet, LD= Low density diet.

Table 6. Effect of the interaction between the treatment[a] and LCA specification on carbon footprint (kg of CO_2 e land use change exclusive) of one kg of broiler meat.

	HD	MD	LD
Database			
Agribalyse	1.65(0.063)	1.7(0.058)	1.66(0.063)
ECO-ALIM	2.19(0.063)b	3.09(0.058a	2.04(0.063)b
GLFI	1.99(0.063)b	2.2(0.058)a	2.27(0.063)a
P value			
Diet	<0.001		
Database	<0.001		
Diet*Database	<0.001		
Allocation method			
Economic	2.13(0.064)b	2.32(0.059)a	2.35(0.064)a
Energy	1.92(0.064)	2.07(0.059)	2.08(0.064)
Mass	1.99(0.064)b	2.2(0.059)a	2.27(0.064)a
P value			
Diet	<0.001		
Allocation method	0.686		
Diet*Allocation method	<0.001		
Impact assessment method			
CLM-AI baseline	1.56(0.049)	1.61(0.045)	1.55(0.049)
IPCC 2013	1.56(0.049)b	1.62(0.045)b	1.87(0.049)a
ReCipe midpoint (H)	1.64(0.049)	1.7(0.045)	1.64(0.049)
P value			
Diet	<0.001		

Impact assessment method	<0.001
Diet*Impact assessment method	<0.001

Means within a row with different letters are significantly different (P≤ 0.05).

a: HD= High density diet, MD= Medium density diet, LD= Low density diet.

Appendix 1. Life cycle inventory specification of the experimental feed (land use change exclusive).

Feed ingredient	GLFI	ECOALIM	Agribalyse
Barley	Barley grain, dried, at farm/UK	Feed barley grain, conventional, France, at storage agency	Barley, organic, animal feed, at farm gate
Wheat	Wheat grain, dried, at farm/UK	Soft wheat grain, conventional, Great Britain, at storage agency	Wheat grain, conventional, national average, animal feed, at storage agency
Potato protein	Potato protein, from wet milling, at plant/RER	Starch potato, conventional, national average, at farm gate/FR	Protein, Potato, at feed plant
Wheat feed	Wheat bran, from wet milling, at plant/RER	Wheat bran, France, at transformation plant	Wheat bran, at industrial mill
Sunflower extract	Sunflower seed meal, from crushing (solvent), at plant/RER	Sunflower meal, with high dehulling, France, at transformation plant	Sunflower meal UA, animal feed, at French port
Soybean meal	Soybean meal, from crushing (solvent), at plant/UK	Soybean meal, Brazil, crushing in Brazil, at French port	Soybean meal, crushing in Brazil, animal feed, at mill, average
Lysine HCl	Total minerals, additives, vitamins, at plant/RER	L-lysine HCl, France, at mill	L-Lysine HCl, animal feed, at retailer gate
DL-Methionine	Total minerals, additives, vitamins, at plant/RER	DL-methionine, Europe, at mill	DL methionine, animal feed, at retailer gate
Threonine	Total minerals, additives, vitamins, at plant/RER	L-threonine, France, at mill	L-Threonine, animal feed, at retailer gate
Soya oil	Crude soybean oil, from crushing (solvent), at plant/UK	Soybean oil, Brazil, crushing in Brazil, at French port	Soybean oil and lecithin, Brazil, animal feed, at mill, average, at plant
Limestone trucal 52	Total minerals, additives, vitamins, at plant/RER	Calcium carbonate (<63µm), Europe, at mill	Limestone, milled, loose, from Switzerland, at feed plant, FR U/kg
Monocalcium phosphate	Total minerals, additives, vitamins, at plant/RER	Monocalcium phosphate, France, at mill	Monocalcium phosphate, animal feed, at retailer gate
Salt	Total minerals, additives, vitamins, at plant/RER	Sodium chloride, powder, France, at mill	Salt
Sodium bicarbonate	Total minerals, additives, vitamins, at plant/RER	Sodium bicarbonate, Europe, at mill	Sodium bicarbonate, animal feed, at retailer gate
BR.trial premix	Total minerals, additives, vitamins, at plant/RER	Sodium bicarbonate, Europe, at mill	Sodium bicarbonate, Europe, at mill
Monteban G100	Total minerals, additives, vitamins, at plant/RER	Sodium bicarbonate, Europe, at mill	Sodium bicarbonate, Europe, at mill

Ronozyme WXCT2000	Total minerals, additives, vitamins, at plant/RER	Sodium bicarbonate, Europe, at mill	Sodium bicarbonate, Europe, at mill
RONO.Hiphos m NUT	Total minerals, additives, vitamins, at plant/RER	Sodium bicarbonate, Europe, at mill	Sodium bicarbonate, Europe, at mill