Reducing environmental impacts of feed using multiobjective formulation: What benefits at the farm gate for pig and broiler production?

Bertrand Méda, Florence Garcia, Léonie Dusart, P. Ponchant, S. Espagnol, Aurélie Wilfart

Animal 15 (2021) 100024

Contents lists available at ScienceDirect

Animal

The international journal of animal biosciences

Reducing environmental impacts of feed using multiobjective formulation: What benefits at the farm gate for pig and broiler production?

B. Méda [a,*], F. Garcia-Launay [b], L. Dusart [c], P. Ponchant [c], S. Espagnol [d], A. Wilfart [e]

[a] INRAE, Université de Tours, BOA, 37380 Nouzilly, France
[b] PEGASE, INRAE, Institut Agro, 35590 Saint-Gilles, France
[c] ITAVI, 37380 Nouzilly, France
[d] IFIP, Institut du porc, BP 35104, 35651 Le Rheu, France
[e] Institut Agro, INRAE, SAS, 35042 Rennes, France

A R T I C L E I N F O

Article history:
Received 9 August 2019
Received in revised form 7 July 2020
Accepted 10 July 2020
Available online 24 December 2020

Keywords:
Feeding strategy
Feedstuff
Life cycle assessment
Livestock
Sustainability

A B S T R A C T

Feed production is the main contributor to several environmental impacts of livestock. To decrease environmental impacts of feed, those of feedstuffs should be considered during formulation. In particular, multiobjective feed formulation (**MOF**) can help reduce several environmental impacts simultaneously while keeping any increase in feed price moderate. The objective of this study was to assess environmental benefits of MOF at the farm gate for fattening pigs and broilers. For pigs, three feeding strategies were tested: classic 2-phase (**2P**), 2-phase with lower net energy content (**2P−**), and multiphase (**MP**). For broilers, two strategies were tested: classic 3-phase (**3P**) and 3-phase with higher digestible amino acid contents and lower metabolisable energy content (**3P+**). Diets were formulated using both least-cost formulation (**LCF**) and MOF, yielding six pig scenarios and four broiler scenarios. Environmental impacts at the farm gate were estimated using a modelling approach based on life cycle assessment. Indicators for six impact categories were then calculated: climate change (**CC**), cumulative non-renewable energy demand (**CEDNR**), acidification (**AC**), eutrophication (**EU**), land occupation (**LO**), and phosphorus demand (**PD**). As expected, MOF had lower farm-gate impacts than LCF (as much as −13%), but the degree of decrease varied by feeding strategy and impact. For pigs, MOF was equally effective in all strategies at reducing PD (−6 to −9%) and AC (−2%). In contrast, MOF was more effective in 2P and 2P− at decreasing CC (−5% to −7%), LO (−9% to −13%) and EU (−6% to −8%) than in MP (CC: −2%; LO: −4%; EU: −3%). The benefit of MOF was found greater in 2P (−7%) than in other pig strategies for CEDNR (−3 to +0%). For broilers, MOF was equally effective in both strategies tested at decreasing PD (−12%), AC (−2%), and EU (−4%). For CC and CEDNR, MOF was more effective in 3P (CC: −9%; CEDNR: −11%) than 3P+ (−6% for both impacts), but not for LO (+3% in 3P vs −1% in 3P+). These differences were due mainly to differences in animal performance (especially feed conversion ratio) among the strategies tested. Finally, in all scenarios, gross margin at the farm gate decreased with MOF comparatively to LCF (pigs: −3% to −11%); broilers: −7% to −11%). These results demonstrate the importance of comprehensive economic and environmental optimisation of feeding strategies by simultaneously considering feed impacts, animal performance, and manure management. To do so, further research is therefore required to develop new modelling tools.

Implications

Multiobjective feed formulation is a relevant method to decrease environmental impacts of feed production. This study investigated consequences at the farm gate of applying this method to different feeding strategies for pig and broiler production systems using a life cycle approach. Results confirmed that multiobjective feed formulation is relevant for decreasing environmental impacts at the farm gate; however, its mitigation potential may vary according to feeding strategy. Therefore, a comprehensive optimisation of feeding strategy and feed composition that considers feed impacts, animal response, and manure emissions is recommended.

Introduction

In the European Union, since the beginning of the 1990s and the Nitrates Directive (91/676/CEE), monogastric livestock producers have

* Corresponding author:
E-mail address: bertrand.meda@inrae.fr (B. Méda).

https://doi.org/10.1016/j.animal.2020.100024

made large efforts to decrease their environmental impacts by focusing mostly on nitrogen excretion and/or ammonia emissions. They have decreased impacts by i) improving animal performance (Zuidhof et al., 2014; Millet et al., 2017), ii) increasing the number of phases to better meet animal requirements and/or decreasing dietary crude-protein content using feed-grade amino acids (Pomar et al., 2014; Belloir et al., 2017), and iii) improving manure management (Loyon et al., 2016).

However, these approaches focused generally on a specific part of the production system and/or one or two impacts, which can make identification of pollution swapping difficult. This phenomenon occurs when a mitigation option introduced to reduce one impact results in the increase of another impact (*e.g.* increasing eutrophication (**EU**) while decreasing climate change [**CC**]). To overcome these limits, Life Cycle Assessment (**LCA**) has been used to assess environmental impacts of pig and poultry production systems since the beginning of the 2000s (de Vries and de Boer, 2010). Life Cycle Assessment is a multicriterion method that estimates multiple potential environmental impacts of products or services throughout their life cycles, from raw material acquisition to production, use, and disposal/recycling, at global and regional scales (van der Werf and Petit, 2002). Using this comprehensive method, feed production has been estimated to contribute the majority of environmental impacts of monogastric livestock production: 50–85% of CC impact, 64–97% of EU potential, 70–96% of energy use, and nearly 100% of land occupation (**LO**) (Garcia-Launay et al., 2018). Nevertheless, environmental impacts of feedstuffs used in animal diets can vary greatly (*e.g.* 0.24 and 1.34 kg CO_2-eq/kg for CC impact of French sunflower meal and average Brazilian soya bean meal, respectively) (Wilfart et al., 2016).

To decrease impacts of feed production and consequently of livestock production, it is thus important to address this variability when formulating animal diets. Several researchers have developed methods that consider environmental impacts during feed formulation, but with possible large increase in feed cost (Nguyen et al., 2012; Mackenzie et al., 2016). In contrast, multiobjective feed formulation (**MOF**), developed by Garcia-Launay et al. (2018), can simultaneously decrease four environmental impacts (CC, energy use, land use, phosphorus demand [**PD**]) while limiting the increase in feed cost. Using MOF, it is expected that decreasing feed impacts will result in substantial decreases in impacts of livestock production.

In both pig and broiler production, acidification (**AC**) and EU impacts are driven mainly by the degree to which nitrogen and/or phosphorus supply exceeds animal requirements (Cadéro et al., 2018a; Méda et al., 2019). But impacts on CC, LO, and cumulative energy demand at the farm gate are driven mainly by the impacts related to feed production (*i.e.* production/transport of feedstuffs, transformation processes in the feed mill, feed transport to the farm) (Garcia-Launay et al., 2014; Méda et al., 2019). Consequently, MOF has great potential to mitigate these last three impacts at farm gates. However, the benefits of MOF could potentially be limited if the feeding strategy impairs animal performance (*e.g.* increased conversion ratio).

Therefore, the objective of this study was to investigate the environmental benefits (at the farm gate) of MOF with a modelling approach based on life cycle assessment. This approach was applied to French conventional pig and broiler production systems for various feeding strategies, either i) 'classic' or ii) 'alternative' ones (number of phases, changes in nutritional levels).

Material and methods

Goal and scope definition

Life Cycle Assessments of pig and broiler production systems were conducted from cradle to farm gate for a 1-year period. System boundaries included production and transport of i) inputs used to produce feedstuffs, ii) off-farm concentrated feeds, and iii) either day-old chicks or piglets at the entry of the fattening unit. On-farm emissions related to animals and manure production and storage were included, but not those associated with the fate of manure during/after spreading (*e.g.* phosphorus runoff) as recommended by Koch and Salou (2015). Direct consumption of water and energy, and impacts associated with buildings for animal production, were also included (Fig. 1).

For both broiler and pig production, the functional unit was one tonne of live weight (**LW**) at the farm gate. The impact categories considered were those selected in the ECOALIM project (Wilfart et al., 2016; Garcia-Launay et al., 2018): CC, EU, AC, LO, cumulative non-renewable energy demand (**CEDNR**), and PD. Phosphorus demand was included to account for the non-renewable phosphorus resource incorporated in fertilisers and feeds.

Description of reference pig and broiler production systems

For pig production, fattened pigs were assumed to be produced on a typical farrow-to-finish farm with 260 sows in Brittany (western France). Gilts are produced on farm. All animals on the farm are reared in confined housing on a fully slatted floor and produce slurry. In all scenarios, pigs are fattened until they reach 117 kg LW. The slurry is stored in the housing, while animals are present and then evacuated to an uncovered outdoor storage pit (Table 1).

For broiler production, conventional production of fast-growing broilers in the Pays-de-la-Loire region (western France) was assumed. In all scenarios, birds are reared on straw bedding at an initial density of 23.4 birds/m^2 until they reach 1.83 kg LW (Table 1).

For both production systems, the feed mill producing and delivering the feed to the farm was assumed to be located 50 km away, and the hatchery producing day-old chicks was considered to be 200 km away (Table 1).

Feeding strategies

For pig production, feeds for sows and post-weaning piglets were identical in all scenarios (Supplementary Table S1). Only differences in feeding strategies for fattening pigs (group feeding) were considered here, as this period represents more than 70% of total feed consumption on the farm (recalculated from Dourmad et al., 2014). Three feeding strategies were tested:

- Classic 2-phase strategy (2P) with a maximum feed allowance of 2.6 kg/pig/day (Cadéro et al., 2018c). Pigs are fed with the first phase diet ('grower') until they reach 65 kg where they are fed with the second phase diet ('finisher') until slaughter.
- 2-phase strategy with lower net energy (**NE**) content and no feed restriction (*ad libitum*) (2P−). The hypothesis investigated was that lower NE content (93% of 2P level *i.e.* −0.7 MJ/kg) decreased environmental impacts of pig feeds enough to compensate for lower animal performance.
- Multiphase strategy (**MP**) with a maximum feed allowance of 2.6 kg/pig/day. It consists of 10 successive diets composed of four concentrated diets blended in different proportions to capture the evolution of nutritional requirements. Each blend is provided to pigs according to their LW with a range of 10 kg of LW (*i.e.* Phase 1 from 30 to 40 kg, Phase 2 from 40 to 50 kg…; Supplementary Table S2). This strategy is designed so that nutrient supply meets pig requirements more closely than that in 2P, to reduce on-farm nitrogen gas emissions.

For broiler production, the feeding strategies tested were applied to the entire rearing period with three successive diets ('starter': 1–9 days of age; 'grower': 10–19 days of age; 'finisher': from 20 days of age until slaughter) distributed *ad libitum*. Two strategies were tested:

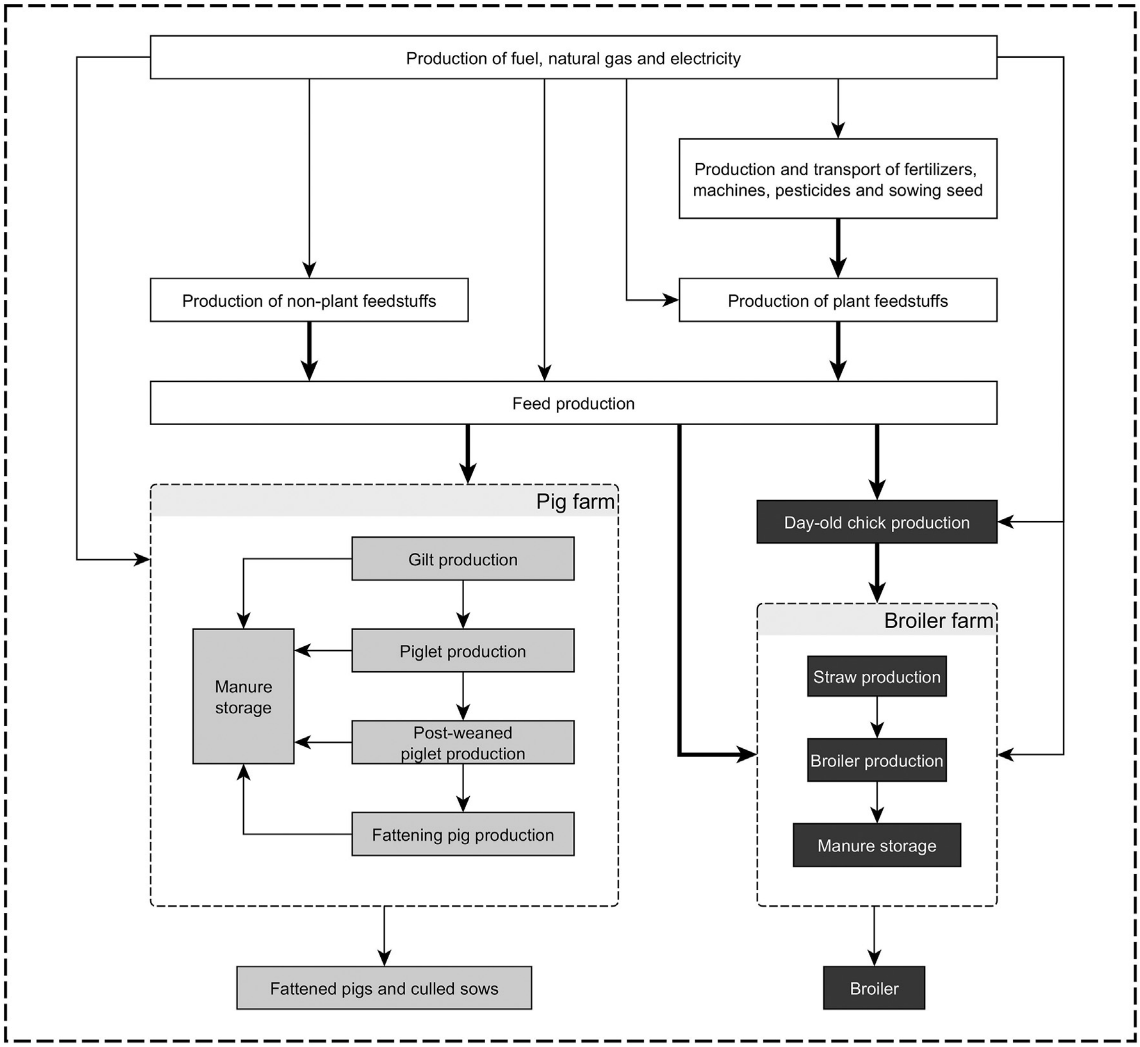

Fig. 1. Diagram of processes and flows for the production of 1 t of live weight at the pig or broiler farm gate within the life cycle assessment boundaries. White boxes: processes common to pig and broiler production; Grey boxes: processes related to pig production; Black boxes: processes related to broiler production; Bold arrows: flow with transport.

Table 1
Characteristics of pig and broiler production systems considered in the study.

Production system	Pig	Broiler
Animals		
Number of sows	260	–
Animal density (birds/m^2)	–	23.4
Breed	(LW × LR) × (LW × PP)[1]	Ross PM3
Slaughter weight (kg)	117	1.83
Housing		
Housing area (m^2)	5200	2 × 1300
Floor type	Fully slatted floor	Straw bedding (4.5 kg/m^2/batch)
Manure management	Slurry pit under pigs + external uncovered storage	Solid manure under broiler + external uncovered storage
Distance from farm (km)		
Feed mill	50	50
Hatchery	–	200

[1] LW: large White; LR: landrace; PP: pietrain.

- Classic 3-phase strategy (3P) with average nutritional levels currently used by French poultry feed producers.
- 3-phase strategy diet with higher digestible amino acid contents (+1.5 g/kg of digestible lysine and other amino acids adjusted to the same profile as in 3P) and lower metabolisable energy (**ME**) content, comparatively to 3P (−0.2 MJ/kg). This strategy (3P+), commonly used in Northern Europe (Dusart, pers. comm.), is designed to improve feed conversion ratio (**FCR**) and growth rate.

Feed formulation

For a given feeding strategy, each diet was formulated using linear programing with either classic least-cost formulation (**LCF**) or MOF as described by Garcia-Launay et al. (2018), resulting in six pig scenarios and four broiler scenarios. Briefly, MOF considers both the cost and environmental impacts (estimated by LCA) of feedstuffs (Eq. (1)). First, LCF provides a baseline for feed cost and potential impacts per kg of feed. Next, the minimised multiobjective function (*min MO*) includes normalised values of feed cost (*Cost*) and the four global LCA impacts (PD, CC, CEDNR, and LO) using LCF values as references (*ref*). Moreover, to prevent pollution swapping among impacts, maximal constraints on the six impact categories (including the local ones, EU and AC) were added, so that feed impacts using MOF could not exceed 105% of their reference values (*i.e.* using LCF). Two additional factors are considered in the multiobjective function: i) the relative influence of economic and environmental objectives (α) and ii) the weight of each environmental impact considered (β). Factor α ranges from 0 (equivalent to LCF) to 1 (price not considered in the objective function). In this study, a specific $\alpha = \alpha_{lim}$ was considered, defined as the point at which the marginal decrease in LCA impacts becomes lower than the marginal increase in feed cost. This α_{lim} value is considered as the best compromise between the decrease of feed impacts and the increase of feed cost as demonstrated by Garcia-Launay et al. (2018). The sum of the β factors of the four LCA impacts considered in MOF must equal 1. β_{PD}, β_{CEDNR}, and β_{LO} were set to 0.2, while β_{CC} was set to 0.4 because CC was considered as a top-priority issue (Gerber et al., 2013; Paris Agreement, 2015).

$$\min MO = (1-\alpha) \times \left(\frac{Cost}{Cost^{ref}}\right) + \alpha \times \left(\beta_{PD}\frac{LCA_{PD}}{LCA_{PD}^{ref}} + \beta_{CC}\frac{LCA_{CC}}{LCA_{CC}^{ref}} + \beta_{NRE}\frac{LCA_{CEDNR}}{LCA_{CEDNR}^{ref}} + \beta_{LO}\frac{LCA_{LO}}{LCA_{LO}^{ref}}\right) \quad (1)$$

Nutritional characteristics of feedstuffs were those of Sauvant et al. (2004). Life Cycle Assessment impacts of feedstuffs used in the diets are described in Supplementary Table S3. They included impacts of production of feedstuffs (ECOALIM database: Wilfart et al., 2016) and road transport to the feed mill in western France (oilseed meals: 100 km; protein crops and oilseeds: 300 km; other feedstuffs: 500 km; Garcia-Launay et al., 2018). Each diet (*i.e.* one phase among a given feeding strategy) was formulated in the same four price contexts considered by Garcia-Launay et al. (2018) (September 2011, June 2012, August 2013, and February 2014; Supplementary Table S4). The price series were selected by experts of the French feed sector for their representativeness of various economic contexts on the French market, taking into account the possible large price variations among feedstuffs (*e.g.* soybean meal to maize ratio varying between 1.5 and 3.The feedstuff compositions of the four formulated diets were then averaged to provide an average diet for the 2011–2014 period. The nutritional characteristics of this average diet were then recalculated.

Constraints on feedstuff incorporation rates were those of Garcia-Launay et al. (2018). For 2P and 3P strategies, nutritional constraints were those of Garcia-Launay et al. (2018), except for minimum content of available P that was updated for pig feeds (IFIP, 2019). For 2P−, minimum NE content equalled 93% of that of 2P with the same digestible lysine (**dLys**):NE ratio. In contrast, MP had the same minimum NE content as 2P (9.5 MJ/kg) but a different dLys:NE ratio. For 3P+, ME content was reduced by 0.2 MJ/kg, whereas dLys was increased by 1.5 g/kg. For all feeding strategies, specific ideal amino acid profiles for pigs and broilers were considered so that all amino acid contents were adjusted directly when dLys content was changed. All constraints for nutritional characteristics and feedstuff incorporation rates are given in Supplementary Tables S5 for pigs and S6 for broilers.

Life cycle inventory

Animal performance

For pig production, performances of gestating-lactating sows and post-weaning piglets were taken from French technical references and considered identical in all scenarios (Supplementary Table S7). Nitrogen and phosphorus excretions of sows and post-weaning piglets were calculated using the mass-balance approach of BRSPorc (CORPEN, 2003), which considers nitrogen and phosphorus intakes and body retentions. Animal performance (growth, feed intake) and nitrogen and phosphorus excretions of finishing pigs were simulated using nutritional characteristics of the formulated diets and the model of Cadéro et al. (2018b). This individual-based model simulates variability in responses of pigs in a batch in a pig-fattening unit. With this model, nitrogen and phosphorus excretions were calculated as intake minus body retention. Mortality rate during the fattening period was assumed to remain constant (3.7%) in all scenarios.

For broiler production, mortality rate and average slaughter weight were assumed to remain constant (4.2% and 1.83 kg, respectively) in all scenarios. As nutritional values of diets formulated with LCF or MOF were very similar or identical, the same slaughtering age was assumed for a given feeding strategy (3P or 3P+). However, based on expert knowledge (nutritionists in the poultry sector), we considered that slaughtering age and FCR were decreased in the 3P+ comparatively to 3P (34 vs 36d and 1.65 vs 1.73, respectively). Nitrogen and phosphorus excretion was estimated as intake minus body retention, using constant values of 29 g N/kg LW (ITAVI, 2013) and 4.6 g P/kg LW (CORPEN, 2006).

Emissions from enteric fermentation and manure

Greenhouse gas emissions (methane (CH_4), nitrous oxide (N_2O)) associated with manure production (housing + storage) from both types of production were estimated using IPCC Tier 2 equations (2006), as was CH_4 emission from enteric fermentation in pigs. For ammonia (NH_3) and nitrogen oxides (NO_x), emissions were estimated using calculated nitrogen excretion and emission factors from EMEP (2013). In pig, it was possible to calculate urinary N and fecal N using N digestibility, CP and amino acid contents of the feed and growth performance, according to the principles of the InraPorc® model (van Milgen et al., 2008). Urinary N was then used as a proxy of total ammoniacal nitrogen (**TAN**) to apply the EMEP (2013) emission factors. In broiler solid manure, TAN was considered to represent 70% of total N excretion as recommended by EMEP (2013).

Background data

Data for energy and water consumption of the feed mill were taken from Gac et al. (2010) (Supplementary Table S8). Values of on-farm consumption of water and energy are given in Supplementary Table S9. Inventories for energy and tap water production and transport came from attributional life cycle inventories in the ecoinvent database (v. 3.1) (Wernet et al., 2016). Inventories for the production of day-old chicks and for construction of animal houses were taken from the Agribalyse® database (Koch and Salou, 2015).

Environmental impact assessment

For the six impact categories chosen (CC, EU, AC, LO, CEDNR, and PD), impacts were estimated according to the International Reference Life Cycle Data System (ILCD method) for CC and AC (JRC, 2012), Centre for Environmental Studies (CML) for EU and LO (implemented in SimaPro® v. 8.0.5.13), CED 1.08 method (implemented in SimaPro® v. 8.0.5.13) for CEDNR and Wilfart et al. (2016) for PD. Impacts per tonne of LW were expressed in kg CO_2-eq for CC, mol H^+-eq for AC, kg PO_4^{3-} for EU, m^2.year for LO, MJ for CEDNR, and kg P for PD. Impacts were calculated using SimaPro® software v. 8.0.5.13 (PRé Consultants, 2020, Amersfoort, The Netherlands) for broiler production, and using the model from Cadéro et al. (2018b) for pig production.

Economic assessment

For each scenario, an average feed price (€/t) based on the consumption and price of each diet was calculated. Using this average feed price, animal performance, (growth, feed intake), and other economic references, an economic indicator at the farm gate was calculated for each scenario (gross margin, €/t LW; Supplementary Table S10). For pigs, only the gross margin of the fattening unit was considered.

Results

Formulated diets

The feedstuff composition of the '2011–2014' average diets for each feeding strategy and formulation method is given in Table 2 for broilers and in Table 3 for pigs. Full nutritional characteristics of these diets are given in Supplementary Tables S11 for broiler and S12 for pigs. In general, compared to using LCF, using MOF did not change the number of feedstuffs in the diets, except for pigs in 2P− strategy (−4 feedstuffs). Non-wheat cereal grains were replaced by wheat grain and co-products, especially middlings in pigs and feed flour in broilers. Incorporation of rapeseed meal increased by 4–8 percentage points for broilers, with a slight decrease in soya bean meal and extruded soya bean. Incorporation of rapeseed meal also increased for pigs (+1–9 percentage points), associated with a decrease in dehulled sunflower meal and an increase in protein crops, especially pea (+1–8 percentage points).

When using LCF, environmental impacts and price per tonne of feed were always higher for broilers than for pigs (Table 4). For pigs, the 7% decrease in NE content in 2P− diets compared to that in 2P diets decreased price by 3–4% and impacts by 1–18%, except for LO (+4%). Compared to the 2P strategy, the MP strategy drastically changed LO (−7%), PD (+31%) and modified price and the other impacts by 3–4%. For broilers, compared to the 3P strategy, the 3P+ strategy increased feed price (+6%), CC (+4%), LO (+5%), PD (+10%), and AC (+1%), while a decrease in CEDNR (−2%) was observed (Table 4).

Compared to LCF, MOF decreased impacts by 0–18% for pigs and broilers, except for LO in the 3P strategy (+4%), while feed price increased by 1–3% for all strategies (Table 4; Fig. 2a). For broilers, MOF decreased AC, EU, and PD in both feeding strategies to a similar degree (*ca.* 4%, 7%, and 11%, respectively). In contrast, MOF decreased CEDNR and CC more in the 3P strategy (CEDNR: −18%; CC: −12%) than in the 3P+ strategy (CEDNR: −10%; CC: −8%). MOF increased LO in the 3P strategy (+4%) but decreased it (−1%) in the 3P+ strategy (Table 4; Fig. 2a). For pigs, MOF decreased all impacts less in the MP strategy than in the 2P and 2P− strategies (Table 4; Fig. 2a). For both 2P and 2P− strategies, MOF decreased to a similar degree AC (−9%), PD (−8%), CC (−13%), and EU (−14%). Finally, MOF decreased CEDNR more in the 2P strategy (−14%) than in the 2P− one (−6%), as it did for LO (−17% in 2P− vs −13% in 2P; Table 4; Fig. 2a).

Animal performance, nutrient excretion, and gaseous emissions

For pigs, the lower dietary NE content in 2P− resulted in lower animal performance than that in 2P (Table 5). In particular, the large worsening of FCR (+0.25 points) was responsible for greater excretion of nitrogen (+11%) and phosphorus (+10%) and gas emissions from manure and enteric fermentation (NH_3: +9%; N_2O: +10%; CH_4: +23%; Table 5). The MP strategy increased FCR for LCF and MOF (+0.02 pts). However, the MP strategy decreased nitrogen excretion and emissions for both LCF and MOF by 5–8% (Table 5) and P excretion to a lower extent (−2 to −3%). More generally, using MOF instead of LCF had little effect on animal performance, excretion, or gas emissions (Table 5).

Because 3P+ diets had higher digestible amino acid contents than 3P diets, dietary crude protein in the 3P+ strategy increased by 1–2 percentage points (Supplementary Table S11). This increase in turn increased nitrogen excretion by *ca.* 14% (Table 5) and consequently NH_3 (14%) and N_2O emissions (18%). Compared to the 3P strategy, the 3P+ strategy decreased phosphorus excretion (−18%) and manure CH_4 emissions (−6%), in relation to the improved animal performance (lower slaughtering age and FCR; Table 5). Finally, compared to LCF, MOF had little effect on nutrient excretion or gas emissions in the 3P and 3P+ strategies.

Environmental and economic indicators at the farm gate

For pigs, regardless of the formulation method used, compared to the 2P strategy, the MP strategy had little effect on all impacts except

Table 2
Feedstuff composition (%) of diets formulated with least-cost (LCF) or multiobjective (MOF) formulation for two feeding strategies in broilers.

Feeding strategy	3P						3P+					
Phase	Starter		Grower		Finisher		Starter		Grower		Finisher	
Formulation method	LCF	MOF	LCF	MOF	LCF	MOF	LCF	MOF	LCF	MOF	LCF	MOF
Wheat	19.76	18.81	22.59	26.39	15.00	25.19	15.00	15.00	15.00	19.85	15.00	16.00
Maize	33.95	26.18	35.32	23.09	47.90	26.86	37.54	27.85	37.88	25.03	43.98	33.90
Triticale	0.97						0.31					
Wheat DDGS	0.91		0.87									
Wheat feed flour		9.10		9.47	0.47	10.00		10.00		10.00	0.12	7.50
Wheat middlings						1.71						1.50
Maize DDGS	4.00		6.00		7.96	0.09	1.93		4.47		1.95	0.42
Maize gluten meal	1.00	0.90	0.50	0.53		0.20	0.49		0.84		0.39	
Rapeseed	2.63	2.05	3.99	2.30	0.15	1.86	3.14	3.00	2.93	2.88	3.37	2.12
Soya bean (extruded)	2.50	2.50	2.50	2.50	3.50	2.08	2.50		2.50		3.75	
Rapeseed meal	1.00	7.95	0.50	7.70		8.14	2.59	7.00	3.55	7.12	1.78	6.21
Soya bean meal	22.88	20.11	15.62	13.97	10.44	7.62	26.79	25.92	20.19	20.62	15.69	16.22
Sunflower meal	5.56	6.00	7.13	7.08	9.00	8.74	5.14	5.13	7.27	7.50	9.00	9.00
Rapeseed oil		2.99		4.00		3.50		2.36		3.83		2.63
Palm oil					1.50	1.50					1.50	1.50
Soya bean oil	1.25		1.80		1.32		0.75		2.13		0.72	0.35
Sodium bicarbonate	0.25	0.23	0.22	0.19	0.19	0.19	0.27	0.28	0.21	0.22	0.19	0.19
Calcium carbonate	1.15	1.04	0.98	0.88	0.82	0.70	1.07	1.03	0.89	0.84	0.69	0.66
Monocalcium phosphate	0.92	0.89	0.60	0.56	0.33	0.25	0.96	0.91	0.62	0.58	0.37	0.31
Sodium chloride	0.18	0.20	0.21	0.23	0.23	0.24	0.16	0.16	0.21	0.21	0.24	0.24
DL-Methionine	0.21	0.18	0.20	0.18	0.18	0.15	0.30	0.30	0.26	0.27	0.24	0.24
L-Lysine HCl	0.33	0.31	0.39	0.36	0.41	0.38	0.41	0.41	0.42	0.41	0.40	0.40
L-Threonine	0.06	0.05	0.08	0.07	0.08	0.08	0.12	0.12	0.10	0.12	0.10	0.11
L-Valine							0.02	0.03	0.00	0.03	0.01	0.01
Premix and vitamins	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50

3P: 'classic 3-phase strategy. 3P+: 3-phase strategy with higher digestible lysine content (+1.5 g/kg) and lower metabolisable energy content (−0.2 MJ/kg).
DDGS: dried distillers grains with solubles.

Table 3
Feedstuff composition (%) of diets formulated with least-cost (LCF) or multiobjective (MOF) formulation for three feeding strategies in growing-finishing pigs.

Feeding strategy	2P				2P−				MP							
Phase	Grower		Finisher		Grower		Finisher		MP1		MP2		MP3		MP4	
Formulation method	LCF	MOF	LCF	MOF	LCF	MOF	LCF	MOF	LCF	MOF	LCF	MOF	LCF	MOF	LCF	MOF
Barley	1.33		9.67		37.02	20.62	37.50	21.37	15.34	0.99	17.84	5.95	7.67	1.33	20.99	5.96
Maize	29.13	23.19	22.86	12.63			0.47	0.38	43.35	52.08	28.35	49.32	26.15	31.49	47.45	60.71
Maize DDGS	2.06				0.07											
Oat							2.50		2.50	3.43	2.50	1.99	1.25	0.90	2.50	2.04
Sorghum	5.00		5.00		1.76		2.01		2.50	1.25	2.50	1.25	5.00	1.74		
Triticale	4.10		2.84		3.88		4.78								7.50	0.00
Wheat	27.65	33.21	32.12	49.11	17.43	30.22	18.36	31.54	0.00	0.00	21.78	3.51	32.50	30.95	0.04	1.26
Wheat bran	3.44	3.11	7.28	5.93	9.78	4.78	8.18	5.80	0.00	0.00	0.00	2.14	8.96	9.50	10.00	10.00
Wheat DDGS					0.14	0.09										
Wheat feed flour	2.00	2.00	1.50	2.00	0.89	2.00		2.00		1.00		2.00	1.26	2.00		0.87
Wheat middlings	4.42	10.00	2.60	10.00	2.50	9.85	0.70	10.00		0.00			5.50	6.89	2.50	6.85
Rapeseed meal	5.11	10.63	0.52	1.40	0.22	9.26				0.00						
Soya bean meal					0.80	0.52	0.06		17.43	16.20	10.06	9.29		0.04		
Sunflower meal (dehulled)	10.00		7.82		9.03		3.61				1.10		2.08			
Sunflower meal (unhulled)	0.00	1.37	1.41	2.79		0.33	4.16	5.22	0.47	2.19	5.64	7.79	3.87	4.69	0.15	0.11
Faba bean	0.75	3.00	1.46	3.00	1.96	3.00	1.66	3.00	0.75	0.96	1.14	1.83	0.75	0.75		
Pea	2.50	10.00	2.50	10.00	9.91	10.00	8.30	10.00	6.58	9.00	5.10	9.25	2.50	6.52		0.12
Rapeseed											0.00					
Dehydrated sugar beet pulp		0.62		0.71	2.00	7.05	4.02	8.44	7.88	9.76	0.78	2.51		0.50	6.68	10.00
Animal fat		0.55		0.02												
Calcium carbonate	1.00	0.94	0.98	1.03	1.28	1.00	1.11	0.97	0.76	0.69	1.10	1.05	1.04	1.27	1.12	1.02
Monocalcium phosphate	0.04								0.65	0.66	0.45	0.43	0.04			
Sodium chloride	0.33	0.35	0.36	0.37	0.40	0.40	0.40	0.40	0.40	0.40	0.38	0.40	0.36	0.39	0.40	0.40
DL-Methionine		0.04	0.01	0.04	0.02	0.03	0.01	0.03	0.17	0.17	0.10	0.11	0.02	0.03		
L-Lysine HCl	0.50	0.38	0.44	0.35	0.33	0.27	0.30	0.27	0.44	0.44	0.49	0.45	0.43	0.39	0.16	0.16
L-Threonine	0.11	0.10	0.10	0.10	0.08	0.08	0.07	0.08	0.17	0.16	0.15	0.14	0.10	0.10		
L-Tryptophan	0.02	0.02	0.01	0.01					0.05	0.06	0.03	0.05	0.01	0.02		
L-Valine									0.03	0.04	0.01	0.01				
Enzymes, premix, and vitamins	0.51	0.51	0.51	0.51	0.51	0.51	0.50	0.50	0.52	0.52	0.52	0.52	0.51	0.51	0.51	0.51

2P: 'classic' 2-phase strategy. 2P−: 2− phase strategy with lower net energy (***NE***) (−0.7 MJ/kg) and the same digestible lysine:NE ratio as in 2P. MP: multiphase strategy based on four diets blended in different proportions over time (10 successive blends; see Supplementary Table S2 for composition of the blends).
DDGS: dried distillers grains with solubles.

CEDNR (+11% with MOF) and PD (+19%). In contrast, the 2P strategy had higher impacts (from +2 to +10%) for CC, AC, EU, LO, and PD. Compared to the 2P strategy, gross margin decreased in both 2P− and MP strategies, but to different degrees (−24% and −8%, respectively; Table 4 and Fig. 2b). Like for the MP strategy for pigs, the 3P+ strategy for broilers had little effect on impacts except for PD (+5% compared to 3P) and on gross margin (−3% with LCF vs +1% with MOF; Table 4 and Fig. 2b).

In pigs, MOF decreased CC by 2–7%, CEDNR by 0–7%, PD by 0–9%, and EU by 3–8%. Multiobjective feed formulation also decreased these

Table 4
Environmental and economic indicators at feed-mill and farm gates for different feeding strategies using least-cost (LCF) or multiobjective (MOF) formulation for pigs and broilers.

Production	Pig						Broiler			
Feeding strategy	2P		2P−		MP		3P		3P+	
Formulation method	LCF	MOF	LCF	MOF	LCF	MOF	LCF	MOF	LCF	MOF
Feed-mill gate (/t feed)										
Climate change (kg CO_2 eq)	493	422	437	387	514	488	827	727	858	788
Acidification (mol H^+)	9.7	8.7	8.0	7.4	9.9	9.8	11.9	11.5	12.0	11.5
Eutrophication (kg PO_4^{3-})	3.6	3.2	3.5	3.0	3.5	3.3	4.4	4.1	4.4	4.1
Cumulative nonrenewable energy demand (MJ)	5052	4357	4293	4033	5224	5230	7574	6179	7434	6690
Land occupation (m^2.yr)	1419	1238	1478	1230	1321	1245	1479	1538	1548	1538
Phosphorus demand (kg P)	3.4	3.2	3.4	3.0	4.5	4.1	7.0	6.2	7.7	6.9
Feed price (€)	215	219	205	212	221	224	294	304	311	317
Farm gate (/t live weight)										
Climate change (kg CO_2 eq)	2363	2206	2497	2378	2409	2354	1947	1777	1932	1819
Acidification (mol H^+)	56.9	55.5	58.4	57.4	55.7	54.9	52.7	51.9	54.7	53.4
Eutrophication (kg PO_4^{3-})	13.7	12.9	14.5	13.4	13.2	12.8	12.5	12.0	12.4	11.9
Cumulative nonrenewable energy demand (MJ)	19647	18251	19114	18547	20221	20233	20595	18240	19728	18530
Land occupation (m^2.yr)	3999	3624	4407	3849	3819	3658	2860	2959	2855	2839
Phosphorus demand (kg P)	11.0	10.0	11.2	10.5	13.0	12.0	12.3	10.8	12.9	11.5
Gross margin (€)	188	182	150	132	173	168	152	136	147	137

2P: 'classic' 2-phase strategy. 2P−: 2− phase strategy with lower NE (−0.7 MJ/kg) and the same digestible lysine:NE ratio as in 2P. MP: multiphase strategy based on four diets blended in different proportions over time (10 successive blends).
3P: 'classic' 3-phase strategy. 3P+: 3-phase strategy with higher digestible lysine content (+1.5 g/kg) and lower metabolisable energy content (−0.2 MJ/kg).

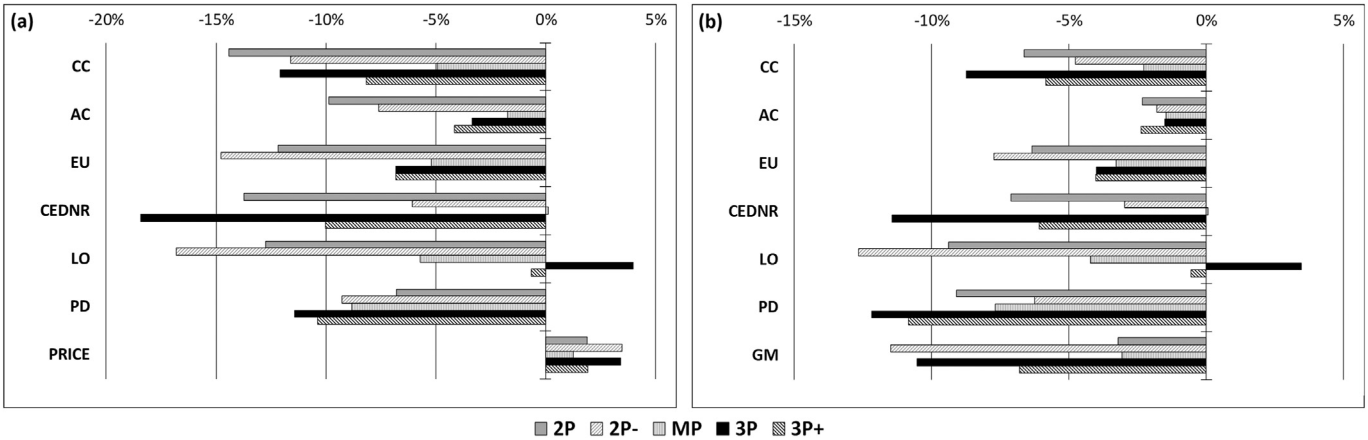

Fig. 2. Differences in environmental and economic indicators for feeding strategies in pigs and broilers formulated using multiobjective formulation compared to least-cost formulation a) per tonne of average feed at the feed-mill gate and b) per tonne of live weight. CC: climate change; AC: acidification; EU: eutrophication; CEDNR: cumulative non-renewable energy demand; LO: land occupation; PD: phosphorus demand; GM: gross margin. Pigs (grey): 2P: 'classic' 2-phase; 2P−: 2− phase with lower net energy content; MP: multiphase. Broilers (black): 3P: 'classic' 3-phase; 3P+: 3-phase with higher digestible amino acid and lower metabolisable energy contents.

impacts in broilers by 6–9% (CC), 6–11% (CEDNR), 11–12% (PD), and 4% (EU). For pigs, MOF decreased LO by 4–13%, while for broilers, MOF increased LO by 3% in the 3P strategy and decreased it by 1% in the 3P+ strategy. Finally, compared to LCF, MOF decreased AC little (less than 2%) (Table3; Fig. 2b). Furthermore, MOF decreased more impacts in 2P and 2P-strategies than in MP for pigs and more in 3P than in 3P+ for broilers. Consistent with the increase in feed price (Table 4; Fig. 2a), gross margin and decreased for both pigs (−3 to −11%) and broilers (−7 to −11%) (Table 4; Fig. 2b).

Discussion

Effect of feeding strategy on impacts at the farm gate (least-cost formulation)

The LCA-based impacts at feed-mill and farm gates for LCF scenarios are consistent with those reported in the literature for pigs (Dourmad et al., 2014; Monteiro et al., 2016; Andretta et al., 2018) and broilers (Leinonen et al., 2012; Prudêncio da Silva et al., 2014; Kebreab et al., 2016). In general, broiler feed had higher impacts at the feed-mill gate than pig feed because broiler feed had higher energy and nutrient concentrations. At the farm gate, however, broilers had lower impacts than pigs because broilers had better FCR than pigs.

For pigs, compared to the 2P strategy, the decrease in NE content in the 2P− strategy had positive effects at the feed-mill gate, with lower impacts (ranging from −18% for AC to −3% for PD) and lower feed price (−4%). However, these benefits were lost at the farm gate, where, compared to the 2P strategy, impacts of the 2P− strategy increased by 2–10%, while gross margin decreased by 24%. This result can be explained by the large worsening in FCR in the 2P− strategy (+0.25 points), due to the ability of pigs to increase feed intake when the energy density of the diet decreases (Li and Patience, 2017). Surprisingly, the MP strategy, designed to match nutrient supply and pig requirements better, had little effect on nitrogen (−5%) and phosphorus excretion (−2%), mostly due to lower animal performance. This can be explained by increased risk of underfeeding the animals with the highest requirements when using a larger number of diets (Monteiro et al., 2016). However, MP strategy strongly increased PD (+19%).

Table 5
Animal performance, nutrient excretion and gas emissions from manure and enteric fermentation according to formulation method (LCF: least-cost formulation; MOF: multiobjective formulation) and feeding strategy for pigs and broilers.

Production	Pig						Broiler			
Feeding strategy	2P		2P−		MP		3P		3P+	
Formulation method	LCF	MOF	LCF	MOF	LCF	MOF	LCF	MOF	LCF	MOF
Animal performance										
Slaughter weight (kg)	117						1.83			
Slaughter age (d)	171	171	170	170	171	171	36		34	
Feed conversion ratio	2.76	2.76	3.01	3.02	2.78	2.78	1.73		1.65	
Proportion of each diet in total feed intake (%)	G_p: 34% F_p: 66%				MP_1: 7% MP_2: 29% MP_3: 58% MP_4: 6%		S_b: 6% G_b: 20% F_b: 74%		S_b: 6% G_b: 23% F_b: 71%	
Mortality rate (%)	3.7						4.2			
Excretion and gas emissions (kg/t live weight)										
Nitrogen excretion	39.2	39.1	43.5	43.7	37.3	37.3	19.9	19.9	22.8	22.5
Phosphorus excretion	8.6	8.6	9.4	9.5	8.5	8.4	4.4	4.4	3.7	3.7
Ammonia (NH_3) emission	11.9	12.1	13.1	13.2	11.3	11.1	6.3	6.3	7.2	7.1
Nitrous oxide (N_2O) emission	0.278	0.280	0.306	0.308	0.263	0.261	0.030	0.030	0.036	0.035
Methane (CH_4) emission	27.4	27.0	33.3	33.2	27.4	27.4	0.570	0.570	0.534	0.534

2P: 'classic' 2-phase strategy. 2P−: 2− phase strategy with lower NE (−0.7 MJ/kg) and the same digestible lysine:NE ratio as in 2P. MP: multiphase strategy based on four diets (MP_1 to MP_4) blended in different proportions over time (ten successive blends).
3P: 'classic' 3-phase strategy. 3P+: 3-phase strategy with higher digestible lysine content (+1.5 g/kg) and lower metabolisable energy content (−0.2 MJ/kg).
G_p and F_p: grower and finisher diets (pigs); MP_1 to MP_4: multiphase diets to be blended (pigs); S_b, G_b, and F_p: starter, grower and finisher diets (broilers).

This was due to the increase in PD at feed-mill gate. Indeed, MP strategy was designed to follow the evolution of P requirements along the fattening period as performed in literature (Pomar et al., 2014; Monteiro et al., 2016), whereas the 2P strategy is based on usual on-farm practice that allows uncovering requirements at the starting of a feeding phase and further compensation. Therefore, MP strategy increased the incorporation of monocalcium phosphate and the associated PD.

Consequently, this strategy had little effect on environmental impacts at the farm gate. From an economic viewpoint, although the MP strategy decreased feed price by 4%, the lower animal performance decreased final gross margin by 8%. In the future, individual precision feeding could be a promising tool to reduce environmental impacts of pig production (Monteiro et al., 2016; Andretta et al., 2018).

For broilers, compared to the 3P strategy, the improvement in animal performance in the 3P+ strategy compensated the increase in price (+6%), resulting in a final gross margin similar to that in the 3P strategy (−3%). The same phenomenon was observed for LO and CC, which had similar values at the farm gate between strategies, despite higher impacts at the feed-mill gate for the 3P+ strategy. PD was also partially compensated, increasing by 10% at the feed-mill gate but by only 5% at the farm gate. For CEDNR, the improved FCR in 3P+ amplified at farm-gate (−4%) the decrease already observed at feed-mill gate (−2%). Finally, the higher amino acid contents (and thus CP content) in the 3P+ strategy led to higher nitrogen excretion and ammonia emissions (+12% to +15%), explaining the increase in AC at the farm gate (+4%). To decrease environmental impacts of broiler production further, other nutritional strategies could be used, such as decreasing CP content or beginning precision feeding, although further research is required (Belloir et al., 2017; Méda et al., 2019).

Effectiveness of multiobjective formulation and interaction with feeding strategy

The LCA-based impacts at feed-mill and farm gates for MOF scenarios (Table 4) are also consistent with those in the literature for pigs (Dourmad et al., 2014; Monteiro et al., 2016; Andretta et al., 2018) and broilers (Leinonen et al., 2012; Prudêncio da Silva et al., 2014; Kebreab et al., 2016). In agreement with Garcia-Launay et al. (2018), MOF decreased feed impacts while keeping the increase in feed price moderate. In agreement with our hypothesis, compared to LCF, MOF also decreased impacts of pig and broiler production at the farm gate (−1% to −13%), except for LO in the 3P strategy (+3%). In particular, MOF decreased CC effectively, as MOF is sensitive to the weighting factor (β) for each impact considered in the objective function (Garcia-Launay et al., 2018), and β was twice as large for CC as for the other impacts considered (*i.e.* CEDNR, PD and LO), as the mitigation of this impact was considered to be a priority (Gerber et al., 2013; Paris Agreement, 2015).

However, benefits of MOF at the farm gate varied by feeding strategy and impact category. For instance, for broilers, MOF was less effective than LCF at decreasing feed and farm impacts in the 3P+ strategy than in the 3P strategy. This can be explained by the use of more 'high-impact' feedstuffs in 3P+ diets such as soya bean meal (+6–9 percentage points) and feed-grade amino acids (+0.15–0.32 percentage points) to reach the higher digestible amino acid contents targeted (Supplementary Table S12). Furthermore, MOF did not decrease all impacts by the same magnitude. In particular, compared to LCF, MOF decreased AC at the farm gate little for either species. This is logical, as i) the objective function of MOF did not include AC and ii) manure emissions contribute most to AC at the farm gate (Supplementary Table S13; Prudêncio da Silva et al., 2014; Dourmad et al., 2014; Kebreab et al., 2016). Therefore, to decrease AC at the farm gate, one should focus on nitrogen excretion and NH_3 emissions by considering dietary crude-protein content and FCR.

Therefore, the use of LCF should be reconsidered. In the future, feed formulation should consider not only feed cost but also environmental and economic consequences at the farm gate. Mackenzie et al. (2016) investigated feed formulation while minimising either one environmental or economic indicator at the farm gate for pig production. Focusing on a single LCA impact when formulating diets, however, can lead to pollution swapping among the impacts considered. For instance, compared to LCF, minimising CC per tonne of carcass (−18%) increased AC, EU, and feed cost by *ca.* 25%, (Mackenzie et al., 2016). To this extent, MOF is an initial step in formulating feeds while considering economic and environmental objectives at the farm gate. However, further work is required to develop new formulation tools simultaneously taking into account the characteristics of i) feedstuffs (*i.e.* price, impacts, nutritional value, etc), ii) animals (*i.e.* age, sex, genetic potential, etc), and iii) farming system (*i.e.* manure management, farm size, etc). The development of such tools will require from nutritionists and animal scientists more data on how animals respond to feed. Close collaborations with mathematicians and computer scientists will also be essential, as those tools will rely on more complex optimisation methods, no longer based on linear programing.

Finally, for each diet formulated in our study, there was no competition with other diets or species for feedstuffs, whereas in commercial feed mills, inter- and/or intra-species competition for feedstuffs can occur. This competition could reduce benefits of MOF when volumes of 'low-impact' feedstuffs (*e.g.* cereal co-products) are low in a given region. Indeed, Espagnol et al. (2017) showed that applying MOF simultaneously to broilers, pigs, and cattle at a regional scale decreased impacts less than formulating each of their diets independently (*e.g.* for CC: −13% vs −5% in broilers and −14% vs −8% in pigs). Consequently, even greater efforts to decrease feed impacts and increase cooperation among operators in the livestock sector will be required to decrease environmental impacts of multiple livestock supply chains simultaneously.

Conclusion

Using life cycle assessment modelling, this paper shows that MOF can decrease several farm-gate environmental impacts of pig and broiler production simultaneously with limited reductions in gross margin. Nevertheless, choosing a feeding strategy maladapted to animal requirements could partially or completely negate environmental benefits of MOF when expanding from the feed-mill gate to the farm gate. Therefore, it is crucial to optimize feeding strategies in a comprehensive manner by considering feed impacts, animal performance, and manure management simultaneously in future modelling tools.

Supplementary materials

Supplementary data to this article can be found online at https://doi.org/10.1016/j.animal.2020.100024.

Ethics approval

Not applicable.

Data and model availability statement

None of the data or the model were deposited in an official repository.

Declaration of interest

None.

Acknowledgements

This study was funded by the French Ministry of Agriculture (ECOALIM project; CASDAR Partenariat et Innovation-2012) and the

French Environment and Energy Management Agency (ADEME REACCTIF-2012, 1260C0061). The authors wish to thank Michael and Michelle Corson (Editor du jour) for reviewing the English language of this paper, and Jean-Yves Dourmad (INRAE), Ludovic Brossard (INRAE), and Nathalie Quiniou (IFIP) for their advises in setting the nutritional constraints for pig feed formulation.

References

Andretta, A., Hauschild, L., Kipper, M., Pires, P.G.S., Pomar, C., 2018. Environmental impacts of precision feeding programs applied in pig production. Animal 12, 1990–1998.

Belloir, P., Méda, B., Lambert, W., Corrent, E., Juin, H., Lessire, M., Tesseraud, S., 2017. Reducing the CP content in broiler feeds: impact on animal performance, meat quality and nitrogen utilization. Animal 11, 1881–1889.

Cadéro, A., Aubry, A., Brun, F., Dourmad, J.Y., Salaün, Y., Garcia-Launay, F., 2018a. Global sensitivity analysis of a pig fattening unit model simulating technico-economic performance and environmental impacts. Agricultural Systems 165, 221–229.

Cadéro, A., Aubry, A., Brossard, L., Dourmad, J.Y., Salaün, Y., Garcia-Launay, F., 2018b. Modelling interactions between farmer practices and fattening pig performances with an individual-based model. Animal 12, 1277–1286.

Cadéro, A., Aubry, A., Dourmad, J.Y., Salaün, Y., Garcia-Launay, F., 2018c. Towards a decision support tool with an individual-based model of a pig fattening unit. Computers and Electronics in Agriculture 147, 44–50.

Comité d'Orientation pour des Pratiques Agricoles Respectueuses de l'Environnement (CORPEN), 2003. Estimation des rejets d'azote-phosphore-potassium-cuivre et zinc des porcs. Influence de la conduite alimentaire et du mode de logement des animaux sur la nature et la gestion des déjections produites. Comité d'Orientation pour des Pratiques Agricoles Respectueuses de l'Environnement, Paris, France.

Comité d'Orientation pour des Pratiques Agricoles Respectueuses de l'Environnement (CORPEN), 2006. Estimation des rejets d'azote, phosphore, potassium, calcium, cuivre, zinc par les élevages avicoles. Comité d'Orientation pour des Pratiques Agricoles Respectueuses de l'Environnement, Paris, France.

Dourmad, J.Y., Ryschawy, J., Trousson, T., Bonneau, M., Gonzàlez, J., Houwers, H.W.J., Hviid, M., Zimmer, C., Nguyen, T.L.T., Morgensen, L., 2014. Evaluating environmental impacts of contrasting pig farming systems with life cycle assessment. Animal 8, 2027–2037.

Espagnol, S., Garcia-Launay, F., Dusart, L., Dauguet, S., Gac, A., Gaudré, D., Méda, B., Tailleur, A., Wilfart, A., Morin, L., 2017. Multiscale influence of feedstuff availability on environmental impact of feed. Proceedings of the 68th annual meeting of the European Association for Animal Production, 28 August-1 September 2017, Tallinn, Estonia, p. 213.

European Monitoring and Evaluation Programme (EMEP), 2013. EMEP/EEA air pollutant emission inventory guidebook 2013. Technical chapter 3.B Manure Management. European Environment Agency, Copenhagen, Denmark.

Gac, A., Cariolle, M., Deltour, L., Dollé, J.B., Espagnol, S., Flénet, F., Guingand, N., Lagadec, S., Le Gall, A., Lellahi, A., Malaval, C., Ponchant, P., Tailleur, A., 2010. GESTIM : Guide méthodologique pour l'estimation des impacts des activités agricoles sur l'effet de serre, version 1.2. Institut de l'Elevage, Paris, France.

Garcia-Launay, F., van der Werf, H.M.G., Nguyen, T.T.H., Le Tutour, L., Dourmad, J.Y., 2014. Evaluation of the environmental implications of the incorporation of feed-use amino acids in pig production using Life Cycle Assessment. Livestock Science 161, 158–175.

Garcia-Launay, F., Dusart, L., Espagnol, S., Laisse-Redoux, S., Gaudré, D., Méda, B., Wilfart, A., 2018. Multiobjective formulation is an effective method to reduce environmental impacts of livestock feeds. The British Journal of Nutrition 120, 1298–1309.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling climate change through livestock – a global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

IFIP, 2019. Notes de conjoncture Aliment IFIP. Retrieved on 09 June 2020 from. https://www.ifip.asso.fr/fr/content/la-note-de-conjoncture-aliment-de-l%E2%80%99ifip-mensuel-dinformation-sur-les-mati%C3%A8res-premi%C3%A8res.

Institut Technique de l'Aviculture (ITAVI), 2013. Estimation des rejets d'azote, phosphore, potassium, calcium, cuivre, zinc par les élevages avicoles. Mise à jour des références CORPEN-Volailles de 2006. Institut Technique de l'Aviculture, Paris, France.

Intergovernmental panel on climate change (IPCC), 2006. Chapter 10: Emissions from livestock and manure management. 2006 IPCC Guidelines for national greenhouse gas inventories. Intergovernmental panel on climate change, Geneva, Switzerland.

Joint Research Centre (JRC), 2012. Characterisation factors of the ILCD recommended life cycle impact assessment methods. Database and supporting information. Retrieved on 07 July 2020 from. https://eplca.jrc.ec.europa.eu/uploads/LCIA-characterization-factors-of-the-ILCD.pdf.

Kebreab, E., Liedke, A., Caro, D., Deimling, S., Binder, M., Finkbeiner, M., 2016. Environmental impact of using specialty feed ingredients in swine and poultry production: a life cycle assessment. Journal of Animal Science 94, 2664–2681.

Koch, P., Salou, T., 2015. Agribalyse®: methodology version 1.2. Retrieved on 7 April 2020, from. https://www.ademe.fr/sites/default/files/assets/documents/agribalyse-methodology-v1_2.pdf.

Leinonen, I., Williams, A.G., Wiseman, J., Guy, J., Kyriazakis, I., 2012. Predicting the environmental impacts of chicken systems in the United Kingdom through a life cycle assessment: broiler production systems. Poultry Science 91, 8–25.

Li, Q., Patience, J.F., 2017. Factors involved in the regulation of feed and energy intake of pigs. Animal Feed Science and Technology 233, 22–33.

Loyon, L., Burton, C.H., Misselbrook, T., Webb, J., Philippe, F.X., Aguilar, M., Doreau, M., Hassouna, M., Veldkamp, T., Dourmad, J.Y., Bonmati, A., Grimm, E., Sommer, S.G., 2016. Best available technology for European livestock farms: availability, effectiveness and uptake. Journal of Environmental Management 166, 1–11.

Mackenzie, S.G., Leinonen, I., Ferguson, N., Kyriazakis, I., 2016. Towards a methodology to formulate sustainable diets for livestock: accounting for environmental impact in diet formulation. The British Journal of Nutrition 115, 1860–1874.

Méda, B., Belloir, P., Narcy, A., Wilfart, A., 2019. Improving environmental sustainability of poultry production using innovative feeding strategies. Proceedings of the 22nd European symposium on poultry nutrition, 10–13 June 2019, Gdańsk, Poland, pp. 82–92.

Millet, S., Aluwé, M., Van den Broeke, A., Leen, F., De Boever, J., De Campeneere, S., 2017. Review: pork production with maximal nitrogen efficiency. Animal 12, 1060–1067.

Monteiro, A.N.T.R., Garcia-Launay, F., Brossard, L., Wilfart, A., Dourmad, J.Y., 2016. Effect of feeding strategy on environmental impacts of pig fattening in different contexts of production: evaluation through life cycle assessment. Journal of Animal Science 94, 4832–4847.

Nguyen, T.T.H., Bouvarel, I., Ponchant, P., van der Werf, H.M.G., 2012. Using environmental constraints to formulate low-impact poultry feeds. Journal of Cleaner Production 28, 215–224.

Paris Agreement to the United Nations Framework Convention on Climate Change, Dec. 12, 2015. T.I.A.S. No. 16-1104. Retrieved on 7 April 2020 from. https://treaties.un.org/doc/Treaties/2016/02/20160215%2006-03%20PM/Ch_XXVII-7-d.pdf.

Pomar, C., Pomar, J., Dubeau, F., Joannopoulos, E., Dussault, J.P., 2014. The impact of daily multiphase feeding on animal performance, body composition, nitrogen and phosphorus excretions, and feed costs in growing–finishing pigs. Animal 8, 704–713.

PRé Consultants, 2020. SimaPro database manual version 4.15. Retrieved on 07 July 2020 from. https://simapro.com/wp-content/uploads/2020/06/DatabaseManualMethods.pdf.

Prudêncio da Silva, V., van der Werf, H.M.G., Soares, S.R., Corson, M.S., 2014. Environmental impacts of French and Brazilian broiler chicken. Journal of Environmental Management 133, 222–231.

Sauvant, D., Perez, J.M., Tran, G., 2004. Tables of composition and nutritional value of feed materials: pigs, poultry, cattle, sheep, goats, rabbits, horses, fish. 2nd edition. INRA, Paris, France.

Van Milgen, J., Valancogne, A., Dubois, S., Dourmad, J.Y., Sève, B., Noblet, J., 2008. InraPorc: a model and decision support tool for the nutrition of growing pigs. Animal Feed Science and Technology 143, 387–405.

de Vries, M., de Boer, I., 2010. Comparing environmental impacts for livestock products: a review of life cycle assessments. Livestock Science 128, 1–11.

van der Werf, H.M.G., Petit, J., 2002. Evaluation of the environmental impact of agriculture at the farm level: a comparison and analysis of 12 indicator-based methods. Agriculture, Ecosystems and Environment 93, 131–145.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. International Journal of Life Cycle Assessment 21, 1218–1230.

Wilfart, A., Espagnol, S., Dauguet, S., Tailleur, A., Gac, A., Garcia-Launay, F., 2016. ECOALIM: a dataset of environmental impacts of feed ingredients used in French animal production. PLoS One 11, e0167343.

Zuidhof, M.J., Schneider, B.L., Carney, V.L., Korver, D.R., Robinson, F.E., 2014. Growth, efficiency, and yield of commercial broilers from 1957, 1978, and 20051. Poultry Science 93, 2970–2982.