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Improving environmental sustainability of poultry production using innovative feeding strategies

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Summary

Poultry production is facing many sustainability challenges, among which the reduction of environmental impacts such as climate change, eutrophication or acidification. In that context, nutrition is a powerful tool to improve the environmental sustainability of poultry production. First, nutrient utilization (in particular nitrogen and phosphorus) should be improved with a better fit between supply and requirements, and by using feed additives (amino acids, enzymes). Secondly, using life cycle assessment (LCA) methodology, the environmental impacts associated to the production of feed ingredients should be considered in feed formulation. Finally, the LCA environmental impacts of poultry production “at farm gate”, taking into account feed production and on-farm emissions, should also be assessed in order to design “environmental friendly” feeding strategies. To do so, modelling tools are still required to simultaneously evaluate these new strategies at different scales (animal performance, manure emission, feed production), both on economic and environmental criteria.

Introduction

Because world population should reach almost 10 billion in 2050, the demand for animal products will strongly increase in the coming decades. In particular, poultry products are expected to have the highest growth rate with 120 and 65% for poultry meat and eggs respectively (MOTTET and TEMPIO, 2017). Simultaneously to the increase of production, poultry supply chains are facing many sustainability challenges (VAARST *et al.*, 2015). Besides consumers' expectations regarding animal welfare, they should tackled several environmental issues, among which climate change, water eutrophication or soil acidification (GERBER *et al.*, 2007). To do so, nutrition is one of the most effective lever as feed is the main driver of animal performance (growth or egg production) and nutrient excretion (nitrogen, phosphorus). Moreover, feed production (*i.e.* the production, transport and processing of feed ingredients) has also been shown to be a source of pollution associated to livestock production (STEINFELD *et al.*, 2006). Consequently, in order to improve its environmental sustainability, poultry production should design new feeding strategies. This review therefore focuses on the environmental consequences of different feeding strategies both at animal scale (feed efficiency and nutrient utilization), at farm scale (manure emissions) and at a production system global scale, including the impacts associated to feed production (life cycle approach).

Decreasing nutrient excretion and emissions from manure

Adjustment of nutrient supply to requirements and improvement of feed utilization

In poultry, ammonia (NH₃) is the main nitrogen compound emitted by manure. It is responsible for several environmental impacts such as water pollution (eutrophication) and soil acidification (GERBER *et al.*, 2007). The most efficient way to reduce NH₃ emissions is to reduce nitrogen (N) excretion of poultry, by adjusting crude protein (CP) supply to the requirements of the animals (MÉDA *et al.*, 2011). The first step is the reduction of dietary CP content over time

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with phase-feeding strategies. In the past two decades, many studies focused on the reduction of dietary CP content during the growing-finishing period. These studies generally succeeded in reducing nitrogen excretion, with an average value of -10% for a reduction of one CP point in the diet (MÉDA *et al.*, 2011). Nevertheless, several authors also reported a negative impact on growth and/or feed efficiency. For instance, when decreasing CP from 23.4 to 19.2% in broiler chicks between 7 and 21d, BREGENDAHL *et al.* (2002) observed an increase of feed conversion ratio by 8% (1.35 and 1.46 respectively) and a 4% decrease of body weight gain (654 and 631 g respectively). AFTAB *et al.* (2006) suggested that essential/non-essential amino acids (AA) or net energy/metabolizable energy ratios could explained these negative effects.

Defining the optimal amino acids profile (*i.e.* all amino acids being expressed according to lysine level) is a therefore challenge for poultry production, and the use of crystalline AA is often required to reach this optimal profile during feed formulation. The profile proposed by MACK *et al.* (1999) for broilers is one of the most famous. Recently, this profile was updated for arginine and threonine, and successfully used in finishing broilers by BELLOIR *et al.* (2017). Using a large range of crystalline AA (lysine, methionine, threonine, arginine, valine, isoleucine and tryptophan), the decrease of dietary CP content by 2 percentage points (from 19 to 17%) had no effect on growth or feed efficiency (Table 1). Concerning N excretion, results were consistent with the literature, with a decrease by about 10% per CP point, even when feed efficiency was negatively impacted below 17% (Table 1). In the future, to achieve an even greater decrease in dietary CP (*i.e.* below 17%), the requirements for the next limiting AA (*e.g.* valine, isoleucine) and non-essential AA (*e.g.* glycine) should be assessed. Finally, the use of exogenous proteases could also improve feed efficiency but contrasted results were reported in the literature. Further research is thus required to better understand the interactions between the animal (genetics, age), dietary characteristics (proteins, fibre) and other exogenous enzymes (ADEOLA and COWIESON, 2001).

Table 1 Effect of dietary crude protein content in finishing broilers on animal performances and nitrogen balance according to BELLOIR *et al.* (2017). Diets were formulated to respect an ideal protein profile (digestible amino acids) and crystalline amino acids were used to balance the diets*. Nitrogen balance was recalculated using data and equations from the study.

	19%	18%	17%	16%	15%
Animal performances					
Body weight (g)	2460	2470	2466	2451	2461
Body weight gain (g)	1479	1496	1494	1446	1478
Feed intake (g)	2430	2477	2472	2459	2528
Feed conversion ratio [†]	1.64 ^b	1.65 ^b	1.65 ^b	1.69 ^a	1.71 ^a
Nitrogen balance					
N intake (g)	73.9	71.3	67.2	63.0	60.7
N retention (g)	42.9	43.4	43.3	41.9	42.9
N excretion (g) [‡]	31.0	28.0	23.9	21.0	17.8
		(-10%)	(-23%)	(-32%)	(-43%)
N volatilization (g) [‡]	8.5	6.6	4.7	3.3	2.1
		(-23%)	(-45%)	(-61%)	(-75%)

*DL-Methionine, L-Lysine-HCl and L-Threonine in all diets + L-Arginine, L-Valine, L-Isoleucine and L-Tryptophan in 18% to 15% diets. [†]p<0.01; [‡]In brackets: reductions compared to the 19% diet.

Phosphorus (P) supply in poultry should also be considered, because of its impact on the environment (water eutrophication) and because phosphate resources are non-renewable (GERBER *et al.*, 2007; CORDELL *et al.*, 2009). Similarly, to nitrogen, significant reductions in P content were achieved in the past. For instance, POWERS and ANGEL (2008) reported that in the middle of the 2000's, the average dietary content for non-phytate P (NPP) in broilers up to 21 days of age was about 3.6 g/kg vs 4.5 g/kg according to the last NRC recommendations (1994). The use of exogenous phytase also add a significant role in the decrease of P supply in poultry diets, as this enzyme can substantially improve P availability in the digestive tract (POWERS and ANGEL, 2008). For example, RIBEIRO JR. *et al.* (2016) estimated that the addition of 500 and 1000 phytase units of *Escherichia coli* is equivalent to the respective addition of 1.3 and 2.4 g of inorganic phosphorus (dicalcium phosphate) per kg in broiler diets between 1 and 21 days. More recently, new feeding strategies based on the adaptive response of birds under P (and calcium) restriction have shown promising results to decrease even further dietary P in poultry. For instance, VALABLE *et al.* (2018) showed that a 25% decrease of NPP contents in growing broilers, followed by "classical" finisher diet did not impaired performance nor bone mineralization. In particular, the adaptive response could involve an improvement of P digestibility and absorption (ROUSSEAU *et al.*, 2016), and consequently an increase in body P retention. NARCY *et al.* (2015) showed indeed that in growing broilers, a simultaneous decrease in dietary NPP and calcium contents (-1.5 and -4 g/kg respectively) improved P body retention by 12%. Using this strategy in growing period and by lowering NPP and calcium contents in finishing period (-1.1 and -4.2 g/kg respectively), ROUSSEAU *et al.* (2016) showed that P manure content could be substantially reduced (about -40%).

In the future, the development of precision feeding (PF) strategies, such as those successfully developed in pigs (POMAR *et al.*, 2010; ANDRETTA *et al.*, 2016), could be a new step for adjusting nutrient supply to the requirements of the animals. DUSART *et al.* (2019) evaluated *in silico* the economic and environmental potential gains when applying a precision feeding strategy in broilers between 10 and 47 days of age. This PF strategy was based on a daily mix of two different pre-diets in different proportions according to the requirements of the birds (d10-d24: pre-diets A/B; d25-d42: pre-diets B/C; d43-d47: pre-diets C/D), and was compared to a classical phase-feeding strategy (3 phases). The authors showed that feeding cost, N and P excretion could be decreased by 6, 11 and 4%, respectively. Yet, PF strategies in poultry are not currently used in commercial farms, as many issues still have to be tackled (modelling of daily requirements, processing of on-farm collected data such as body weight, implementation of decision rules into farm equipment...).

Reduction of ammonia emissions from manure

As reported by MÉDA *et al.* (2011), many factors control ammonia emission from poultry manure. Besides the amount of ammoniacal N available in manure, manure moisture is a key factor in the ammonification process, *i.e.* the aerobic decomposition by microorganisms of excreted uric acid into NH₃. According to GROOT KOERKAMP (1994), the optimal rate of ammonification is observed when manure moisture is between 40 and 60%. Manure moisture is essentially controlled by ventilation rate in the poultry house, bedding material characteristics and direct water inputs (water spillage), but feeding can also influence this parameter (MÉDA *et al.*, 2011). First, feed viscosity directly affects water excretion in poultry as reported by FRANCESCH and BRUFAU (2004). Yet, the practical characterization of viscosity (*e.g.* by feed producers) is somehow difficult. Secondly, as reported by BORGES *et al.* (2004), the increase in dietary electrolytic balance (DEB) linearly increases water consumption (+30% for an increase of DEB from 40 to 340 mEq/kg of feed), and consequently, manure moisture. As reported by QUINIOU and NARCY (2019), the optimal DEB associated to the lowest litter moisture content should be close to 150 mEq/kg of feed (quadratic response). So far, in

conventional diets, DEB is generally above this value, mostly because of the use of K^+ -rich feed ingredients, such as soybean meal.

The decrease of soybean use in low-CP diets can thus help reducing excreta or manure moisture, as shown by several authors in the literature (HERNÁNDEZ *et al.*, 2012; FERGUSON *et al.*, 1998). Such a decrease in manure moisture could have indeed a positive effect on ammonia volatilization as shown by BELLOIR *et al.* (2017). By reducing dietary CP (and soybean meal use) in the finisher diet of broilers, the authors showed a synergic effect on total N volatilization associated both to the decrease of N excretion and to the lower volatilization rate of the excreted N (-4 percentage point per CP point). For a CP level of 15% (vs a control diet at 19%), this means a decrease by 75% of volatilized N for a reduction by “only” 43% of N excretion (Table 1). Finally, another way of reducing NH_3 volatilization is to decrease manure pH, the chemical equilibrium between NH_4^+ and NH_3 being shifted towards the non-volatile form NH_4^+ (MÉDA *et al.*, 2011) by using acidifying compounds in feed (LI *et al.*, 2008; WU-HAAN *et al.*, 2007).

Taking into account the environmental impacts of feed ingredients

Evaluation of the environmental impacts of feed ingredient using Life Cycle Assessment (LCA)

Because of its normalized methodological framework (ISO 14040 and 14044, 2006) and its large set of environmental impact categories, Life Cycle Assessment (LCA) has become one of the most popular method to assess, using a holistic approach, the environmental impact of a product or a system throughout its life cycle.

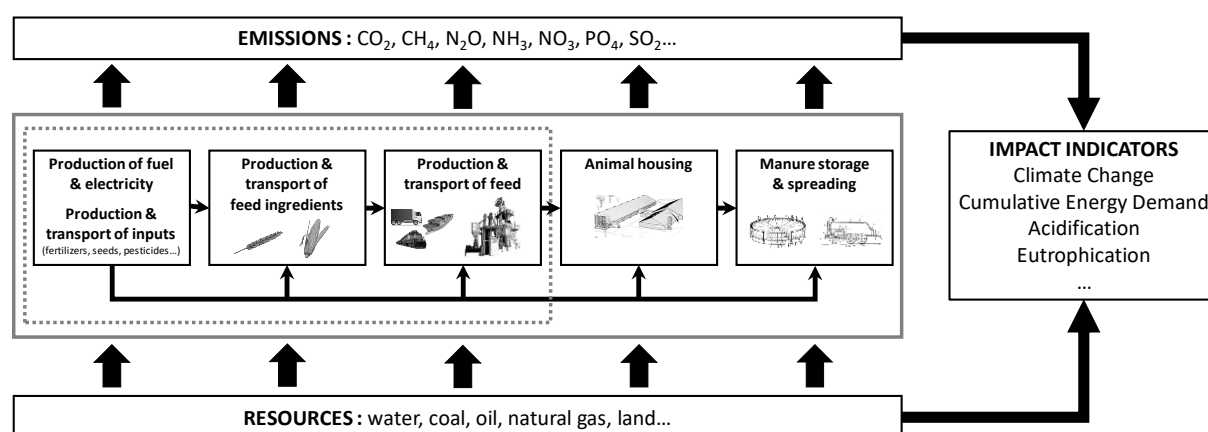


Figure 1 System boundaries for the environmental assessment of feed and poultry production (dotted and full grey lines respectively) using life cycle assessment. For each stage of the production process, all the resources consumed and the compounds emitted into the environment are considered in order to calculate environmental impact indicators.

To perform a LCA, the first step is to define the goal and scope of the studied system by determining its boundaries and the function of the product/system. In the case of feed production, all the stages, from the production of inputs (fuel, electricity, seeds, fertilizers...) for the production of feed ingredients until their processing in the feed mill and the transport of concentrated feed to the poultry farm, have to be considered (Figure 1). When focusing on the environmental impacts of poultry production, the rearing of animals in the farm and manure emissions will also be taken into account in the LCA (Figure 1). The second step is the inventory analysis, during which, all the resources consumptions and the emissions to the environment are listed (using enquiries, database, models, expertise...). The last step is the aggregation of the resources use and emissions into impact categories for environmental impacts such as

climate change or eutrophication (Figure 1). Depending on the function of the product/system considered in step 1, the results will be expressed using a specific functional unit. In the case of poultry production, the functional units to be considered would be the ton of feed and the ton of live weight (or eggs) for concentrated feed and poultry productions, respectively.

WILFART *et al.* (2016) proposed a consistent database for LCA impacts of feed ingredients used in animal nutrition in France (ECOALIM database). According to the authors, LCA impacts vary greatly according to the category of feed ingredients considered. For instance, vegetal fats or crystalline AA have the largest climate change (CC) impacts per ton of ingredient whereas cereals grains, oil seeds and proteins crops have the lowest impacts (Table 2). The variability observed among and within feed ingredient categories is mostly due to the production process of the feed ingredient (for crops: fertilizers, pesticides; for industrial products such as vitamins or AA: energy input) and/or to the economic allocation of impacts such as in cereals coproducts (*i.e.* coproducts are generally cheaper than the primary products, and produced in smaller volumes). For instance, WILFART *et al.* (2016) showed that acidification (AC) and eutrophication (EU) impacts for conventional wheat grain (*i.e.* with mineral fertilization) are about 15% higher than wheat grain produced with a systematic organic fertilization (data not shown), due to lower ammonia emission and nitrate leaching in the field.

Table 2 Variability of environmental impacts (per ton of feed ingredient) assessed using life cycle assessment for different feed ingredient categories. CC: Climate Change; CED: Cumulative Energy Demand; AC: Acidification; EU: Eutrophication.

Feed ingredient category	CC (kg CO ₂ -eq)	CED (GJ)	AC (kg SO ₂ -eq)	EU (kg PO ₄ -eq)
Cereals*	493 ± 207	24 ± 5	1818 ± 628	42 ± 14
Cereals coproducts*	583 ± 533	25 ± 22	954 ± 709	46 ± 45
Oil seeds and protein crops*	484 ± 438	26 ± 6	3103 ± 1177	24 ± 27
Oil meals*	769 ± 832	21 ± 8	2283 ± 1058	24 ± 8
Vegetal fats*	2334 ± 1727	52 ± 20	4972 ± 2343	78 ± 56
Animal coproducts*	557 ± 641	13 ± 13	800 ± 1331	46 ± 63
Insects (fresh and meals) ^{†, ‡}	2205 ± 1317	52 ± 60	17 ± 13	10 ± 7
Algae and duckweed [†]	1810 ± 683			
Yeast and bacteria meals [†]	1285 ± 290			
Minerals*	967 ± 900	14 ± 15	175 ± 205	23 ± 41
Crystalline amino acids*	11021 ± 6101	284 ± 144	2510 ± 1758	311 ± 210

* ECOALIM French database (WILFART *et al.*, 2016); [†] TALLENTIRE *et al.*, 2018; [‡] OONINCX and DE BOER, 2012; THÉVENOT *et al.*, 2018; VAN ZANTEN *et al.*, 2015.

The LCA impacts of new feed ingredients such as insects (fresh or meal), aquatic biomass (algae, duckweed) and single cell protein sources (yeast and bacteria meals) have also been studied, although few data are available in the literature (Table 2). In Europe, such feed ingredients are considered as alternatives to replace imported soybean meal, but further work is still required to conclude on their environmental benefits as environmental impacts are found to be either lower (*e.g.* TALLENTIRE *et al.*, 2018) or higher (THÉVENOT *et al.*, 2018) than those of soybean meal. Furthermore, as stressed out for insect production by THÉVENOT *et al.* (2018) and VAN ZANTEN *et al.* (2015), production processes are still in development. Large improvements are thus possible to decrease the impacts of these new ingredients. In

particular, in the European Union, authorizing the use of bio-waste (manure or household waste) should be considered to produce insects in a more sustainable way.

Finally, the incorporation rate of the feed ingredient in the diet must also be considered. By doing so, the LCA impacts per ton of ingredient can be put into perspective. For instance, in the study by TALLENTIRE *et al.* (2017), crystalline AA impacts are generally 10 times higher (or more) than the impacts of most of the other feed ingredients (cereal grains and coproducts, oil meals...). However, as the total incorporation rate of synthetic AA in broilers feeds is very low (<1%), they only contribute to less than 10% of the final impacts of the feed, whereas cereals + soybean meal contribute to 10 to 70%. Similar results were found in the studies of GARCIA-LAUNAY *et al.* (2018) and WILFART *et al.* (2018).

Feed formulation with environmental criteria

LCA impacts of feed ingredients can be easily integrated as new criteria in formulation matrices to calculated environmental impacts of the formulated diet. Maximal constraints on impacts can be set to limit the environmental impacts (*e.g.* defining a maximal CC impact per ton of feed). If the objective is to reduce substantially one impact, linear programming is adapted to perform a “least-impact” formulation rather than the classical “least-cost” one. Yet, this approach has been shown by several authors to increase feed price, sometimes up to +30%, and to cause pollution swapping among impacts (NGUYEN *et al.*, 2012; TALLENTIRE *et al.*, 2017). For instance, when formulating a UK broiler diet using a “least-CC” approach, TALLENTIRE *et al.* (2017) managed to decrease CC impact per ton of feed by about 35% but with an increase by about 15 and 30% in price and the use of non-renewable energy, respectively.

In order to avoid (or limit) pollution swapping among impacts while controlling the increase in feed price, GARCIA-LAUNAY *et al.* (2018) proposed a method called “multi-objective formulation” (MOF) that takes simultaneously into account feed price and several environmental impacts. MOF is based on linear programming as “least-cost” formulation (LCF). The objective function to be minimized (*min MO*) includes here both a price and an environmental component, with a weighting factor α ($0 \leq \alpha \leq 1$) to set the weight of the environmental component. When $\alpha = 0$, MOF is similar to LCF, while when $\alpha = 1$, feed price is no longer considered in formulation. Four LCA impacts are considered in the environmental component of the objective function: climate change (CC), non-renewable energy use (NREU), land occupation (LO) and phosphorus demand (PD). Impacts are normalized by the impacts of feed formulated with LCF, and the relative weight of each LCA impact can be set using the β coefficients. For instance, GARCIA-LAUNAY *et al.* (2018) chose to give more weight to climate change ($\beta_{CC} = 0.4$) compared to the other β s (0.2). Finally, acidification and eutrophication (AC and EU) impacts are indirectly considered by setting a maximal constraint so that these impacts cannot exceed 105% of LCF feed impacts. The best compromise between environmental impact reduction and price increase can be identified when the marginal decrease in the environmental impact becomes lower than the marginal increase in the price ($\alpha = \alpha_{lim}$).

$$\min MO = (1 - \alpha) \times \left(\frac{Cost_{MOF}}{Cost_{LCF}} \right) + \alpha \times \left(\beta_{CC} \frac{CC_{MOF}}{CC_{LCF}} + \beta_{NREU} \frac{NREU_{MOF}}{NREU_{LCF}} + \beta_{LO} \frac{LO_{MOF}}{LO_{LCF}} + \beta_{PD} \frac{PD_{MOF}}{PD_{LCF}} \right)$$

with $\beta_{CC} + \beta_{NREU} + \beta_{LO} + \beta_{PD} = 1$.

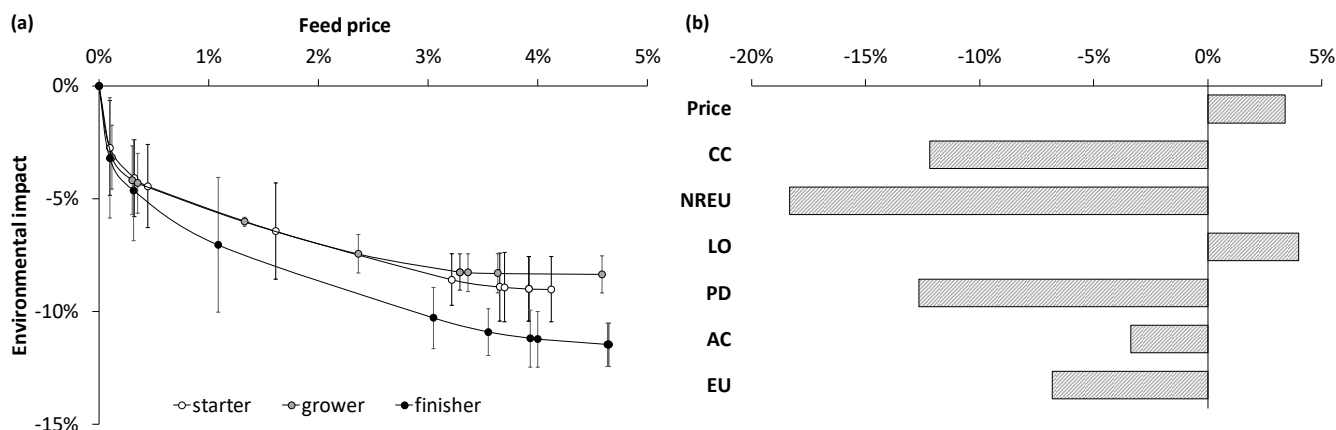


Figure 2 a) Variations of price and environmental impacts for broiler feeds using multiobjective formulation (α from 0 to 1 with a step of 0.1), compared to least-cost formulation. b) Variations of price and environmental impacts for an average broiler feed (starter 6%; grower 20%; finisher 74%) using multiobjective formulation ($\alpha = \alpha_{lim}$) compared to least-cost formulation (CC: climate change; NREU: non-renewable energy use; LO: land occupation; PD: phosphorus demand; AC: acidification; EU; eutrophication). (adapted from GARCIA-LAUNAY *et al.*, 2018)

Using this approach, GARCIA-LAUNAY *et al.* (2018) showed that, in broilers, a substantial reduction in environmental impact of feed is achievable for an increase in feed price below 5% (Figure 2a). In particular, at $\alpha = \alpha_{lim}$, five of the six considered LCA environmental impacts could be decreased: NREU (-18%), PD (-17%), CC (-12%), EU (-7%) and AC (-3%), while LO and feed price were increased by 4 and 3% respectively per ton of average feed (Figure 2b). This improvement in the environmental impact of broiler feed was possible with several changes in the feed composition. For instance, in finishing broiler, maize coproducts and protein seeds (8 and 4% in LCF feed) were totally removed in MOF feed, while wheat coproducts were increased up to 12% (0% in LCF feed). In the same time, cereals were decreased by 11 percentage points while oil meals were increased by 6 percentage points (GARCIA-LAUNAY *et al.*, 2018; data not shown).

Finally, it is essential to remind that the actual reduction in the environmental impacts of feed will greatly depend on the price, the availability and the origin of feed ingredients. For instance, TALLENTIRE *et al.* (2017) showed that the CC impact of broiler feed produced in the UK could be three times higher in the USA. This can be explained by the use, in the UK diet, of soybean from South America with a CC impact almost 8 times higher than the US one (3.1 and 0.4 kg CO₂-eq/kg respectively), in relation with the recent land use change for the cultivation of soybean in South America (mainly deforestation releasing carbon from large carbon sinks).

Getting the big picture: assessing the consequences of feeding strategies on environmental sustainability of poultry production

As previously mentioned, LCA is one of the most adequate method to assess the environmental sustainability of poultry production “at farm gate”, and many studies can be found in the literature, mostly focusing on broiler and egg productions. In these studies, regardless of the species or the production system (conventional, organic...), feed production stage is described as the main contributor to several environmental impacts expressed per kg of product. In particular, the contribution of feed production to climate change and energy use represents about 60-75% of the total impact (Figure 3). Feed production also significantly contributes to eutrophication (35-60%; Figure 3) and in a lesser extent to acidification (<30%; Figure 3), because of the major contribution of NH₃ emissions from manure to this impact.

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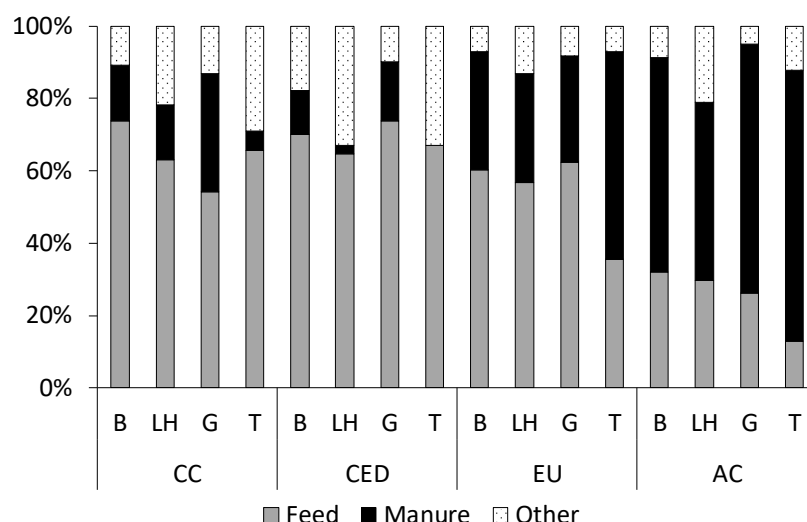


Figure 3 Average contribution of feed production and manure emissions to environmental impacts per kg of product at farm gate for different poultry productions (CC: Climate Change; CED: Cumulative Energy Demand; EU: Eutrophication; AC: Acidification). Broiler (B): PRUDÊNCIO DA SILVA *et al.* (2014); LEINONEN *et al.* (2012a); PELLETIER (2008). Laying hen (LH): LEINONEN *et al.* (2012b); DEKKER *et al.* (2011); MOLLENHORST *et al.* (2006). Goose “foie gras” (G): ARROYO *et al.* (2013). Turkey (T): LEINONEN *et al.* (2014).

Given the significant contribution of feed production to environmental impacts of poultry production, different feeding strategies in poultry have been assessed in the literature using LCA at farm gate (*i.e.* impacts per kg of live weight, kg of edible carcass, kg of egg...), especially in fast-growing broiler (Table 3). The study of KEBREAB *et al.* (2016) perfectly illustrates the environmental benefits that were obtained in Europe in the past with the use of crystalline AA in broiler diets. This led to an important decrease in dietary CP content (-80 g/kg on average from a diet without any AA supplementation to a diet using lysine, methionine and threonine + phytase) and an improvement of feed conversion ratio (1.85 vs 2.01 in the “reference” scenario). This strategy reduced significantly N intake (-38% per kg of body weight gain) and consequently, N excretion and N emissions (about -55% per kg of body weight gain; recalculated using data available in the study). Therefore, EU and AC impacts were decreased by about 50% (Table 3). In the diets supplemented with crystalline AA, soybean meal use was decreased by about -50%, leading to a reduction of 44% of CC impact (Table 3), because of soybean meal was considered to be imported from South America. The studies of LEINONEN and WILLIAMS (2015) and MÉDA *et al.* (2017) showed that in « actual » diets, CP reduction is still a relevant tool to reduce the environmental impacts in poultry, especially CC, EU and AC impacts but to a lesser extent compared to the “historical” initial situation described by KEBREAB *et al.* (2016) with very high dietary CP contents.

Other European studies focused on the partial or total substitution of one or several feed ingredients in the diet. For instance, DEKKER *et al.* (2013) showed that in the Netherlands, replacing several imported feed ingredients (wheat, sunflower and soybean meals...) by Dutch ones, the CC impact and energy use of organic egg production could be decreased by 9% and 21%, respectively. Similarly, the substitution of maize and soybean meal, by sorghum and other protein sources respectively, was found to be very efficient to decrease environmental impact in geese “fois gras” production and slow-growing chicken, respectively (ARROYO *et al.*, 2013; MÉDA *et al.*, 2017). Concerning the use of insects, TALLENTIRE *et al.* (2018) concluded that using insect meal could be promising to significantly decrease CC impact in broilers, because

of a lower CC impact per ton of meal compared to soybean meal. Yet, further research on insects is required, as other authors found opposite results (*e.g.* THÉVENOT *et al.*, 2018).

Finally, the environmental benefits of using multiobjective formulation taking into account feed price and impacts (MOF; GARCIA-LAUNAY *et al.*, 2018) are confirmed when the final environmental impacts of broiler production at farm gate are considered. WILFART *et al.* (2018) indeed found that, in conventional broiler, MOF could decrease CC impact and energy use per ton of broiler by 12 and 14% respectively (Table 3).

Table 3 Potential reductions in the environmental impacts at farm gate for different poultry production systems in Europe using various feeding strategies. Reductions are expressed comparatively to the “reference” system considered in each study (CC: Climate Change; CED: Cumulative Energy Demand; EU: Eutrophication; AC: Acidification).

Production	Feeding strategy	CC	CED	EU	AC	Reference
Standard broiler	Inclusion of crystalline amino acids (+ phytase)	-44%	-6%	-50%	-50%	KEBREAB <i>et al.</i> (2016)
Standard broiler	Crude protein reduction (-5 to -20 g/kg) + protease	-2%		-3%	-5%	LEINONEN and WILLIAMS (2015)
Standard broiler	Crude protein reduction in finisher period (-30 g/kg)	-8%	-1%*	-7%	-5%	MÉDA <i>et al.</i> (2017)
Standard broiler	Multiobjective formulation accounting for cost and impacts	-12%	-14%*	-5%	-2%	WILFART <i>et al.</i> (2018)
Free range broiler	Soy-free diets	-41%	+5%	0%		MÉDA <i>et al.</i> (2015)
Goose “foie gras”	Total substitution of maize by sorghum	-17%	-23%	0%	-12%	ARROYO <i>et al.</i> (2013)
Organic egg	Substitution of imported feed ingredients by Dutch ones	-9%	-21%		-1%	DEKKER <i>et al.</i> (2013)

* Non-renewable energy only

Conclusions

Designing new feeding strategies to improve the environmental sustainability of poultry production is crucial as poultry products are expected to be more and more consumed in the next decades. In particular, nutritionists should continue their efforts in adjusting nutrient supply to the requirements of the animals, through a better knowledge of these requirements, the use of feed additives (amino acids, enzymes), and the development of new formulation systems (*e.g.* to consider interactions between nutrients or diet components). The environmental impacts associated to the production, transport and processing of feed ingredients should also be taken into account using life cycle assessment. To consider all these aspects, modelling tools are required to design and evaluate feeding strategies at different scales (animal, farm, life cycle) both on economic and environmental criteria.

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