Animal 18 (2024) 101155

Contents lists available at ScienceDirect

Animal

The international journal of animal biosciences

Access to bedding and outdoor runs for growing-finishing pigs: is it possible to improve welfare without increasing environmental impacts?

A.K. Ruckli [a,b,1], S. Hörtenhuber [a,1], S. Dippel [c], P. Ferrari [d], M. Gebska [e], M. Heinonen [f], J. Helmerichs [c], C. Hubbard [g], H. Spoolder [h], A. Valros [f], C. Winckler [a], C. Leeb [a,*]

[a] Department of Sustainable Agricultural Systems, University of Natural Resources and Life Sciences, Gregor-Mendel-Str. 33, 1180 Vienna, Austria
[b] Centre for Proper Housing of Ruminants and Pigs, Federal Food Safety and Veterinary Office, Agroscope, Tänikon, 8356 Ettenhausen, Switzerland
[c] Institute of Animal Welfare and Animal Husbandry, Friedrich-Loeffler-Institut, Dörnbergstr. 25/27, 29223 Celle, Germany
[d] Department of Agricultural Engineering and Economics, Centro Ricerche Produzioni Animali, 42121 Reggio Emilia, Italy
[e] Management Institute, Warsaw University of Life Sciences, Nowoursynowska 166, 02-787 Warsaw, Poland
[f] Department of Production Animal Medicine and Research Centre for Animal Welfare, Faculty of Veterinary Medicine, University of Helsinki, P.O. Box 57, FI- 00014 Helsinki, Finland
[g] Newcastle University, Kings Road, NE1 7RU Newcastle upon Tyne, United Kingdom
[h] Wageningen Livestock Research, Wageningen University & Research, De Elst 1, 6708WD Wageningen, the Netherlands

ARTICLE INFO

Article history:
Received 9 December 2023
Revised 29 March 2024
Accepted 4 April 2024
Available online 10 April 2024

Keywords:
Acidification
Eutrophication
Exploratory behaviour
Global warming
Life Cycle Assessment

ABSTRACT

Providing bedding or access to an outdoor run are husbandry aspects intended to improve pig welfare, which is currently financially supported through animal welfare schemes in several European countries. However, they may significantly affect the environment through changes in feed efficiency and manure management. Therefore, the aim of this paper was to compare farms differing in animal welfare relevant husbandry aspects regarding (1) the welfare of growing-finishing pigs and (2) environmental impact categories such as global warming (**GW**), acidification (**AC**), and freshwater (**FE**) and marine eutrophication (**ME**), by employing an attributional Life Cycle Assessment. We collected data on 50 farms with growing-finishing pigs in seven European countries. Ten animal-based welfare indicators were aggregated into three pig welfare indices using principal component analysis. Cluster analysis of farms based on husbandry aspects resulted in three clusters: **NOBED** (31 farms without bedding or outdoor run), **BED** (11 farms with bedding only) and **BEDOUT** (eight farms with bedding and outdoor run). Pigs on farms with bedding (BED and BEDOUT) manipulated enrichment more often ($P < 0.001$), pen fixtures less frequently ($P = 0.003$) and showed fewer oral stereotypies ($P < 0.001$) than pigs on NOBED farms. There were fewer pigs with a short(er) tail on farms with than without bedding ($P < 0.001$). Acidification of BEDOUT and BED farms was significantly higher (compared to NOBED farms $P = 0.002$) due to higher ammonia emissions related to farmyard manure. Also, BEDOUT farms had higher ME than NOBED farms ($P = 0.035$). There were no significant differences regarding GW and FE between husbandry clusters, due to the large variability within clusters regarding feed composition and conversion. Therefore, both husbandry aspects associated with improved animal welfare have a significant influence on some environmental impacts, such as acidification and marine eutrophication. Nevertheless, the large variation within clusters suggests that trade-offs may be minimised through e.g. AC and ME.

Implications

This study contributes to knowledge on the environmental impacts of animal welfare improvement measures for growing-finishing pigs (bedding, outdoor run) with a focus on estimating potential trade-offs between these measures and the environment. The large variation between farms with the same welfare improvement measures indicates the potential to reduce ammonia emissions through management. Therefore, current best practices and innovations should be encouraged to reduce ammonia emissions in pig housing systems with bedding. Our findings also show that farms with animal welfare improvement measures do not necessarily perform worse than intensive housing systems regarding freshwater and marine eutrophication as well as global warming.

* Corresponding author.
E-mail address: christine.leeb@boku.ac.at (C. Leeb).
[1] Equally contributing authors.

https://doi.org/10.1016/j.animal.2024.101155
1751-7311/

Introduction

In the past, the need to increase productivity has driven pig farming towards more intensive indoor husbandry systems with a rather barren environment, often with fully slatted floors and high stocking densities, especially in the growing-to-finishing phase of pig production. Such housing systems are unable to meet pigs' behavioural needs and may thus direct their intrinsic motivation to explore towards inappropriate objects or other pigs, especially their tails (EFSA, 2022). Other frequently reported animal welfare problems in intensive systems include body lesions and lameness (Pandolfi et al., 2017a). As a consequence, addressing those pig welfare problems has become an important issue for both science (EFSA, 2022) and society (European Commission, 2016). In several European countries, private farm assurance schemes (e.g., RSPCA (United Kingdom), Hofkultur (Austria), Beter Leven (The Netherlands), Haltungsform (Germany)) aiming at improved pig welfare include husbandry aspects such as increased space allowance, reduction of slatted flooring, provision of bedding or access to an outdoor run which are exceeding the European legal minimum requirements regarding animal welfare.

However, trade-offs regarding other aspects of sustainability (e.g., production costs, farmers' workload, emissions) need to be considered. Emissions from pig production such as methane (**CH_4**), nitrous oxide (**N_2O**), carbon dioxide (CO_2), ammonia (**NH_3**), phosphorous or nitrogen contribute to global warming, acidification and eutrophication of water bodies (Philippe et al., 2011a; Philippe and Nicks, 2015).

Trade-offs between animal welfare and the environment have already been documented. For example, on the one hand, providing bedding is important for fulfilling behavioural needs regarding exploration as well as comfort around resting (EFSA, 2022). On the other hand, bedding might lead to higher N_2O but lower CH_4 emissions, since farmyard manure (=solid manure as opposed to liquid manure, i.e. slurry) provides anaerobic and aerobic conditions which are optimal for N_2O formation, whereas CH_4 formation requires primarily anaerobic conditions (Philippe and Nicks, 2015). However, there is conflicting evidence on the impact of bedding on NH_3 emissions, since bedded systems compared to fully slatted flooring systems are often confounded with increased space allowance and thus potentially higher NH_3 emissions. In addition, the release of NH_3 depends also on other factors such as air velocity and temperature (Philippe et al., 2011a). Access to an outdoor run usually coincides with higher space allowance and thus improves locomotion and the separation of functional areas (EFSA, 2022) in addition to providing different climatic conditions and sunlight. The more space, however, may also result in higher NH_3 emissions, whereas access to an outdoor run might lead to increased energy demands of pigs due to increased locomotion and thermoregulation, which in turn impairs feed conversion (Patience et al., 2015). Since the feed conversion ratio is an important factor in reducing environmental impacts (Reckmann and Krieter, 2015), providing access to an outdoor run may present a trade-off between animal welfare and environmental impacts. However, little knowledge based on on-farm data is currently available on whether housing systems for growing-finishing pigs differing in animal welfare relevant aspects also differ in terms of their contributions to global warming (**GW**), freshwater and marine eutrophication (**FE, ME**) and acidification (**AC**).

Therefore, we aimed to investigate how farms providing bedding and/or access to an outdoor run differ regarding animal welfare and regarding environmental impact as measured through the Life Cycle Assessment impact categories GW, AC, FE and ME.

We hypothesised, that:

- provision of bedding and access to an outdoor run is associated with improved animal welfare (e.g. less tail lesions, reduced lameness; EFSA, 2022).
- provision of bedding and access to an outdoor run is associated with (a) higher GW (due to higher N_2O emissions and decreased feed efficiency), (b) higher EP (due to decreased feed efficiency) and (c) higher AC (due to higher NH_3 emissions).

Material and methods

Farms and data collection

We collected the data between May and October 2018 in a convenience sample of 50 farms with growing-finishing pigs, in which we aimed to include a large variety of farms to represent the range of possible situations regarding animal welfare and environmental impacts. In total, 23 finishing and 27 breeding-to-finishing pig farms in seven European countries (Austria, Germany, Finland, Italy, Netherlands, Poland, United Kingdom) were assessed. Farms included 17 conventional and seven organic farms and 26 farms producing for voluntary labelling schemes related to aspects of sustainability, e.g., higher animal welfare standards and genetically modified organism-free feeding (Table 1). The assessment protocol consisted of a farmer interview and direct observations of animals and the housing system (Munsterhjelm et al., 2021). During the 1-day visit to each of these farms, a researcher from the respective country conducted the farmer interview, whilst resource- and animal-based data were collected directly in the barn by one of two trained persons (direct observations).

Assessment of animal- and resource-based indicators

For the direct observations, we developed a standard operating protocol (The SusPigSys Team, 2020) based on literature such as Welfare Quality® (2009) and ProPig (Leeb et al., 2019) as well as expert knowledge from within the SusPigSys project consortium. The two observers conducting the direct observations were trained and tested for inter-observer reliability (before and after the farm visits). The Supplementary Material S1, Supplementary Tables S1 and S2 contain information on the inter-observer reliability test.

In farms with less than 15 pens for finishing pigs, all pens were assessed and included in the study. If there were more than 15 pens for growing-finishing pigs, 15 pens were pseudo-randomly selected before entering the buildings, considering different age categories.

Exploratory and stereotypic behaviours (Table 2) were assessed at the group level using scan sampling and expressed as a percentage of active pigs showing the respective behaviour. The assessment started 2 min after the observer had stood in front of the pen to standardise the pigs' behavioural reaction to the presence of the observer. All pigs visible from outside the pen that were sitting or standing but not eating or drinking were scanned once for performing exploratory and stereotypic behaviours (Mullan et al., 2009).

After that, clinical indicators (Table 2) were assessed in the same pens and expressed as pen prevalence. For this purpose, the observer walked slowly through the pen and gently encouraged pigs lying down to stand up to facilitate the assessment of the clinical indicators. All animals were inspected in pens containing up to 100 pigs, while for larger groups, a representative sample of at least 50% of the pigs was selected. Mortality was calculated for the year preceding the visit based on farm records.

Table 1
Descriptive characteristics of housing and selected productivity indicators of the three pig farm clusters NOBED (farms without bedding and outdoor run), BED (farms with bedding but no outdoor run) and BEDOUT (farms with bedding and outdoor run).

Farm cluster	NOBED			BED			BEDOUT		
Farms (n)		31			11			8	
FF/BF (n)		16/15			5/6			2/6	
C/O/L (n)	10/0/21			7/2/2			0/5/3		
Country (n)	5 AT, 6 DE, 1 FI, 4 IT, 5 NL, 5 PL, 5 UK			3 FI, 1 IT, 5 PL, 2 UK			4 AT, 1 DE, 1IT, 2 NL		
Item	Q1	M	Q3	Q1	M	Q3	Q1	M	Q3
Housing									
Number of finishing pigs sold	2 581	5 000	7 000	380	519	3 668	854	1 646	2 404
k-value[1] (space allowance per pig)	0.05	0.06	0.07	0.06	0.07	0.09	0.11	0.14	0.17
Slatted floor (% of area)	49	90	100	0	0	38	12	30	44
Bedding (% of pens)	0	0	0	93	100	100	100	100	100
Outdoor (% of pens)	0	0	0	0	0	0	97	100	100
Proportion of farmyard manure (%)	0	0	0	14	100	100	27	40	58
Productivity									
Weight beginning (kg)	29	30	33	28	30	30	30	30	32
Weight end (kg)	116	119	127	112	127	139	118	122	130
kg BMNS pig[1]	85	89	97	84	97	109	85	91	99
Average daily gain (g/d)	758	845	877	700	771	929	747	814	841
Feed conversion ratio (kg/kg)	2.6	2.9	3.7	2.8	3.1	3.8	2.6	3.6	3.7
Feed composition[2]									
Homegrown feed (%)	0	0	29	0	31	57	0	8	42
Bought-in cereals, grain legumes and oil crops (%)	13	40	67	4	36	53	14	56	82
Bought-in by-products and other feed (%)	1	20	34	0	0	17	2	12	22
Compound feeds (%)	0	6	24	7	17	36	0	0	14

Abbreviations: FF = finishing farm; BF = breeding-to-finishing farm; C = conventional; O = organic; L = other labels; Q1 = first quartile; M = median; Q3 = third quartile; BMNS = body mass net sold.
[1] Considering weight classes from the beginning to the end of fattening as described above.
[2] More detailed data about the feed can be found in Supplementary Tables S3 and S4.

Resource-based indicators (e.g. bedding, access to an outdoor run, floor type) were assessed for all pens in which clinical and behavioural assessments had been carried out (The SusPigSys Team, 2020). A pen was counted as having bedding when at least a thin layer of bedding (thin layer = floor visible or/and occasional holes where the floor can be seen; straw or sawdust) was present. An outdoor run was defined as a fully, partly, or unroofed area with fully or partly slatted or solid concrete flooring physically separated from the pen, which provided access to the outdoor climate. No farm provided access to pasture to their pigs. Bedding and outdoor runs were summarized at the farm level as percentages of pens with bedding or outdoor run, respectively. The size of each slatted and solid floor area was also measured. As a proxy for the mean space allowance while accounting for the different weight categories, we calculated the k-value for space requirement per pig at pen level using the following formula (Petherick and Phillips, 2009):

$$k = \text{total area}/\text{number of pigs}/W^{0.67} \quad (1)$$

where W = average weight of the pigs in the pen in kg. The total area is in m^2.

k-value and percentage of the slatted area were then computed as the arithmetic means across all pens at farm level.

Life cycle assessment

We conducted an attributional Life Cycle Assessment with the system boundary from the 'cradle' to the farm gate (Fig. 1). To make the results of breeding-to-finishing farms comparable with finishing farms, only the results of the growing-finishing phase were used for the present study. The four Life Cycle Assessment impact categories and their impact assessment methods were:

- Global warming (GW; kg CO_2-eq; GWP_{100} according to IPCC 2013 v1.03)
- Marine eutrophication (ME; g N-eq; ILCD 2011 Midpoint + v1.10 / EC-JRC Global)
- Freshwater eutrophication (FE; g P-eq; ILCD 2011 Midpoint + v1.10/EC-JRC Global)
- Acidification (AC; g SO_2-eq; CML-IA non−baseline 3.04 / EU25)

They were expressed per 1 kg body mass net sold (=sold amounts of pigs' body mass minus body mass bought-in in kg; on breeding-to-finishing farms, the body mass bought-in was the body mass when moved from the weaning unit to the finishing unit).

For each farm, we used farm-specific primary data (farm size, productivity figures, number of bought-in and sold pigs per age category, feed and manure management, and amount of bedding) wherever possible. Detailed information on the average feed composition can be found in Supplementary Table S3. Otherwise, we used default values, e.g. for the composition of three types of compound feed (Supplementary Table S4) and the nitrogen excretion per growing-finishing pig (12.1 kg per pig place and year; EMEP/EEA, 2016). This was mainly due to a lack of information on feed components regarding the CP content and pigs' feed intake. We further calculated Life Cycle Assessment impact factors of the background data (feed components, straw) with SimaPro version 9 based on Ecoinvent (Wernet et al., 2016), Agribalyse (Koch and Salou, 2015) and Agri-footprint (Durlinger et al., 2017) data, using economic allocation wherever allocation was needed. Construction of infrastructure (machinery and buildings) was not considered within the Life Cycle Assessments due to missing data. Life Cycle Assessment calculations have been described in more detail in Ruckli et al. (2021).

Table 2
Description of the animal-based indicators used for the on-farm assessment of pigs.

Indicators	Description
Behaviours	
Stereotypies	Repeated, relatively invariable sequence of movement that has no obvious function. This includes tongue sucking, tongue rolling, sham-chewing, and stone chewing.
Manipulation of other pigs	Snout/mouth is in obvious/prolonged contact (min 5 sec) with any part of another pig excluding the head
Manipulation of pen fixtures	Snout/mouth is in obvious/prolonged contact (min 5 sec) with manure, barren floor or fixtures of the pen.
Manipulation of enrichment	Snout/mouth is manipulating (obviously/prolonged contact, min 5 sec) either object (e.g. chain, wooden block, plastic toy) and organic material (e.g. straw, hay, sawdust, roughage, lucerne pellets) provided on the floor (incl. bedding) or in a rack.
Clinical indicators	
Tail lesions	Dry crust (brown) or fresh blood (red) of any size, swelling, or a combination.
Short tail	At least 2 cm shorter than expected natural, undocked length. All docked pigs were counted as having short tails.
Ear lesions	At least one ear edge is affected by crusted, reddened ear skin surface (>1cm diameter), anatomically changed structure, and clearly missing parts of ear tips or/and earlobes. Does not include lesions which are not on the ear edge, especially scratches on the outer side of the ear due to social interactions.
Lameness	Clearly visible reduced weight bearing on one limb (‘limping’) up to the animal being unable to walk. A stiff gait is not considered as lameness.
Hospitalisation	One or more pigs present in group that would benefit from being in a hospital pen: obviously sick, weak, may have problems accessing food and water or be bullied, should be separated to avoid deterioration of health or spread of infection.
Mortality	Percentage of pigs that died before slaughter out of the total pigs

Statistics

Statistical analysis was done in SAS 9.4 (SAS Institute Inc., 2016). Graphical plots were created with R 4.1.3.

Cluster analysis

We performed a cluster analysis (PROC CLUSTER; hierarchical cluster analysis with Ward method) to group the farms systematically based on the two husbandry aspects ‘provision of bedding’ and ‘access to outdoor run’. The husbandry aspects were included as a share of pens with access to outdoor run and a share of pens with bedding, respectively, standardised (PROC STANDARD) with a mean of 0 and a SD of 1 before clustering. The number of clusters was based on Cubic Clustering Criterion, Pseudo F, and Pseudo T-squared statistics. Additionally, the average distance between the clusters was graphically checked in a dendrogram.

Principal component analysis

To reduce the number of tests for investigating trade-offs between animal welfare and Life Cycle Assessment impact categories, we conducted a principal component analysis (PROC PRINCOMP) to condense the ten animal-based indicators listed in Table 2 into fewer principal components. The ten indicators were standardised (PROC STANDARD) with a mean of 0 and a SD of 1 before the principal component analysis. Principal components were chosen based on an Eigenvalue larger than one. In the following, we use the term ‘pig welfare indices’ to refer to the principal components.

Differences between farm clusters regarding animal welfare

To analyse differences in animal welfare between the three identified farm clusters (**BEDOUT**; farms with bedding and outdoor run, **BED**; farms with bedding but no outdoor run, **NOBED**; farms without bedding and outdoor run), all ten animal-based indicators (Table 2) were first tested individually to gain insights into specific animal welfare issues. This was followed by testing the three pig welfare indices as those were also used to assess the trade-offs with Life Cycle Assessment impact categories. For both types of analyses, we used a mixed model (PROC MIXED) with farm clusters as a fixed effect. Country was used as a random effect to take country-specific differences into account (e.g. feed, breed, observer). Residuals were graphically checked for normal distribution and homoscedasticity (PROC UNIVARIATE). If we found a signifi-

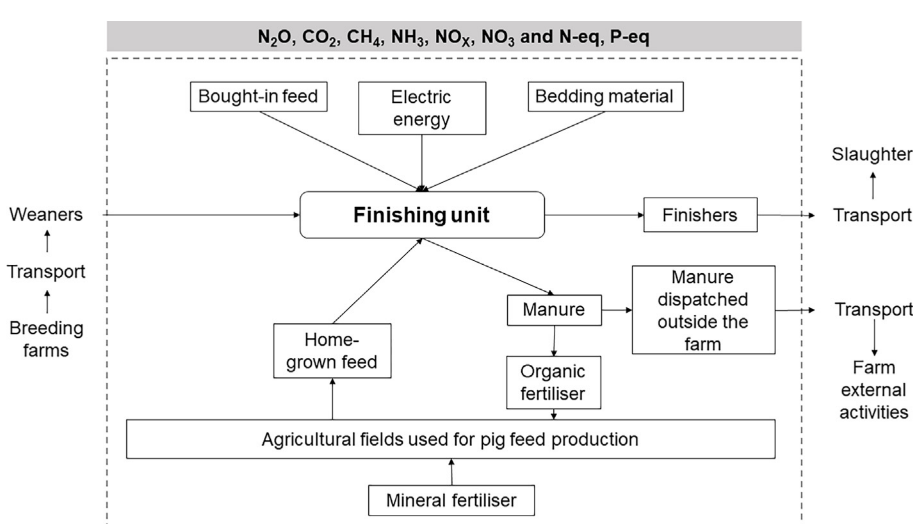

Fig. 1. System boundaries for finishing pig farms and the finishing unit of breeding-to-finishing pig farms.

cant difference in the global *P*-value, we used a posthoc test (Kruskal-Wallis Test with Bonferroni-Holm correction) to determine the differences between the farm clusters. A *P*-value ≤ 0.05 was considered to indicate a significant difference.

Differences between farm clusters regarding Life Cycle Assessment impact categories

The four Life Cycle Assessment impact categories (GW, AC, ME, FE) were tested for differences across the three farm clusters using the same model as described for the animal welfare indices.

Results

Farm clusters

Three farm clusters were identified: (i) NOBED included 31 farms that neither provided bedding nor access to outdoor runs, (ii) BED included 11 farms with bedding but without outdoor runs, and (iii) BEDOUT included eight farms with both bedding as well as access to concrete outdoor runs (no pasture access; Table 1).

BEDOUT and BED farms had a lower percentage of slatted floors than NOBED farms (BEDOUT: 30%, BED: 0% and NOBED: 90%; median). BEDOUT farms provided the largest space allowance to their pigs (BEDOUT: k = 0.14, BED: k = 0.07 and NOBED: k = 0.06; median).

Pig welfare indices

The first three pig welfare indices of the principal component analysis accounted for 57% of the overall variance of the data set (Table 3). The indicators short tails, stereotypies and manipulation of pen fixtures contributed most to the index **'Stereo&ShortTail'**, lameness, hospitalisation and tail lesions contributed most to **'Lame&Hospital'**, and mortality and manipulation of enrichment and other pigs contributed most to **'Mortality&ManEnrich'**.

Differences between farm clusters regarding animal welfare

Stereotypic behaviour (NOBED: 7.6 ± 5.8, BED: 0.7 ± 1.5, BEDOUT: 2.1 ± 3.2% of active pigs; means ± SD; $P < 0.001$; Fig. 2 and Supplementary Table S5) and manipulation of pen fixtures (NOBED: 4.7 ± 3.7, BED: 0.9 ± 1.1, BEDOUT: 1.1 ± 1.7% of active pigs, $P < 0.001$) were less prevalent in farms with bedding compared to farms without, whereas manipulation of enrichment (NOBED: 2.3 ± 2.8, BED: 21.6 ± 21.1, BEDOUT: 15.0 ± 7.9% of active pigs; $P < 0.001$) was more frequently observed in farms with bedding compared to farms without.

Statistically significant differences regarding clinical indicators were only found for the prevalence of short tails and mortality, with farms with bedding (BED: 25.2 ± 38.3, BEDOUT: 28.1 ± 32.1% of pigs; means ± SD; Fig. 3 and Supplementary Table S5) having fewer animals with short tail compared to farms without (NOBED: 94.3 ± 17.9% of pigs, $P < 0.001$), and a lower mortality in BED (1.1 ± 0.7% of pigs) farms compared to the other two farm clusters (NOBED: 2.4 ± 1.1, BEDOUT: 2.9 ± 1.7% of pigs; $P < 0.001$). Animal welfare index values for Stereo&ShortTail were significantly better on farms with bedding (BEDOUT: −1.28 ± 0.42, BED: −2.12 ± 0.36) compared to NOBED farms (1.09 ± 0.26, $P < 0.001$; Fig. 4, Table 4). The indices Lame&Hospital and Mort&ManEnrich did not differ between the three farm clusters.

Table 3
Loading of the 10 animal-based indicators on the three pig welfare indices (Principal components PC1-PC3). Loadings of >= 0.4 and <=-0.4 indicate the highest contributing indicators per PC.

Animal-based indicators	Pig welfare indices		
	Stereo&ShortTail PC1	Lame&Hospital PC2	Mort&ManEnrich PC3
Variation explained	30%	15%	12%
Stereotypies	0.449	−0.102	−0.111
Manipulation of other pigs	0.240	−0.188	0.380
Manipulation of pen fixtures	0.418	−0.191	0.211
Manipulation of enrichment	−0.329	0.155	0.434
Short tail	0.449	−0.130	−0.175
Tail lesions	0.225	0.427	−0.241
Ear lesions	0.364	0.048	0.022
Lameness	0.080	0.601	0.118
Hospitalisation	0.191	0.573	0.011
Mortality	0.178	0.049	0.712

Abbreviations: Stereo&ShortTail = principal component 1 to which the indicators short tails, stereotypies and manipulation of pen fixtures contributed most; Lame&Hospital = principal component 2 to which the indicators lameness, hospitalisation and tail lesions contributed most; Mortality&ManEnrich = principal component 3 to which the indicators mortality, manipulation of enrichment and manipulation of other pigs contributed most.

Differences between farm clusters regarding Life Cycle Assessment impact categories

The three farm clusters overlapped regarding GW and FE (Fig. 4), while AC was significantly higher in farms with bedding (BEDOUT: 67.1 ± 7.5, BED: 73.5 ± 6.3) compared to NOBED farms (44.3 ± 3.8 g SO_2-eq per kg body mass net sold; $P = 0.002$; Fig. 4, Table 4). Furthermore, ME was higher in BEDOUT compared to NOBED farms (BEDOUT: 36.6 ± 5.0, BED: 19.0 ± 2.6 g N-eq per kg body mass net sold; $P = 0.035$), whereas BED farms did not differ significantly from the other two clusters (Table 4). Neither GW nor FE differed between the three farm clusters (Fig. 4, Table 4).

Discussion

Confirming our hypothesis, the provision of bedding was associated with an improved situation regarding animal welfare indicators used in this study (especially those regarding exploratory behaviour) but simultaneously with higher AC (and partly ME). The other Life Cycle Assessment impact categories did not differ from a statistical point of view. In contrast, access to outdoor runs in addition to bedding was not associated with further improvement in animal welfare. However, ME of farms with an outdoor run in addition to bedding was higher than that of farms without bedding.

Farm clusters

While our sample of typical farms for each country can be considered to reasonably reflect the diversity of pig farming systems in Europe, it has to be kept in mind that the visited farms are a convenience sample and therefore results have to be carefully interpreted. Cluster analysis revealed three farm groups that differed in terms of housing conditions: one group with neither bedding nor outdoor run (NOBED) and two farm groups which provided bedding but differed regarding the provision of an outdoor run (BED, BEDOUT). NOBED farms can be considered as the typical conventional farms and are very uniform across Europe since they are mostly producing according to the minimum requirements regarding the housing of pigs (EU Council Directive 2008/120/EC). Farms producing in compliance with higher welfare standards (providing

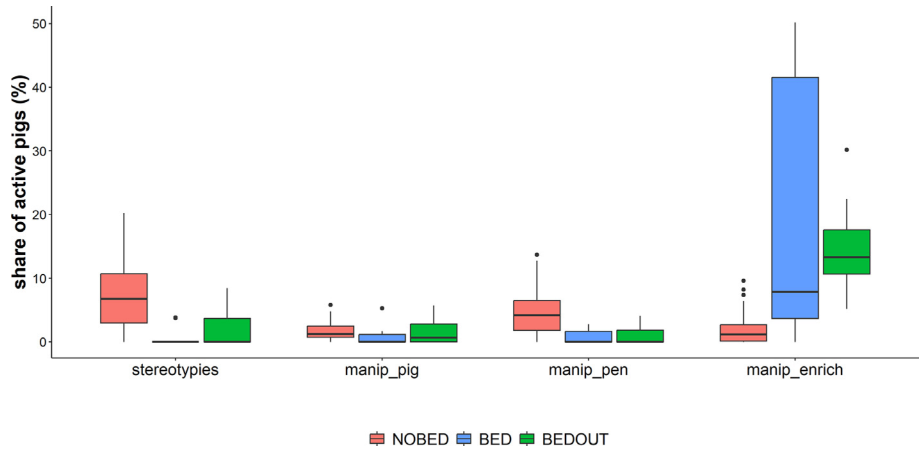

Fig. 2. Boxplots of the share of active pigs (in %) performing stereotypies, manipulating other pigs (manip_pig), manipulating pen fixtures (manip_pen) and manipulating enrichment (manip_enrich) by farm cluster (NOBED = farms without bedding and outdoor run, BED = farms with bedding but no outdoor run, BEDOUT = farms with bedding and outdoor run). Horizontal lines in the box represent the median value, the coloured boxes represent quartiles 2 and 3 (50% of data), and the top and bottom line minimum and maximum values (excluding outliers, which are represented by points).

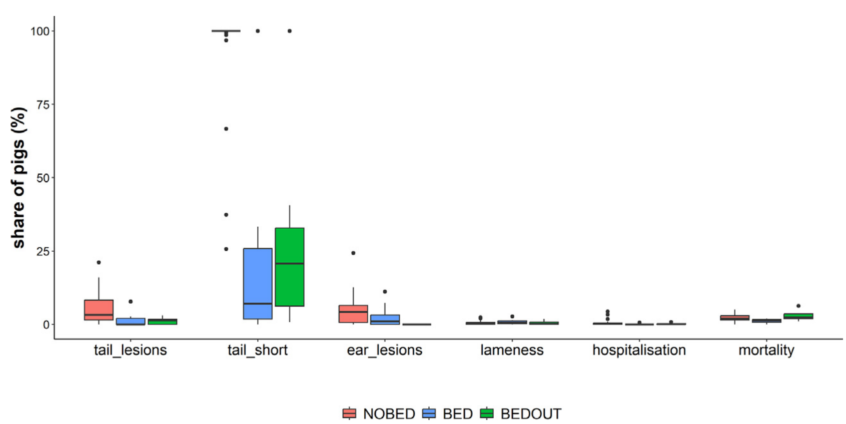

Fig. 3. Boxplots of the share of pigs (in %) with tail lesions, short tails, ear lesions, being lame, needing hospitalisation as well as mortality of the finishing pigs by farm cluster (NOBED = farms without bedding and outdoor run, BED = farms with bedding but no outdoor run, BEDOUT = farms with bedding and outdoor run). Horizontal lines in the box represent the median value, the coloured boxes represent quartiles 2 and 3 (50% of data), and the top and bottom line minimum and maximum values (excluding outliers, which are represented by points).

bedding, outdoor run) are still the minority across Europe. For example, less than 1% of pigs in the European Union in 2020 were produced organically (Augère-Granier, 2020). Those farms vary widely regarding their characteristics, depending on their labelling scheme as well as individual management, which is reflected by our farm sample.

The NOBED farms were characterised by more fattening pigs sold per year, but other productivity data were comparable to the other farm clusters and in the range of the average European pig farm (Deblitz et al., 2020). Interestingly, the k-values on all assessed farms were higher than the European legal minimum requirement (EU Council Directive 2008/120/EC; e.g. k-value = 0.02–0.04 for pigs weighing 30–110 kg), especially on BEDOUT farms (median k-value: BEDOUT: 0.14, BED: 0.07, NOBED: 0.06). The comparatively high k-values even in NOBED farms may be explained by the inclusion of pigs of all weight categories observed on the farms when calculating the k-value, as pigs with a lower weight at the beginning of the fattening period are housed in the same pens and, therefore, contribute to the high k-values.

Differences between farm clusters regarding animal welfare

The observation of more pigs manipulating enrichment material and fewer pigs performing stereotypic behaviour or manipulating pen fixtures in herds with bedding (BEDOUT, BED) confirms our hypothesis. Bedding, especially straw (Tuyttens, 2005), is essential for pigs to fulfil their motivation for exploratory behaviour including foraging and rooting (Studnitz et al., 2007). Several studies have in fact found that pigs with access to bedding show less exploratory behaviour directed towards pen mates and pen fixtures (Pedersen et al., 2014) and less stereotypic behaviour (Lawrence and Terlouw, 1993). Stereotypies have mostly been reported for pregnant sows fed restrictively, and there are limited data available on the occurrence (prevalence, type) of stereotypic behaviour in growing-finishing pigs. Growing-finishing pigs kept on fully slatted floor systems compared to solid floor systems (with or without bedding) may have a higher risk of developing stereotypic behaviour (Spoolder et al., 2000).

The prevalence of short tails was lower on farms with bedding (BEDOUT, BED) than on farms without (NOBED). In this study, we assessed whether tails were shorter than their natural length irrespective of the cause because it could not be validly determined whether loss of length was due to tail docking or tail biting. Even though tail docking must not be performed routinely in the European Union (EU Council Directive 2008/120/EC), it is still a common measure practised by farmers (De Briyne et al., 2018) for reducing the risk of tail biting (EFSA, 2022). This is reinforced by our data, where 62% of the farms performed tail docking on all their pigs as a routine (farmer questionnaire, results not shown).

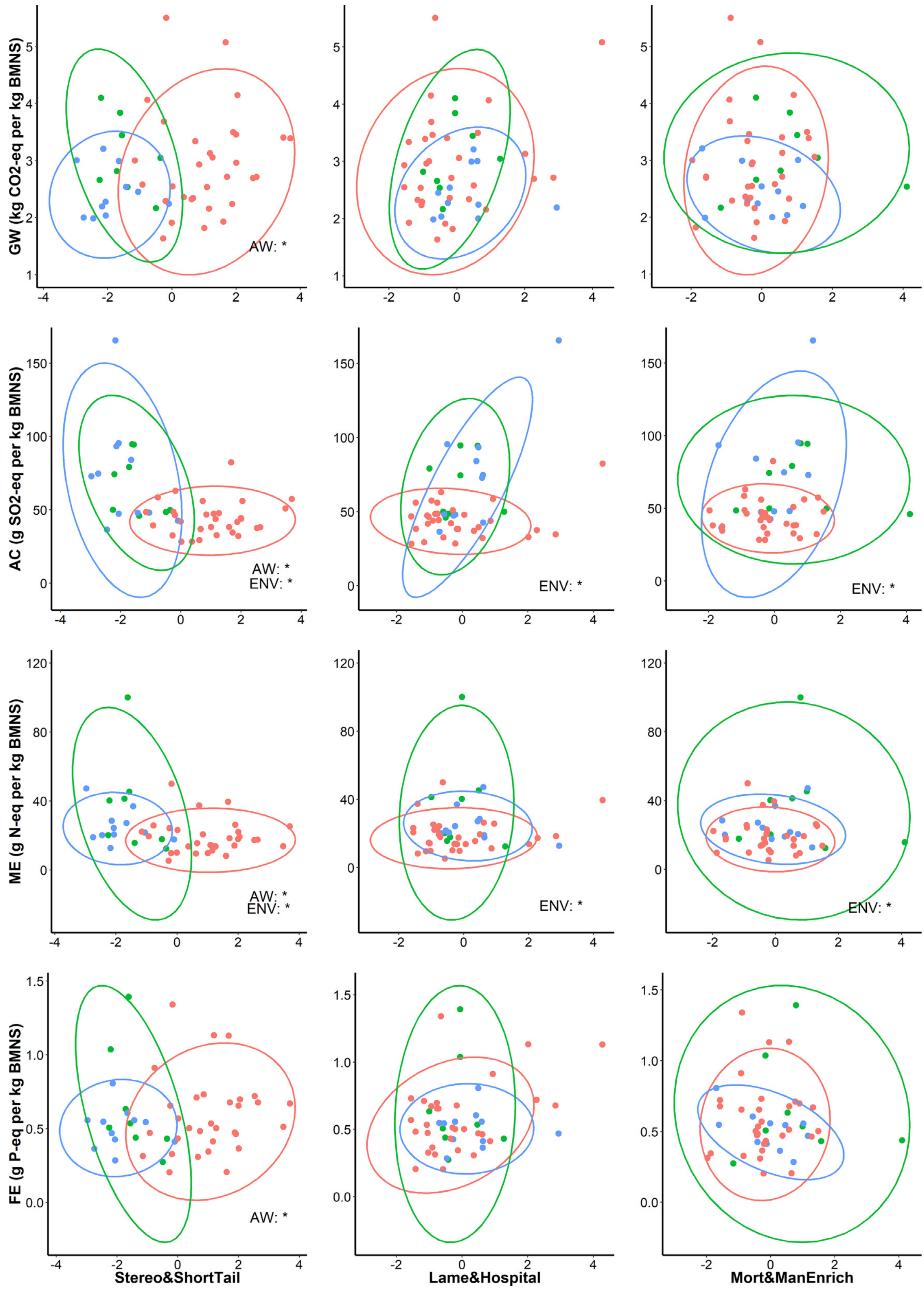

Fig. 4. Scatterplots representing pig farms of the three farm clusters (red: NOBED = farms without bedding and outdoor run, blue: BED = farms with bedding but no outdoor run, green: BEDOUT = farms with bedding and outdoor run) arranged by the three pig welfare indices (horizontal: Stereo&ShortTail = principal component 1 to which the indicators short tails, stereotypies and manipulation of pen fixtures contributed most; Lame&Hospital = principal component 2 to which the indicators lameness, hospitalisation and tail lesions contributed most; Mortality&ManEnrich = principal component 3 to which the indicators mortality, manipulation of enrichment and manipulation of other pigs contributed most; values below zero = higher welfare, values above zero = lower welfare; principal component analysis) and impacts on global warming (GW), acidification (AC), marine (ME) and freshwater (FE) eutrophication (vertical). Significant differences between farm clusters regarding Life Cycle Assessment impact categories (ENV) and animal welfare (AW) are based on a mixed model. Significant differences (P < 0.05) are indicated by an asterisk (*).

Table 4
Model estimates (LSM; SEM; *P*-value) for the pig farm clusters NOBED (farms without bedding and outdoor run), BED (farms with bedding but no outdoor run) and BEDOUT (farms with bedding and outdoor run) regarding the pig welfare indices (higher numbers indicate poorer welfare) and the Life Cycle Assessment impact categories.

	Farm cluster						
	NOBED		BED		BEDOUT		*P-value*
Dependent variable	LSM	SEM	LSM	SEM	LSM	SEM	
Pig welfare indices							
Stereo&ShortTail	1.09[b]	0.26	−2.12[a]	0.36	−1.28[a]	0.42	<0.001
Lame&Hospital	−0.09	0.25	0.26	0.40	−0.05	0.46	0.717
Mort&ManEnrich	−0.19	0.19	−0.07	0.32	0.83	0.37	0.114
Life Cycle Assessment							
Global warming[1]	2.95	0.15	2.41	0.25	3.12	0.28	0.220
Marine eutrophication[2]	19.0[b]	2.6	25.1[ab]	4.3	36.6[a]	5.0	0.035
Freshwater eutrophication[3]	0.59	0.05	0.51	0.08	0.66	0.09	0.473
Acidification[4]	44.3[b]	3.8	73.5[a]	6.3	67.1[a]	7.5	0.002

Abbreviations: LSM = least-squares means; Stereo&ShortTail = principal component 1 to which the indicators short tails, stereotypies and manipulation of pen fixtures contributed most; Lame&Hospital = principal component 2 to which the indicators lameness, hospitalisation and tail lesions contributed most; Mortality&ManEnrich = principal component 3 to which the indicators mortality, manipulation of enrichment and manipulation of other pigs contributed most.
Values within a row with different superscripts differ significantly at $P < 0.05$. *P*-values were corrected for multiple testing with the Bonferroni-Holm procedure.
[1] Global warming in kg CO_2-eq per kg body mass net sold.
[2] Marine eutrophication in g N-eq per kg body mass net sold.
[3] Freshwater eutrophication in g P-eq per kg body mass net sold.
[4] Acidification in g SO_2-eq per kg body mass net sold.

We explain the lower prevalence of short tails in BEDOUT and BED farms with those two clusters including all organic farms and several farms certified by other labels/schemes, and all Finnish farms, where tail docking is banned by law.

Tail and ear lesions tended to be lower in farms with bedding, which aligns with existing knowledge that bedding can lower the risk for tail and ear biting (EFSA, 2022). However, tail biting remains a multifactorial problem and can therefore also occur in farms with bedding (Valros and Heinonen, 2015).

We did not find a statistically significant difference between farms with bedding (BEDOUT, BED) and farms without (NOBED) regarding lameness and hospitalisation. The result for lameness was surprising since farms providing bedding also had a lower percentage of slatted flooring considered a risk factor for lameness. However, more than sparse bedding might be required (KilBride et al., 2009), which may explain the lack of difference in our data. The overall very low prevalence of both indicators (median < 1%), which is comparable with other studies observing lameness and hospitalisation (Leeb et al., 2019; Pandolfi et al., 2017b), also hampers the identification of differences. The prevalence of both of these clinical indicators depends to a large extent on the quality of management, especially the identification and treatment of sick animals (KilBride et al., 2009). Therefore, for those clinical indicators management might be more relevant than housing characteristics. Mortality was lower in farms providing bedding only (BED) compared to the other two farm clusters. We do not have a plausible explanation for this finding.

Our assumption that access to an outdoor run in addition to bedding would further improve animal welfare was not confirmed. This is surprising, especially since BEDOUT farms also provided much more space to their pigs. An explanation could be the overall low number of farms with an outdoor run (n = 8) and the variation of those (e.g. fully slatted floors vs bedded outdoor run). Also, the selected animal welfare indicators might be insufficient to reflect the actual impact of this system and indicators reflecting other aspects of welfare (e.g. separation of functional areas, thermoregulation, social behaviour) might have led to different results (Wimmler et al., 2022).

Differences between farm clusters regarding Life Cycle Assessment impact categories

Global warming

There were no differences between farm clusters concerning the GW impact category, which did not confirm our hypothesis. In contrast, other studies reported higher greenhouse gas emissions for systems with bedding compared to without (Dourmad and Casabianca, 2013; Rigolot et al., 2010). We explain our finding through a combination of feed (efficiency and composition) and manure management–related factors with an overlay of diverse effects. This is supported by Rigolot et al. (2010) who found that variations in ammonia and greenhouse gas emissions are as high within systems as across systems.

GW strongly increases at higher feed conversion ratios (Reckmann and Krieter, 2015; Ruckli et al., 2021) and higher proportions of bought-in as opposed to home-grown feed (Ruckli et al., 2021). Feed conversion was numerically worst in BEDOUT farms, followed by BED and NOBED farms (median: BEDOUT: 3.6 kg/kg, BED: 3.1 kg/kg, NOBED: 2.9 kg/kg). This is in line with our hypothesis that pigs with access to an outdoor run might need more energy for thermoregulation and activity. At the same time, BEDOUT farms and especially BED farms used higher proportions of home-grown feed than NOBED farms (median: BEDOUT: 8%, BED: 31%, NOBED: 0%), which reduces GW.

Furthermore, GW is also influenced by emissions from manure (N_2O, CH_4) which are released in the barn, during storage and spreading. N_2O emissions from farmyard manure are usually higher than from slurry since farmyard manure provides optimal conditions for incomplete de-/nitrification processes. CH_4 emissions, on the other hand, are usually higher in slurry than in farmyard manure due to the anaerobic conditions in the slurry (Philippe and Nicks, 2015). In our study, BED farms had the highest proportion of farmyard manure (median: 100%) compared to BEDOUT (60%) and NOBED farms (0%), thus contributing to the overall comparable GW. It should be considered, however, that our calculations are based on standard values for emissions from manure and not real performance results (see'Acidification' below).

Marine and freshwater eutrophication

We found that ME was significantly higher on BEDOUT than NOBED farms, while BED farms did not differ from the two other clusters. Since the primary ME factor is nitrate leaching from feed production, both the feed conversion ratio and the feed components have a high impact on ME (Ruckli et al., 2021). Therefore, one explanation for our findings could be the numerically worse feed conversion ratio of BEDOUT compared to NOBED farms. Furthermore, BEDOUT farms fed more home-grown feed than NOBED (median: 8 vs 0%) and NOBED farms fed more (0 vs 20%) bought-in by-products (e.g., whey). Additionally, five out of eight BEDOUT farms were organic farms and growing organic crops or buying organic feed for the pigs increases ME since yield per hectare is usually lower (Tuomisto et al., 2012). Therefore, a combination of feed efficiency and feed composition might explain our findings.

Interestingly, FE, which is also mainly influenced by feed production (Ruckli et al., 2021), did not significantly differ between the three farm clusters. FE is strongly influenced by phosphorous losses, primarily caused by soil erosion. We do not have a proper explanation for these findings but believe that the type of crops might have had an impact on these results.

Acidification

AC was significantly higher in farms with bedding (BEDOUT, BED) than in farms without (NOBED), thus confirming our hypothesis and supporting the findings of other studies (Garcia-Launay et al., 2014; Rigolot et al., 2010). However, we did not find an additional effect of the outdoor run. The main reason for a higher AC in bedded systems is that Life Cycle Assessment calculations assign higher NH_3 emissions to farmyard manure than slurry (EMEP EEA, 2016). However, results from experiments about NH_3 emissions from deep litter systems compared to fully slatted systems are inconclusive. Some experimental studies found higher NH_3 emissions from bedded systems compared to fully slatted systems (Philippe et al., 2007; Cabaraux et al., 2009), whereas others found lower NH_3 emissions from (deep) bedded systems compared to fully slatted systems (Kim et al., 2008; Philippe et al., 2011b). Any emission results should be carefully interpreted due to other possible confounding factors. In several studies that found higher NH_3 emissions from bedded systems, space allowance was also 60–167% higher compared to fully slatted floors (Philippe et al., 2007; Cabaraux et al., 2009). In studies where space allowance was the same for slatted and bedded systems, NH_3 emissions were similar or even lower in bedded systems (Kim et al., 2008; Philippe et al., 2011b; Zhou et al., 2015). NH_3 emissions from surfaces soiled with faeces play a considerable role (Philippe et al., 2011a) on livestock farms. Therefore, the size of soiled surface should be considered in future Life Cycle Assessment studies since farmers can reduce the soiled area by implementing functional areas (e.g. for resting, feeding, defecating) and frequent cleaning, thus mitigating NH_3 emissions. However, reliable assessments of soiled surfaces need considerable efforts regarding observer training or other more technological approaches, e.g. using cameras.

Another limitation, mainly due to lack of farm-specific data, is that our calculation of the nitrogen amount excreted by the pigs was based on a default value for conventional systems (growing-finishing pig: 12.1 kg/pig per year) instead of basing it on a balance between nitrogen intake and nitrogen retention. While the default value is considered valid for the largely uniform conventional production, it does not take the higher variability of organic or label production farms, or the differences between alternative and conventional production into account. This variability can be considerable and has mainly been attributed to feed management (Jørgensen, et al., 2013). Hence, a nitrogen balance could be considered in future pig Life Cycle Assessment studies based on N intake and N retention calculations.

General limitations and outlook

Apart from the manure system, a careful management (e.g. frequent cleaning, covering of slurry storage) can further substantially reduce ammonia and greenhouse gas emissions (Rigolot et al., 2010). Such information should be included in further Life Cycle Assessment studies and might help farmers to take specific action to mitigate emissions originating from their farms. Furthermore, an uncertainty analysis based on Monte Carlo simulations, and a sensitivity analysis should be included in further Life Cycle Assessment studies. The latter would allow to consider the variability of default values and of management factors as well as methodological aspects such as the choice of emission factors or allocation, similar to Zira et al. (2023).

A Life Cycle Assessment also has its limitations concerning a comprehensive assessment of environmental impacts. Solid manure systems might release more ammonia emissions therefore resulting in higher AC values. However, 'Animal welfare friendly' husbandry systems may also reduce the need to use antibiotics hence also the risk of antibiotic resistance (De Passillé and Rushen, 2005), which can be seen as a synergy between animal welfare and environmental impact. In addition, specific treatments of manure and slurry, e.g. biogas fermentation, could be used to derive co-benefits such as power and heat from pigs' waste (Holm-Nielsen et al., 2009).

Additionally, interactions with other sustainability dimensions should be studied as well. For example, straw-based systems have a higher societal acceptability but might require a higher workload and can increase production costs (Grethe, 2017). Improving pig welfare by, for example, increasing straw use, could also be positively related to the farmer's welfare through improved job satisfaction (Pinillos et al., 2016; Hansen and Osteras, 2019). More research using on-farm data is needed to understand these interactions and to take holistic decisions for improving farm sustainability.

Conclusion

We conclude that while the provision of bedding improved pig welfare, it also increased some Life Cycle Assessment impact categories. Our results, however, indicate that negative environmental trade-offs caused by the provision of bedding may be mitigated through better manure and feed management. Thus, we suggest a need for improved knowledge transfer and support for developing technological innovations, especially regarding manure management. This needs to be facilitated by more research on assessing farm individual emissions rather than standard values. Furthermore, more knowledge is needed on interactions with other aspects of sustainability (e.g. social aspects).

Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.animal.2024.101155.

Ethics approval

In none of the participating countries, ethical approval was legally required for this type of study, as all animal-based indicators were assessed non-invasively. Farmer participation was informed and voluntary, and participants could choose to end the interview/visit at any time. Participants were made clearly aware of the aims and contents of workshops and farm visits, and informed according to GDPR. All data were anonymised before storage on European servers. Only the national contact person knew the identity of a farm. Observers were experienced with pigs and instructed to behave in a calm manner around the pigs. Observations in a group of pigs were cancelled, if it became apparent that the group was stressed or agitated by the presence of the observer.

Data and model availability statement

None of the data were deposited in an official repository. The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy reasons.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

Author ORCIDs

Sabine Dippel: https://orcid.org/0000-0002-4824-7606.
Monika Gębska: https://orcid.org/0000-0001-6196-5904.
Juliane Helmerichs: https://orcid.org/0000-0003-3326-4515.
Mari Heinonen: https://orcid.org/0000-0002-5732-0692.
Carmen Hubbard: https://orcid.org/0000-0001-5711-252X.
Stefan Hörtenhuber: https://orcid.org/0000-0002-0602-3049.
Christine Leeb: https://orcid.org/0000-0002-1242-9731.
Paolo Ferrari: https://orcid.org/0000-0002-9736-3443.
Antonia Katharina Ruckli: https://orcid.org/0000-0001-9858-0688.
Hans Spoolder: https://orcid.org/0000-0002-9492-2019.
Anna Valros: https://orcid.org/0000-0002-4431-3346.
Christoph Winckler: https://orcid.org/0000-0002-2221-0186.

CRediT authorship contribution statement

A.K. Ruckli: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **S. Hörtenhuber:** Writing – review & editing, Writing – original draft, Supervision, Software, Funding acquisition, Conceptualization. **S. Dippel:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Data curation, Conceptualization. **P. Ferrari:** Writing – review & editing, Investigation. **M. Gebska:** Writing – review & editing, Resources, Investigation. **M. Heinonen:** Writing – review & editing. **J. Helmerichs:** Writing – review & editing, Validation, Investigation, Data curation. **C. Hubbard:** Writing – review & editing. **H. Spoolder:** Writing – review & editing. **A. Valros:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **C. Winckler:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **C. Leeb:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of interest

The authors declare no conflict of interest. The funders had no role in the design of the study, nor in the collection, analyses, or interpretation of data, nor in the writing of the manuscript or in the decision to publish the results.

Acknowledgements

Training of observers was carried out by Christine Leeb and Camilla Munsterhjelm. Direct observation data were collected by Juliane Helmerichs (in DE, IT, NL and UK) and Antonia Ruckli (in AT, FI and PL). Interview data were collected by Rachel Chapman (UK), Paolo Ferrari (IT), Monika Gebska and Agata Malak-Rawlikowska (PL), Juliane Helmerichs (DE), Antonia Ruckli (AT), Kirsi Swan (FI), and Herman Vermeer (NL). This research is part of a Doctoral thesis: Ruckli, A., 2023. A sustainability assessment tool for European pig farmers: from indicator selection to a trade-off assessment. PhD Dissertation, University of Natural Resources and Life Sciences (BOKU), Vienna, Austria.

Financial support statement

This research was made possible by funding from SusAn, an ERA-Net co-funded under the European Union's Horizon 2020 research and innovation programme (www.era-susan.eu), under Grant Agreement n°696231.

References

Augère-Granier, M.L., 2020. The EU pig meat sector. Retrieved on 12 February 2024 from https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/652044/EPRS_BRI(2020)652044_EN.pdf.
Cabaraux, J.-F., Philippe, F.-X., Laitat, M., Canart, B., Vandenheede, M., Nicks, B., 2009. Gaseous emissions from weaned pigs raised on different floor systems. Agriculture, Ecosystems & Environment 130, 86–92.
Commission, E., 2016. Attitudes of Europeans towards animal welfare. Report Special Eurobarometer 442, 84.
De Briyne, N., Berg, C., Blaha, T., Palzer, A., Temple, D., 2018. Phasing out pig tail docking in the EU - present state, challenges and possibilities. Porcine Health Management 4, 1–9.
De Passillé, A., Rushen, J., 2005. Food safety and environmental issues in animal welfare. Revue Scientifique Et Technique-Office International Des Épizooties 24, 757.
Deblitz, C., Mandes, V., Rohlmann, C., 2020. Retrieved on 12 February 2024 from http://catalog.agribenchmark.org/blaetterkatalog/Pig_Report_2020/#page_1.
Dourmad, J.Y., Casabianca, F., 2013. Effect of husbandry systems on the environmental impact of pig production. Acta Agriculturae Slovenica Supplement 4, 197–204.
Durlinger, B., Koukouna, E., Broekema, R., van Paassen, M., Scholten, J., 2017. Agri-Footprint 4.0 part 2: description of data. blonk consultants. Retrieved on 7 September 2023 from https://simapro.com/wp-content/uploads/2018/02/Agri-Footprint-4.0-Part-2-Description-of-data.pdf.
EFSA, 2022. Scientific opinion on the welfare of pigs on farm. EFSA Journal 20, 319.
EMEP EEA, 2016. Air pollutant emission inventory guidebook 2016. Technical Guidance to Prepare National Emission Inventories. Retrieved on 15 October 2020 from https://www.eea.europa.eu/publications/emep-eea-guidebook-2016.
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.
Grethe, H., 2017. The economics of farm animal welfare. Annual Review of Resource Economics 9, 75–94.
Hansen, B.G., Osteras, O., 2019. Farmer welfare and animal welfare- exploring the relationship between farmer's occupational well-being and stress, farm expansion and animal welfare. Preventive Veterinary Medicine 170, 104741.
Holm-Nielsen, J.B., Al Seadi, T., Oleskowicz-Popiel, P., 2009. The future of anaerobic digestion and biogas utilization. Bioresource Technology 100, 5478–5484.
Jørgensen, H., Prapaspongsa, T., Vu, V.T.K., Poulsen, H.D., 2013. Models to quantify excretion of dry matter, nitrogen, phosphorus and carbon in growing pigs fed regional diets. Journal of Animal Science and Biotechnology 4, 1–9.
KilBride, A., Gillman, C., Green, L., 2009. A cross-sectional study of the prevalence of lameness in finishing pigs, gilts and pregnant sows and associations with limb lesions and floor types on commercial farms in England. Animal Welfare 18, 215–224.
Kim, K.Y., Ko, H.J., Kim, H.T., Kim, Y.S., Roh, Y.M., Lee, C.M., Kim, C.N., 2008. Quantification of ammonia and hydrogen sulfide emitted from pig buildings in Korea. Journal of Environmental Management 88, 195–202.
Koch, P., Salou, T., 2015. AGRIBALYSE®: Rapport Méthodologique – Version 1.2. In, p. 393. Version, Ed ADEME, Angers, France. Retrieved on 7 September 2023 from https://nexus.openlca.org/ws/files/8455.

Lawrence, A.B., Terlouw, E.C., 1993. A review of behavioral factors involved in the development and continued performance of stereotypic behaviors in pigs. Journal of Animal Science 71, 2815–2825.
Leeb, C., Rudolph, G., Bochicchio, D., Edwards, S., Früh, B., Holinger, M., Holmes, D., Illmann, G., Knop, D., Prunier, A., Rousing, T., Winckler, C., Dippel, S., 2019. Effects of three husbandry systems on health, welfare and productivity of organic pigs. Animal 13, 2025–2033.
Mullan, S., Browne, W.J., Edwards, S.A., Butterworth, A., Whay, H.R., Main, D.C., 2009. The effect of sampling strategy on the estimated prevalence of welfare outcome measures on finishing pig farms. Applied Animal Behaviour Science 119, 39–48.
Munsterhjelm, C., de Roest, K., Dippel, S., Guy, J., Hörtenhuber, S., Hubbard, C., Kasperczyk, N., Leeb, C., Ruckli, A., Valros, A., Team, T.S., 2021. Sustainable pig production systems deliverable 2.1 Report on the development of the detailed and condensed SusPigSys protocols. Retrieved on 7 September 2023 from https://www.researchgate.net/publication/348606780_Sustainable_Pig_Production_Systems_Deliverable_21_Report_on_the_development_of_the_detailed_and_condensed_SusPigSys_protocols.
Pandolfi, F., Kyriazakis, I., Stoddart, K., Wainwright, N., Edwards, S.A., 2017a. The 'Real Welfare' scheme: identification of risk and protective factors for welfare outcomes in commercial pig farms in the UK. Preventive Veterinary Medicine 146, 34–43.
Pandolfi, F., Stoddart, K., Wainwright, N., Kyriazakis, I., Edwards, S.A., 2017b. The 'Real Welfare' scheme: benchmarking welfare outcomes for commercially farmed pigs. Animal 11, 1816–1824.
Patience, J.F., Rossoni-Serão, M.C., Gutiérrez, N.A., 2015. A review of feed efficiency in swine: biology and application. Journal of Animal Science and Biotechnology 6, 1–9.
Pedersen, L.J., Herskin, M.S., Forkman, B., Halekoh, U., Kristensen, K.M., Jensen, M.B., 2014. How much is enough? the amount of straw necessary to satisfy pigs' need to perform exploratory behaviour. Applied Animal Behaviour Science 160, 46–55.
Petherick, J.C., Phillips, C.J.C., 2009. Space allowances for confined livestock and their determination from allometric principles. Applied Animal Behaviour Science 117, 1–12.
Philippe, F.-X., Cabaraux, J.-F., Nicks, B., 2011a. Ammonia emissions from pig houses: influencing factors and mitigation techniques. Agriculture, Ecosystems & Environment 141, 245–260.
Philippe, F.X., Laitat, M., Canart, B., Vandenheede, M., Nicks, B., 2007. Comparison of ammonia and greenhouse gas emissions during the fattening of pigs, kept either on fully slatted floor or on deep litter. Livestock Science 111, 144–152.
Philippe, F.X., Nicks, B., 2015. Review on greenhouse gas emissions from pig houses: production of carbon dioxide, methane and nitrous oxide by animals and manure. Agriculture, Ecosystems & Environment 199, 10–25.
Philippe, F.X., Laitat, M., Wavreille, J., Bartiaux-Thill, N., Nicks, B., Cabaraux, J.F., 2011b. Ammonia and greenhouse gas emission from group-housed gestating sows depends on floor type. Agriculture, Ecosystems & Environment 140, 498–505.
Pinillos, R.G., Appleby, M.C., Manteca, X., Scott-Park, F., Smith, C., Velarde, A., 2016. One welfare - a platform for improving human and animal welfare. Veterinary Record 179, 412–413.
Reckmann, K., Krieter, J., 2015. Environmental impacts of the pork supply chain with regard to farm performance. The Journal of Agricultural Science 153, 411–421.
Rigolot, C., Espagnol, S., Robin, P., Hassouna, M., Béline, F., Paillat, J.M., Dourmad, J.Y., 2010. Modelling of manure production by pigs and NH_3, N_2O and CH_4 emissions. part II: effect of animal housing, manure storage and treatment practices. Animal 4, 1413–1424.
Ruckli, A.K., Dippel, S., Durec, N., Gebska, M., Guy, J., Helmerichs, J., Leeb, C., Vermeer, H., Hörtenhuber, S., 2021. Environmental sustainability assessment of pig farms in selected european countries: combining LCA and key performance indicators for biodiversity assessment. Sustainability 13, 11230.
SAS Institute Inc., 2016. SAS user's guide. SAS Institute Inc., Cary, NC, USA.
Spoolder, H., Edwards, S., Corning, S., 2000. Legislative methods for specifying stocking density and consequences for the welfare of finishing pigs. Livestock Production Science 64, 167–173.
Studnitz, M., Jensen, M.B., Pedersen, L.J., 2007. Why do pigs root and in what will they root? a review on the exploratory behaviour of pigs in relation to environmental enrichment. Applied Animal Behaviour Science 107, 183–197.
The SusPigSys Team, 2020. Condensed protocol from Era-Net SusAn project 'Sustainable pig production systems' (SusPigSys) - a starting point for connecting data bases for integrated sustainability assessment. Retrieved on 7 September 2023 from https://www.researchgate.net/publication/348466379_Condensed_protocol_from_Era-Net_SusAn_project_Sustainable_pig_production_systems_SusPigSys.
Tuomisto, H.L., Hodge, I.D., Riordan, P., Macdonald, D.W., 2012. Does organic farming reduce environmental impacts? - a meta-analysis of European research. Journal of Environmental Management 112, 309–320.
Tuyttens, F.A.M., 2005. The importance of straw for pig and cattle welfare: a review. Applied Animal Behaviour Science 92, 261–282.
Valros, A., Heinonen, M., 2015. Save the pig tail. Porcine Health Management 1, 1–7.
Welfare Quality®, 2009. Assessment protocol for pigs (sows and piglets, growing and finishing pigs). Retrieved on 7 September 2023 from https://www.researchgate.net/publication/263444662_Welfare_QualityR_assessment_for_pigs_sows_and_piglets_growing_and_finishing_pigs.
Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment 21, 1218–1230.
Wimmler, C., Vermeer, H.M., Leeb, C., Salomon, E., Andersen, H.L., 2022. Concrete outdoor runs for organic growing-finishing pigs – a legislative, ethological and environmental perspective. Animal 16, 100435.
Zhou, C., Hu, J., Zhang, B., Tan, Z., 2015. Gaseous emissions, growth performance and pork quality of pigs housed in deep-litter system compared to concrete-floor system. Animal Science Journal 86, 422–427.
Zira, S., Salomon, E., Åkerfeldt, M., Röös, E., 2023. Environmental consequences of pig production scenarios using biomass from rotational grass-clover leys as feed. Environmental Technology & Innovation 30, 103068.