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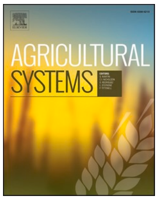

Analysis of synergies and trade-offs between animal welfare, ammonia emission, particulate matter emission and antibiotic use in Dutch broiler production systems

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ABSTRACT

Context: Intensive broiler production systems are criticized by EU citizens because of their negative impact on animal welfare, the environment and human health.
Objective: To inform the development of sustainable broiler production systems, this paper provides insight in the synergies and trade-offs between different external factors originating from broiler production systems by developing a new analysis approach.
Methods: The approach was applied to the Dutch conventional, New Dutch Retail Standard and Extensive Indoor+ systems. The latter two systems have more stringent standards on animal welfare relative to the conventional system. Four external factors were considered, i.e. animal welfare (indicated by Welfare Quality Index score), ammonia emission (kg NH_3/animal place/year), particulate matter emission (g PM_{10}/animal place/year) and antibiotic use (defined daily doses animal).
Results and conclusions: Results show that the shift from a fast-growing breed towards a slower-growing breed caused synergy by improving animal welfare and lowering antibiotic use. Furthermore, the reduction in protein content of the feed, and possibly the reduction in stocking density, caused synergy by enhancing animal welfare and lowering ammonia emission. System changes that stimulated activity, such as the reduction in stocking density, enhanced animal welfare but caused a trade-off with particulate matter emission. Although the New Dutch Retail Standard and Extensive Indoor+ system were characterized by a higher ammonia and particulate matter emission per animal place per year relative to the conventional system, experts estimated that these emissions were partially (New Dutch Retail Standard) or fully (Extensive Indoor+) offset at farm level via a lower stocking density. Overall, we conclude that future development of broiler production systems can exploit the synergy between animal welfare, antibiotic use, and ammonia emission and minimize the trade-off between animal welfare and particulate matter emission.
Significance: The insights obtained from this paper can support the development of sustainable broiler production systems that minimize external factors originating from these systems.

1. Introduction

EU citizens have expressed widespread concerns about the loss of biodiversity, the presence of antibiotic residues in meat, and the welfare of farmed animals (Eurobarometer, 2015, 2016, 2019). Broiler production is an important source of these concerns through its negative side-effects, defined as external factors,[1] on Animal Welfare (AW), the environment and human health (Homidan et al., 2003; Cambra-López et al., 2010; Bracke et al., 2019; Van Geijlswijk et al., 2019). Most prominent among the concerns in broiler production are the leg disorders that fast-growing broilers may develop when reared in intensive production systems (Broom, 2017). In an attempt to increase awareness among citizens for the leg disorders, the Dutch NGO Wakker Dier introduced the term ‘plofkip’ (‘exploding chicken’). In the past two decades, the EU passed legislation on AW, the environment and food safety associated with livestock production to resolve the societal concern

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[1] In this paper, an ‘external factor’ is defined as a side-effect from an activity (e.g. broiler production) that affects the well-being of an uninvolved person in ways that are not reflected in market transactions. Economists generally define this phenomena as ‘externalities’.

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(European Council Directive, 2007; 2009; 2016). However, the legislation is deemed to be insufficient as criticism persists as of today. To counteract the critique on AW, private chain actors introduced more extensive systems containing slower-growing breeds, such as the Label Rouge in France and Better Life in the Netherlands. Although these systems are found to improve AW (Bracke et al., 2019), these systems have a higher environmental burden (expressed per kg edible carcass weight) relative to the more intensive conventional systems (Leinonen et al., 2012). This suggests a trade-off where taking measures to address AW, increase environmental issues.

The example above illustrates that external factors in broiler production are interrelated. Hence, the development of new broiler production systems requires a multi-dimensional approach that analyzes systems in terms of their economic, ecological, and social performance (Bokkers and De Boer, 2009). So far, only Bokkers and De Boer (2009), Rocchi et al. (2019) and Gocsik et al. (2016) used such a multi-dimensional approach. However, these studies have their shortcomings. While Bokkers and De Boer (2009) and Rocchi et al. (2019) considered multiple external factors in broiler production, they did not assess the individual contribution of system attributes, such as the broiler breed, to these external factors. Gocsik et al. (2016) analyzed the contribution of system attributes to AW, but ignored the contribution of these attributes to environmental factors. Hence, neither Bokkers and De Boer (2009), nor Rocchi et al. (2019), nor Gocsik et al. (2016) considered the effect of changes in system attributes on multiple external factors, thus ignoring the potential synergies[2] and trade-offs caused by these changes. To fill this gap in the literature, this paper aims to obtain insight in the synergies and trade-offs between external factors originating from broiler production systems by developing an approach that allows an analysis of these factors. This insight can support the development of sustainable broiler production systems that minimize external factors originating from these systems and the price premium required for its introduction.

2. Approach

2.1. Overview of approach

A five-step approach was developed and applied to existing Dutch broiler production systems to analyze the synergies and trade-offs in these systems. These steps are shown in Fig. 1 and discussed in detail in the remainder of this section.

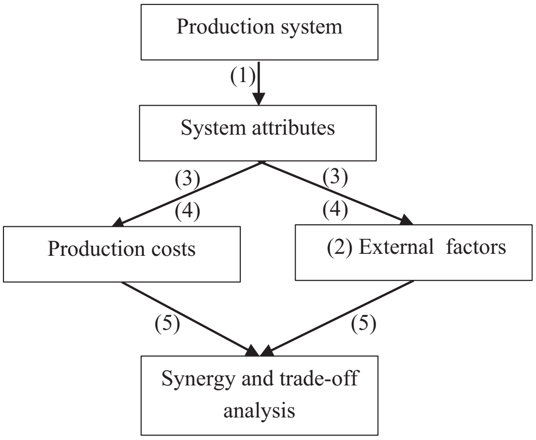

Fig. 1. Overview of research approach.

2.2. Step 1: Decompose the production system into system attributes

The Dutch conventional system, New Dutch Retail Standard (NDRS) and Extensive Indoor+ system were selected for the analysis as these systems are the prevailing ones in the Dutch broiler market. These systems were decomposed into system attributes. The Dutch conventional production system adheres to the minimum legal requirements on AW laid down by the European Council Directive (2007) and is mainly used for export markets (Vissers et al., 2019). The NDRS contains the minimum AW requirements of Dutch retailers, which include a lower stocking density and a slower-growing breed relative to the minimum legal requirements. The Extensive Indoor+ system is specific to the Dutch market, produced under a national welfare label, and contains a covered veranda (indoor free-range area) and natural light entrance in the house. Table 1 shows the system attributes of all three systems.

2.3. Step 2: Identify and select external factors

We reviewed Dutch newspapers and the scientific and semi-scientific literature for external factors related to the selected broiler production systems. The search terms included Dutch target words such as “kritiek veehouderij” (criticism livestock farming) and English target words such as “external factors poultry production”. Eleven external factors were identified, shown in Table 1. We selected four external factors, based on the following criteria: 1) the external factor originates primarily from the broiler production system, i.e. not from other chain actors; 2) data is available about the external factor; and 3) the data can be linked to a broiler production system. As such, the external factors AW, ABU, ammonia (NH_3) emission and particulate matter (PM_{10}[3]) emission were selected. For external factors with multiple indicators, we selected the most widely used indicator in literature. All emissions were expressed per animal place per year and considered only at farm gate.

2.4. Step 3: Establish linkages

Using a three-step procedure, linkages were established between each system attribute and the indicators of the external factors. First, the conventional system was selected as the baseline for analysis, as it contains fewest system attributes. Second, all changes in system attributes of the NDRS and Extensive Indoor+ system, relative to the conventional system, were identified from Table 2. Third, a yes/no indication of a linkage was established between each identified system attribute and each indicator based on a thorough literature review. The linkages are denoted by an ‘X’ in Table 3. For instance, the system attribute ‘stocking density’ was linked to the Welfare Quality index score (WQ index score), kg NH_3/animal place/year and g PM_{10}/animal place/year. The linkage with WQ index score can be explained by the positive relationship of stocking density with various diseases, such as footpad dermatitis and breast blister (Bessei, 2006). The linkage between stocking density and kg NH_3/animal place/year can be explained by the positive effect of stocking density on the moisture content of the litter. A higher moisture concentration favors the production and release of ammonia (Homidan et al., 2003). The linkage between stocking density and g PM_{10}/animal place/year can be explained by its negative relationship with the activity of the broiler (Sørensen et al., 2000). A higher broiler activity elevates indoor PM_{10} concentration and emission (Calvet et al., 2009).

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[2] In this paper, a synergy is defined as the mitigation of multiple external factors; a trade-off is defined as the mitigation of one external factor and the elevation of another.

[3] PM_{10} is defined as *‘particulate matter which passes through a size-selective inlet with a 50% efficiency cut-off at 10 μm aerodynamic diameter’* (Cambra-López et al., 2010).

Table 1
Overview of production system attributes of the selected production systems.

System attribute	Unit	Production system		
		Conventional	NDRS	Extensive Indoor+
Broiler breed	Type	Ross 308[1]	Hubbard JA987[1]	Hubbard JA757[1]
Length growth period	Days	39[2]	49[2]	56[2]
Weight at delivery	Grams	2380[2]	2380[2]	2380[2]
Stocking density	Kg/m^2	42[1]	38[1]	25[1]
Straw bale enrichment	# bales/1000 broilers	No[1]	1[1]	1[1]
Grain enrichment	g/broiler	No[1]	No[1]	2[1]
Length dark period	Hours/day	6, 4 uninterrupted[1]	6, uninterrupted[1]	8, uninterrupted[1]
Light intensity	lux	20[3]	20[3]	20[3]
Natural light	% of surface area	No[1]	No[1]	3[1]
On-farm hatching	Yes/no	No[1]	No[1]	No[1]
Early feeding	Yes/no	No[1]	No[1]	No[1]
Empty barn period	# days	8[2]	7[2]	7[2]
Litter type	Type	Wood shavings[3]	Wood shavings[3]	Wood shavings[3]
Feed composition	Type	Concentrates +30% wheat[4]	Concentrates +15% wheat (reduced protein content relative to conventional feed)[4]	Min. 70% grain or grain byproducts (reduced protein content relative to conventional feed)[4]
Feeding phases	# phases	4[4]	4[4]	4[4]
Manure management	Type	Disposed at end of production cycle[5]	Disposed at end of production cycle[5]	Disposed at end of production cycle[5]
Flock size	# broilers	90,000[6,a]	81,035[a]	54,911[a]
Veterinary medicines	Type	Antibiotics and coccidiostats[1,b]	Antibiotics and coccidiostats[1, b]	Antibiotics and coccidiostats[1, b]
Outdoor access	Yes/no	No[3]	No[3]	Covered veranda min. 20% of surface area[3]
Emission reduction technique	Type	None[c]	None[c]	None[c]

[1] Stadig (2019).
[2] Blanken et al. (2019).
[3] Vissers et al. (2019).
[4] J. van Harn, personal communication, 2020.
[5] P. van Horne, personal communication, 2020.
[6] Gocsik et al. (2016).
[a] In line with Gocsik et al. (2016), a flock size of 90,000 broilers was assumed in the conventional system. Based on this flock size, floor surface equaled 4928m^2. The floor surface was assumed to be equal for all systems. Based on this floor surface, the flock size in the NDRS and Extensive Indoor+ system was calculated.
[b] Dutch farmers must comply with strict rules on antibiotic use (Government of the Netherlands, 2020). For instance, antibiotics may only be prescribed by veterinarians and the farmer must register all antibiotics they use.
[c] The impact of NH_3 and PM_{10} abatement techniques on external factors is beyond the scope of this paper and therefore not further considered.

Table 2
Overview of external factors associated with Dutch broiler production.

External factor	Indicator
Ammonia emission	kg NH_3/animal place/year[1]
Animal health	–
Animal welfare	Welfare Quality index score[2]
Antibiotic use	Defined daily doses animal[3]
Poultry house fire	–
Global warming	–
Odor emission	–
Particulate matter emission	g PM_{10}/animal place/year[1]
Visual pollution	–
Water pollution	–
Zoonoses	–

[1] Expertise Centre Infomil (2019).
[2] Welfare Quality Protocol® (2009)
[3] Van Geijlswijk et al. (2019).

2.5. *Step 4: assign weights to linkages*

We followed the procedure of Gocsik et al. (2016) to assign weights to the linkages. To do so, the relative importance of each linkage was obtained from the scientific literature and scored on a scale of 1 to 3, where a higher score indicates a higher relative importance. In case the literature was inconclusive, the relative importance of a linkage was estimated via Expert Knowledge Elicitation (EKE). A detailed description of the EKE procedure is provided in supplementary material A. The relative importance scores were transformed into importance weights, such that the importance weights for each indicator sum up to one. In case the indicator is decomposed into sub-indicators, the weights sum up to one per sub-indicator (Table 4). These welfare measures are sub-indicators of the indicator WQ index score. Because many factors affect NH_3 and PM_{10} emission in broiler production (e.g. humidity) (Homidan et al., 2003; Cambra-López et al., 2010), EKE indicated that it was not possible to assign importance scores to the linkages between system attributes and NH_3 and PM_{10} emission. Since importance scores were lacking for these linkages, it was not possible to establish weights between the system attributes and NH_3 and PM_{10} emission.

2.6. *Step 5: calculation of external factors and production costs*

2.6.1. *External factors*

The contribution of each system attribute to the external factors was calculated via a three-step procedure. First, the score of the production system per indicator and, if applicable, per sub-indicator, was obtained from scientific data and literature. The WQ index score and WQ score per welfare measure of the production systems were obtained from De Jong et al. (2015). The Defined Daily Doses Animal ($DDDA_F$) of a system was obtained from Van Geijlswijk et al. (2019). Since Van Geijlswijk et al. (2019) did not distinguish $DDDA_F$ for different systems that use slower-growing breeds, we assumed that $DDDA_F$ was similar in the NDRS and Extensive Indoor+ system. The NH_3 and PM_{10} emission factors of the conventional system were obtained from Expertise Centre Infomil (2019). Since these emission factors were lacking for the NDRS

Table 3
Overview of linkages between production system attributes and indicators of external factors.

System attribute	Indicator of external factor			
	WQ Index score	Kg NH_3/ animal place/ year	g PM_{10}/ animal place/ year	Defined daily doses animal
Broiler breed	X[1,3]	X[2]	X[3,6]	X[4]
Length growth period	X[5]	X[2]	X[6,10]	
Stocking density	X[3,7]	X[2]	X[2,6]	
Straw bale enrichment	X[8,11]		X[11,6]	
Grain enrichment	X[8,9]			
Length dark period	X[3,5]		X[6]	
Natural light	X[11]		X[11,6]	
Empty barn period		X	X	
Feed composition	X[12]	X[12]	X[2]	
Flock size	X[13]			
Outdoor access	X[14]			

[1] EFSA, 2010
[2] Homidan et al. (2003)
[3] Bessei (2006)
[4] Van Geijlswijk et al. (2019)
[5] Knowles et al. (2008)
[6] Calvet et al. (2009)
[7] Tullo et al. (2017)
[8] Riber et al. (2018)
[9] Waldenstedt (2006)
[10] Winkel et al. (2015).
[11] Bailie et al. (2013).
[12] Van Harn et al. (2019).
[13] Rodenburg and Koene (2007).
[14] Stadig et al. (2017).

and Extensive Indoor+ system, they were elicited via EKE. EKE is often used to address uncertainty about parameters in large environmental models (EFSA, 2014). EKE is less suitable for precise estimations of the NH_3 and PM_{10} emission factor of broiler production systems as they are affected by many factors (Homidan et al., 2003; Cambra-López et al., 2010). However, EKE is more suited for estimations of the relative position of systems based on their emission factors, particularly if it is carried out together with a thorough sensitivity analysis on ranking robustness. In the EKE, each expert provided individual estimates of the emission factors. The following two steps were followed to derive the distributions from the individual estimates: 1) computing the average values for the minimum, maximum and mode from the individual estimates, and then 2) deriving the PERT distribution using these average values. The PERT-fitted distributions were simulated using @risk, with 10,000 iterations.

Second, the absolute difference in score of the systems with the baseline (conventional) was calculated for each (sub-)indicator. Third, the contribution of a system attribute to an external factor was calculated by multiplying the difference in score with the weight related to that system attribute and (sub-)indicator. As weights were lacking for the linkages between the system attributes and kg NH_3/animal place/year and g PM_{10}/animal place/year emission (see step 4), the contribution of the system attributes to these external factors could not be calculated. Instead, EKE was carried out to obtain qualitative estimations of the contribution of the system attribute to these external factors (see supplementary material A for detailed procedure).

2.6.2. *Production costs*

The production costs were calculated for each production system using the deterministic model of Gocsik et al. (2016). Input prices and production performance indicators were obtained from Blanken et al. (2019) and can be found in supplementary material B. As delivery weight was similar for all systems (2380 g), no corrections had to be made for the emission factors and production costs per delivered broiler. Production costs were expressed per delivered broiler and were assigned to system attributes. Most production cost components were linked to a single attribute (e.g. day-old-chick costs to broiler breed). However, cost components related to the technical performance indicators ‘feed conversion rate’ (feed costs), ‘mortality rate’ (mortality costs) and ‘daily weight gain’ (housing costs) were linked to multiple attributes. They were assigned to system attributes using weights between the attributes and the technical performance indicators that were obtained from literature (as done for the external factors in step 3 and 4). These weights are provided in Supplementary Material C. The income earned from the production systems was indicated by the net return to labor and management (total revenues minus total costs excluding labor costs). The production costs, net return to labor and management and external factors were expressed both per animal and per farm level.

2.6.3. *Sensitivity analysis*

A sensitivity analysis was carried out to test the impact of price fluctuations and uncertainty with respect to the estimated emission factors on the robustness of the results. The impact of price fluctuations

Table 4
Matrix showing weights between the welfare measures and system attributes for animal welfare (obtained from Vissers et al. (2019), adapted).

	Welfare measures of WQ index score											
Attribute	Plumage cleanliness	Litter quality	Panting	Stocking density	Lameness	Hock burn	Footpad dermatitis	Breast blister	Mortality	Ascites	ADT[1]	QBA[2]
Broiler breed			0.50		0.14	0.25	0.25	1	0.50	0.67		
Length growth period	0.25	0.20			0.14	0.25	0.13					
Stocking density	0.25	0.40	0.50	1	0.28	0.25						0.14
Straw bale enrichment	0.25				0.14		0.13					0.28
Grain enrichment							0.13					
Length dark period		0.20			0.14	0.25	0.13		0.50	0.33	0.5	0.28
Natural light		0.20			0.14							0.14
Empty barn period												
Feed composition							0.13					
Flock size											0.5	0.14
Outdoor access	0.25						0.13					

[1] Avoidance Distance Test; [2] Qualitative Behavior Assessment.

on net return to labor and management was tested by using different feed price levels. Feed price was selected as these prices are subject to considerable fluctuations and feed costs are the main cost component in broiler production (Gocsik et al., 2016). In this respect, two cases were analyzed for the period 2015–2019, i.e. a best-case and a worst-case scenario. The best-case scenario uses the minimum feed price and the worst-case scenario the maximum feed price. The impact of uncertainty with respect to the estimated emission factors was tested by using the average maximum value and average minimum value from the individual estimates as best and worst case scenarios, respectively.

3. Results and discussion

3.1. Synergy and trade-offs per animal

The effects of changes in system attributes on external factors were analyzed to identify the synergies and trade-offs caused by these changes. In this analysis, the external factors NH_3 emission and PM_{10} emission were expressed per animal place per year. Insight in the synergies and trade-offs was used to assess the potential for mitigating multiple external factors in broiler production systems. Table 5 and Table 6 show the effects of changes in system attributes on the external factors and production costs in the NDRS and Extensive Indoor+ systems relative to the conventional system. Overall, these changes in system attributes improve AW and lower ABU. On the other hand, these changes elevate NH_3 and PM_{10} emissions per animal place per year, and increase the production costs per animal. The reduction of ABU can be explained by the synergy that was generated by 'broiler breed' (+WQ index score, $-DDDA_F$). A slower-growing breed is less susceptible to diseases such as lameness and hock burn (Kjaer et al., 2006; EFSA, 2010). Welfare improvements, such as a slower-growing breed, can reduce ABU through reduced stress-induced immunosuppression and a reduced incidence of diseases (De Passillé and Rushen, 2005; Dawkins, 2017). Our results are in line with Bokma-Bakker et al. (2017), who found that the use of a slower-growing breed was one of the main factors for reduced ABU in the NDRS and Extensive Indoor+ system relative to the conventional system. However, the reduction of ABU was not only caused by the different broiler breed, but also by other factors such as differences in the quality of the day-old-chicks and farmer's perception towards antibiotics (Bokma-Bakker et al., 2017).

The results in Table 5 and Table 6 also provide evidence of other synergies and trade-offs. Synergy between AW and NH_3 emission is found in the NDRS and Extensive Indoor+ systems; this synergy is attributable to changes in the system attributes 'feed composition' (+WQ index score, $-$kg NH_3/animal place/year) and possibly 'stocking density' (+WQ index score, $-/0/+$ kg NH_3/animal place/year). The synergy caused by 'feed composition' can be explained by the lower protein content of the diet, which reduces the nitrogen excretion and NH_3 emission from broiler houses (Namroud et al., 2008; Van Harn et al., 2019). In addition, a study by Van Harn et al. (2019) showed that a lower crude protein in the diet improves litter quality and thereby reduces the risk of footpad dermatitis. It should be noted that slower-growing broilers are less susceptible to footpad dermatitis relative to fast-growing broilers (Kjaer et al., 2006; EFSA, 2010). Therefore, the contribution of a reduced protein content in feed to reduced risk of footpad dermatitis is most likely small for slower-growing broilers. A lower stocking density enhances AW by reducing the risk of health problems such as panting and lameness (Sørensen et al., 2000; EFSA, 2010). In addition, a reduced stocking density may lower NH_3 emission, although this depends on the magnitude of two opposite effects. On the one hand, a reduced stocking density enlarges the emitting area of the broiler. On the other hand, a (substantial) reduction of the stocking density may enhance the dry matter content of the litter (Sørensen et al., 2000). According to Groot Koerkamp et al. (2000), a dry matter content below 60% or above 80% mitigates the formation of NH_3 from litter. Currently, there is no scientific evidence on the magnitude of both effects when lowering the stocking density. The synergy caused by 'feed composition' and possibly also 'stocking density' indicate that improvements in AW do not necessarily increase NH_3 emission per se, because these attributes do not deteriorate or improve the litter quality. This finding is in line with Leinonen et al. (2014), who found that alternative systems that enhance bird welfare can have the same or a lower acidification potential compared to a conventional system, at least when the feed conversion ratio is not significantly increased.

In the NDRS and Extensive Indoor+ system, most changes in system attributes caused a trade-off between AW and PM_{10} emission. This trade-off can be explained by the positive effect of these changes on broiler activity. A higher broiler activity improves the leg health of broilers (Bessei, 2006; Bailie et al., 2013). On the other hand, a higher activity increases dust production, causing higher PM_{10} concentrations and emission rates (Calvet et al., 2009; Peña Fernández et al., 2019). As broilers are more active at the end of the growing cycle, the contribution of broiler activity to PM_{10} concentrations plays a more important role at the end of the growing cycle than at the beginning of the cycle (Peña

Table 5
Effect of the change in system attributes from the conventional to the NDRS system on the external factors and production costs (+ = increase, − = decrease, 0 = no effect) expressed per animal.

System attribute	Change in system attribute		External factor				Economic Indicator
	Conventional	NDRS	Animal welfare WQ index score	Ammonia emission kg NH_3/animal place/year	Particulate matter emission g PM_{10} /animal place/year	Antibiotic use $DDDA_F$	Production costs Eurocents/animal
Broiler breed	Ross 308	Hubbard JA987	+35.5	0/+	+	−10.7	+15.0
Length growth period	40 days	49 days	+13.3	+	+		+12.4
Stocking density	42 kg/m^2	38 kg/m^2	+20.8	+	+		+6.6
Straw bale enrichment	None	1 bale/1000 broilers	+7.4	0	0/+		+4.8
Empty barn period	8 days	7 days	0	+	+		−0.7
Length dark period	6 h/day, 4 h/day uninterrupted	6 h/day, uninterrupted	+0.6	0	0		+1.6
Feed composition	Concentrates +30% wheat	Concentrates +15% wheat (red. Protein cont.)	+6.6	−	+		+3.7
Flock size	90,000	81,429	+1.4	0	0		0
Total			+85.6	+5%; +13%; +22%[1]	+23%; + 38%; +53%[1]	−10.7	+43.4

[1] minimum change; most likely change; maximum change.

Table 6
Effect of the change in system attributes from the conventional to the Extensive Indoor+ system on the external factors and production costs (+ = increase, − = decrease, 0 = no effect) expressed per animal.

System attribute	Change in system attribute		External factor				Economic indicator
	Conventional	Extensive Indoor+	Animal welfare WQ index score	Ammonia emission kg NH_3/animal place/year	Particulate matter emission g PM_{10}/animal place/year	Antibiotic use $DDDA_F$	Production costs Eurocents/animal
Broiler breed	Ross 308	Hubbard JA757	+47.3	0/+	+	−10.7	+22.7
Length growth period	40 days	56 days	+28.5	+	+		+20.8
Stocking density	42 kg/m^2	25 kg/m^2	+69.9	−/0/+	+		+16.9
Straw bale enrichment	None	1 bale/1000 broilers	+12.4	0	0/+		+4.2
Grain enrichment	None	2 g/broiler	+6.6	0	+		+8.4
Length dark period	6 h/day, 4 h uninterrupted	8 h/day, uninterrupted	+16.3	0	0		+3.6
Natural light	None	3% of surface area	+15.9	0	+		+1.5
Empty barn period	8 days	7 days	0	+	+		−1.0
Feed composition	Concentrates +15% wheat	70% grain in feed (red. Protein cont.)	+6.6	−	+		+4.7
Outdoor access	None	Covered veranda	0	0	0		+2.6
Flock size	90,000	54,911	+2.3	0	0		0
Total			+205.7	+8%; +17%; +25%[1]	+23%; +40%; +57%[1]	−10.7	+84.4

[1] minimum change; most likely change; maximum change

Fernández et al., 2019). Next to broiler activity, other factors such as ventilation rates play a major role in PM concentrations and emissions (Cambra-López et al., 2010). A higher ventilation rate dilutes indoor PM_{10} concentration, gradually decreasing the level of indoor PM_{10} concentration (Peña Fernández et al., 2019). However, increased ventilation rates may result in increased PM emissions (Cambra-López et al., 2010).

To obtain insight in the cost-efficiency of the system attributes, the impact of the attributes on production costs and external factors were analyzed simultaneously. Fig. 2 shows the cost-efficiency of the system attributes in terms of the change in AW per percentage increase in production costs (X-axis) and their corresponding effect on the emission of NH_3 and PM_{10} per animal place per year (Y-axis). These effects are ranked from 'no effect on NH_3 and PM_{10} emission' to 'a positive effect on NH_3 and PM_{10} emission'. The figure shows that the system attributes 'outdoor access', 'flock size' and 'empty barn period' were the least cost-efficient in terms of AW. The attributes 'natural light', and to a lesser extent 'length of dark period', were the most cost-efficient in terms of AW. Both attributes did not affect NH_3 emission, and only 'natural light' elevated PM_{10} emission. Hence, 'length dark period' was the only system attribute that was cost-efficient in terms of AW and did not evoke trade-offs on NH_3 and PM_{10} emission.

3.2. *Synergy and trade-offs at farm level*

For each system, NH_3 emission, PM_{10} emission and the net return to labor and management originating at farm level was calculated and expressed per farm per year. The NH_3 and PM_{10} emission was calculated at farm level to assess whether the shift from conventional system towards the NDRS or Extensive Indoor+ system caused a synergy or a trade-off on NH_3 and PM_{10} emissions. Table 7 shows the net return to labor and management and the external factors originating from the systems at farm level. The NH_3 and PM_{10} emitted per farm per year was lowest in the Extensive Indoor+ system, followed by the conventional and NDRS system. This ranking can be explained by the differences in the emission per animal place and stocking density. Since we assumed floor surface to be fixed, a lower stocking density implies less broilers reared in the poultry house. When comparing the NDRS system with the conventional system, the higher emission per animal place per year offsets the lower number of broilers reared at the farm (approx. 81,500 broilers per round vs. 90,000 broilers per round). When comparing the Extensive Indoor+ system with the conventional system, results suggest that the higher emission per animal place per year is offset by the decrease in emission that is caused by the reduced number of broilers at the farm (approx. 55,000 broilers per round vs 90,000 broilers per

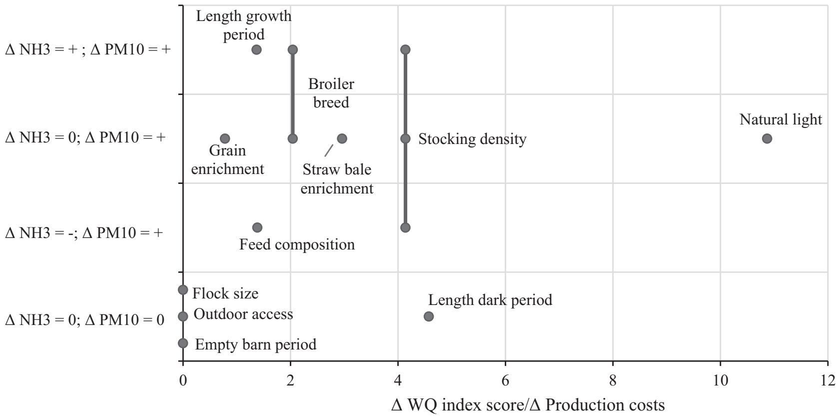

Fig. 2. Cost-efficiency of system attributes in the Extensive Indoor+ system relative to the conventional system.

Table 7
External factors and net return to labor and management generated from the production systems expressed per farm per year (based on 4928 m^2 floor space).

	External factor				Economic Indicator		
Production system	Animal welfare WQ index score	Ammonia emission Kg NH_3/farm/year	Particulate matter emission Kg PM_{10}/farm /year	Antibiotic use $DDDA_F$	Production costs Thousand euro/farm/year	Revenues Thousand euro/farm/year	Net return to labor and management Thousand euro/farm/year
Conventional	593.1	6,120[1]	1,980[1]	14.3	1513.7	1571.6	36.7
NDRS	678.7	6,275[2]	2,478[2]	3.6	1224.4	1287.4	40.1
Extensive Indoor+	798.8	4,356[2]	1,691[2]	3.6	962.1	1026.7	48.9

[1] based on emission factors provided by Expertise Centre Infomil (2019).
[2] based on emission factors estimated by experts.

round). Hence, elevated emissions per animal place, e.g. caused by a longer growth period, can be partly or fully compensated at farm level via a reduction of the stocking density. It should be taken into account that these results are partially obtained from expert estimation, and further research is required for final confirmation.

The results indicate that the highest net return to labor and management was earned in the Extensive Indoor+ system, followed by the NDRS and conventional system. These findings are in line with the findings of Van Horne (2020). The ranking is caused by the additional price premium farmers receive in the NDRS and Extensive Indoor+ system, which outweighs the higher production costs per animal and the reduction in broiler production per year. Gocsik et al. (2013) and Gocsik et al. (2015) underline the importance of price premiums for the long run profitability of alternative broiler production systems. Gocsik et al. (2013) show that the alternative Dutch broiler production systems were more economically feasible than the conventional system, provided that the price premium was received in the alternative system. However, in case of a 50% lower price premium the alternative systems performed worse than the conventional system in terms of economic feasibility. Given the uncertainty that may be associated with the level of the price premium, the alternative systems may lead to a higher income risk for farmers (Gocsik et al., 2015).

3.3. Sensitivity analysis

A sensitivity analysis was carried out to study the effect of price fluctuations and data uncertainties on the robustness of the results. Fig. 3 shows that the ranking of the systems based on kg NH_3/farm/year differed between the conventional and NDRS system only, while the ranking of the systems based on kg PM_{10}/farm/year emission was unaffected by the scenarios. Fig. 3 shows that the net return to labor and management ranged between 6.9 K EUR (worst case) and 88.7 K EUR (best case) in the conventional system. In the Extensive Indoor+ system, net return to labor and management ranged between 16.3 and 81.8, and between 28.4 and 78.1 K EUR, respectively. Results indicate that for the NDRS and Extensive Indoor+ system, the net return to labor and management is less sensitive to feed price fluctuations, compared to the conventional system. This finding can be explained by the lower amount of feed required in the NDRS and Extensive Indoor+ system compared to the conventional system. In this regard, two opposite forces occur: a higher feed conversion rate of the broiler (more feed per animal) and a lower stocking density (less feed per m^2) (Blanken et al., 2019). Verspecht et al. (2011) indicate that the impact of feed price fluctuations on farm profits might be less negative at lower stocking densities. The lower sensitivity of the NDRS and Extensive Indoor+ system to feed price fluctuations is reflected in the ranking of these systems. In the worst case scenario, net return to labor and management was highest in the Extensive Indoor+ system and lowest in the conventional system. In contrast, in the best case scenario, net return to labor and management was highest in the conventional system and lowest in the Extensive Indoor+ system.

3.4. Policy implications and outlook

The European Commission (2020) set up the Farm to Fork Strategy to accelerate the transition towards more sustainable food systems. This strategy includes goals such as a reduction in nutrient losses (especially nitrogen and phosphorus) and a reduction in the sales of antimicrobials for farmed animals and in aquaculture by 50% in 2030. Our study provides valuable insights that support policy making in the development of systems that coincide with these goals. First, our findings suggest that there is a scope for designing optimal broiler production systems by selecting system attributes based on their cost-efficiency in terms of AW and their impact on ABU, NH_3 and PM_{10} emission. Using this approach, multiple external factors can be mitigated at a minimum increase in production costs and the price premium required for its

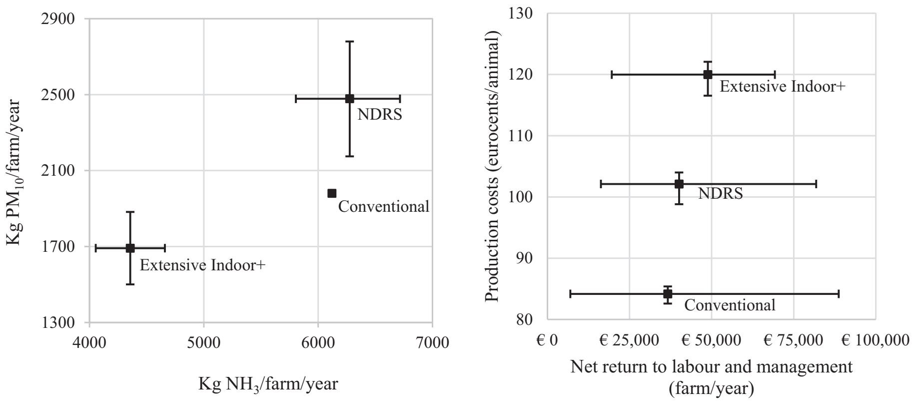

Fig. 3. Sensitivity analysis results on kg NH_3 and PM_{10} emitted from the production systems expressed per farm per year and net return to labor and management expressed per year (based on 4928 m^2 floor space).

introduction. Second, our study showed that most changes in system attributes that enhanced AW had a trade-off in terms of NH_3 and PM_{10} emission per animal place per year. However, these effects were partly (NDRS) or fully (Extensive Indoor+) offset at farm level via a lower stocking density. This insight is particularly relevant because a major shift towards more extensive broiler production systems is projected to occur in the EU in 2026. In 2026, over 100 leading food companies across Europe will adopt the AW standards of the Better Chicken Commitment (2020). Third, our study showed that the changes in system attributes in the NDRS and Extensive Indoor+ system enhanced production costs per animal and lowered the output of broilers relative to the conventional system. Broiler farmers switching to towards the NDRS or Extensive Indoor+ system could maintain or even improve their income due to the price premiums associated with their products. Whereas the price premiums resulted in a higher consumer price, in case of the NDRS, the price increase did not lower consumer welfare as it was offset by the increase in consumer valuation of the product (Vissers et al., 2021). The lower output of broilers can be explained by the longer growth period of the broiler and the lower stocking density in the NDRS and Extensive Indoor+ system relative to the conventional system. Implementation of measures that lower total annual output of broilers might harm the profitability of the processing industry if not combined with a price premium or an expansion of broiler production capacity.

4. Conclusions

The findings from this paper indicate that improvements in AW may cause a synergy with ABU and do not necessarily cause a trade-off with NH_3 emission. Nearly all AW improvements caused a trade-off with PM_{10} emission. Findings also indicate that the cost-efficiency of the system attributes in terms of AW and their corresponding effect on the emission of NH_3 and PM_{10} per animal place per year differed among system attributes. Based on these findings, we conclude that the development of broiler production systems can exploit the synergy between AW, ABU and NH_3 emission and minimize the trade-off between AW and PM_{10} emission. The insights obtained from this paper can serve as a basis for future research that explores the potential of future broiler production systems minimizing external factors originating from broiler production systems. We suggest that future research applies this approach to other livestock production systems to expose the synergy and trade-offs caused by these systems and the potential for optimization of these livestock production systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2021.103070.

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