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Effects of space allowance, roughage supplement, and enrichment provision on growth, carcass weight and meat quality in conventional indoor pig husbandry

Mathilde Coutant [a,*], Marlene Schou Grønbeck [b], Marchen Hviid [b], Lene J. Pedersen [a], Mona L.V. Larsen [a]

[a] Department of Animal and Veterinary Sciences, Aarhus University, Tjele, Denmark
[b] Danish Technological Institute, Danish Meat Research Institute, Taastrup, Denmark

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ABSTRACT

Extensification of indoor pig husbandry is increasingly under focus, but effects on meat quality remain to be determined. This study investigated the effects of extensification factors on growth, carcass weight and meat quality of fattening pigs. Three factors were studied on pigs from 30 kg up to slaughter at approximately 120 kg: increase space allowance to 1.4 (S9, n pigs = 108, n samples = 42) or 2.1 (S6, n pigs = 72, n samples = 42) m2 per pig, provision of various enrichments (E, n pigs = 114, n samples = 44), and daily provision of roughage (R, n pigs = 115, n samples = 45). Treatments were compared to a control group with 0.7 m2 per pig and no extra enrichment nor roughage (C, n pigs = 115, n samples = 48). The study was performed over two batches, in spring and in autumn. The treatments had overall no effect on meat quality as measured by temperature and pH, colour, driploss, cooking loss or texture. However, the meat from S9 pigs had a significantly lighter colour than the meat from C, R or E and in addition, pigs from S6 had a higher growth rate (ADG) and carcass weight than C and R. Overall, the treatments had little to no effect on meat quality but increasing space allowance by a factor three notably improved pig growth. In contrast, the experimental batch significantly influenced several parameters of meat quality as well as growth and carcass weight, highlighting that un-controlled factors varying between batches, including seasonal effects, had a greater impact on meat quality than the treatments alone.

1. Introduction

Pork is the most consumed type of red meat in the world, and its consumption has steadily increased over the years (Ritchie et al., 2023). Yet, this rise in demand is accompanied by growing societal concerns over intensive pork husbandry in most countries. An increasing number of consumers demand meat from animals raised under more extensive conditions (Lin-Schilstra et al., 2022), which translates into a higher willingness to pay for, e.g., animal welfare-labeled products (Gross et al., 2021). Extensification of pig husbandry conditions can be implemented at different levels, from providing pigs with more space and greater environmental complexity to offering a more diverse diet with foraging opportunities or selecting (local) robust breeds (Ludwiczak et al., 2023). While the outcomes of such extensification processes have been discussed in terms of animal welfare (e.g., Chidgey, 2023; Machado et al., 2017; Nannoni et al., 2019) and sustainability (e.g., Rauw et al., 2020; Van Grinsven et al., 2020), the impact of these husbandry conditions on the resulting meat production and quality has received comparatively less focus.

Pork quality is determined by a variety of complex traits, which are influenced by numerous factors along the meat production chain (Ludwiczak et al., 2023). From a consumer's point of view, purchase decisions often result from a visual perception involving the colour of the meat, the percentage of lean meat, or the amount of visible drip. In addition, other quality traits, such as pH or water-holding capacity, can impact the chemical and microbiological quality of the meat during chilled storage and, more generally, the sensory attributes of the meat upon consumption (Knox et al., 2008; Rahman et al., 2013). In combination, these attributes can be used to categorize meat quality defects such as Pale Soft Exudative (PSE) and Dark Firm Dry (DFD) meat, which can be described as unattractive meat parts, rejected by consumers, with poor processing characteristics (Adzitey & Nurul, 2011).

* Corresponding author.
E-mail address: mathilde.coutant@anivet.au.dk (M. Coutant).

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In a recent review, Ludwiczak et al. (2023) concluded that increasing space allowance, space quality, or providing a foraging diet do not generally impact the quality of pork meat. However, these factors were often confounded in the studies analysed, and the effects of single extensification factors within a specific type of husbandry remained complex to obtain from the review. Overall, evidence of the effects of single extensification factors in conventional husbandry on meat quality are scarce in the literature. Space allowance, for instance, was shown not to modulate pork quality (Nannoni et al., 2019; Rossi et al., 2008), while enriching the environment or diet had little to no effect on the quality of the meat (Casal et al., 2018; Tavares et al., 2023).

Besides the quality of the meat, the impact of the extensification factors on meat production is an important factor to weigh in for both producers and the industry. Increasing floor space by 50 %, for instance, has been suggested to create up to 25 % more additional costs (Van Grinsven et al., 2015). Parameters such as the growth patterns of the pigs, carcass weight, or percentage of meat on the carcasses can therefore be decisive in the productivity, sustainability, and general economic resilience of pork production, ultimately influencing stakeholders' attitudes toward extensive husbandry conditions.

The aim of this study was to evaluate the impact of three extensification factors (space quantity via the reduction in group size, space quality via the provision of various enrichments, and diet diversity via the daily provision of roughage) on the growth, carcass weight, and meat quality attributes of pork from conventional indoor husbandry.

2. Materials and methods

2.1. Animals

Ethical review and approval were not required for this study because the experimental procedures and care of the animals under study were carried out in accordance with the Ministry of Food, Agriculture and Fisheries, The Danish Veterinary and Food Administration, under Act 474 of May 15, 2014, and Executive Order 2028 of December 14, 2020.

A total of 824 animals were enrolled in the study held at the experimental facility of AU-Viborg (Aarhus University, Tjele, Denmark). The study was conducted in two batches: Batch 1 (414 animals) from March to April 2023 (Spring season), and Batch 2 (410 animals) from September to November 2023 (Fall season). The pigs were purchased from two private herds and arrived at the facility from local breeders (two different breeders for Batch 1 and Batch 2) at an average weight of 29.41 ± 6.26 kg (mean ± SD). All pigs were DanBred genetics Duroc × [Landrace × Yorkshire] (DLY). Upon arrival, animals were randomly allocated to one of 30 experimental pens, as outlined in the 2.3.

The pigs were not routinely tail docked at birth, but due to issues in the rearing farms, only 83 % and 21 % of the pigs had intact tails at arrival, in Batch 1 and Batch 2, respectively. In addition, 3 % of pigs in Batch 2 were identified as uncastrated male pigs at arrival. Both pigs with short tails and uncastrated males were distributed among treatments with 18 pigs per pen and were excluded from meat quality analysis.

2.2. Housing and feeding

All pens (2.48 × 5.45 m) were composed of three areas of equal size, each characterized by a solid, drained, and slatted floor. Each pen had a feeder (1.02 × 0.38 m) with three head spaces with shoulder separation, two drinking nipples, and two fixed wooden beams as enrichment. Showers were activated at regular intervals above the slatted area of the pen to limit fouling and to cool down the pigs. The lights (182 lx) were on from 7:00 to 22:00. Indoor temperature followed the standard temperature curve of 21 °C on arrival and was manually adjusted continuously to ensure an optimal climate for the pigs.

Initially, the pigs were not intended to receive straw to properly test the effects of the enrichment treatment. However, outbreaks of tail biting in the early weeks of Batch 1 led to the decision to provide a bucket of straw daily, scattered across the solid floor, for the remaining fattening period of Batch 1 (from week 5 onwards) and throughout Batch 2.

Pigs were given a combination of two commercial pelleted dry-feed diets (see composition in Supplementary Table 1). Diet 1 (finisher diet, 15,5 % crude protein, 4,0 % crude fat, 3,5 % crude fiber, net energy 9,7 MJ/kg) was given throughout the experiment (see Supplementary Table 2), with diet 2 (weaner diet, 17,6 % crude protein, 3,9 % crude fat, 3,4 % crude fiber, net energy 9,8 MJ/kg) being supplemented in first weeks of the study (week 1–4 Batch 1 and week 0–3 in Batch 2). In Batch 1, weaner diet was provided between week 1 and 4 as a support as the animals were facing an unexpected outbreak of tail biting. In Batch 2, the animals were given weaner feed immediately upon arrival and up to week 3 as they faced an unforeseen outbreak of pneumonia. As soon as these issues were stabilized, the pigs were fed the conventional finisher diet until the end of the experiment. The amount of weaner diet given on average per pig each week did not differ among treatments (see Supplementary Table 2). The feed was always dispensed ad libitum, with potential refilling at 07.00, 15.30 and 23.00.

2.3. Treatments

As mentioned previously, upon arrival, the pigs were randomly allocated to a pen, which was itself allocated to one of five treatments. In each batch, each treatment was applied in 6 pens, randomized across 2 experimental rooms to ensure a balanced number of treatment pens in each room and subsets of the rooms.

The five treatments were defined as follows:

2.3.1. Control

The pigs were housed in the conventional density of 0.7 m^2 per pig (corresponding to 18 pigs per pen) and managed as described previously.

2.3.2. Space 9

The pigs are housed with a density of 1.4 m2 per pig (corresponding to 9 pigs per pen) and managed as described previously.

2.3.3. Space 6

The pigs were housed with a density of 2.1 m2 per pig (corresponding to 6 pigs per pen) and managed as described previously.

2.3.4. Enrichment

The pigs were housed in the conventional density of 0.7 m^2 per pig (corresponding to 18 pigs per pen) and provided enrichment in the morning between 8 and 9 a.m. The enrichment strategy consisted of ropes, empty paper feed bags, and wood logs, which were rotated over a week. On Mondays, each pen was provided with 3 wood logs (one small, one medium, and one large). The logs were removed on Wednesday, and 3 paper bags were given. On Thursday, the leftover bags were removed, and 3 new paper bags were provided. On Fridays, the leftover bags were removed and 3 ropes were hung on the pen fixtures. Each rope had a length of 2 m and was attached to the inventory toward the section corridor, so each rope had two equally long tails that did not reach the pen floor, resulting in a total of 6 tails of rope. The ropes were removed on the following Monday, and the rotation started again. Apart from these enrichments, the pigs were managed as described previously.

2.3.5. Roughage

The pigs were housed in the conventional density of 0.7 m^2 per pig (corresponding to 18 pigs per pen) and provided a bucket of maize-based roughage each day at 11 a.m. The roughage was given directly on the solid floor of the pen.

The quantity of roughage provided was as follows:

- 2 kg per pen during the first production week
- 3 kg per pen during the second production week
- 4 kg per pen during the third production week
- 5 kg per pen from the fourth production week until slaughter.

Apart from the roughage, the pigs were managed as described previously.

2.4. Weight measures

All pigs were weighed using a commercial scale (MTW2-STACON, Schauer Agrotronic GmbH, Germany, accuracy: ±0.3 kg) on the day of their arrival at the facility, 4 weeks after the start of the fattening period, 7 weeks after the start of the fattening period (Batch 1 only), and on the day prior to slaughter.

2.5. Slaughtering and meat sampling

In each batch, the pigs were slaughtered by pen at week 11 or 12 (Batch 1) or week 10 or 11 (Batch 2) of the fattening period. The slaughter weeks were decided for each pig based on the average weight of the pens at mid-fattening weighing, with the goal of reaching an average of 120 kg at slaughter.

In each pen, 6 pigs were selected for meat sampling, with a balanced distribution of castrates and females. The selection criteria included the following:

- Close to average estimated pen weight
- Fit for transport (no severe clinical condition e.g. hernia or lameness)
- No tail biting (Batch 1)
- Intact tail at arrival
- No uncastrated male

The pigs selected for meat sampling were tattooed with a unique number on each side of their ham (visible on the carcass) during weighing. The next day, all pigs were loaded into a single commercial truck, which drove for approximately 1.5 h prior to reaching the slaughterhouse.

2.6. Meat analyses

2.6.1. Carcass weight and meat percentage

The hot carcass weights and lean meat percentages, measured with an AutoFom III™ (Frontmatec Group, Smoerum, Denmark), were collected from the slaughter line as part of the standard slaughterhouse measures.

2.6.2. Temperature, pH and drip loss

Approximately 45 min after slaughter, the temperature (Temp45) and pH (pH 45) in the left longissimus lumborum (LL) muscle between the second and third lumbar vertebrae were collected at the slaughter line using a thermometer (Testo 105, Testo SE, Titisee-Neustadt, Germany) and portable pH meter (Pro2Go pH-meter, Mettler Toledo with an Ingold Glass-electrode Ø 6 mm (potassium chloride electrolyte) Lot 406-M6-s7/25). For pH measurement, the buffers were manufactured by Reagecon, and calibration was performed using a two-point system in buffers with pH values of 4.005 and 7.00. Additionally, the electrode was verified in buffers with pH values of 4.005, 5.00, and 7.00. The temperature of the buffers followed the temperature of the measurement medium, meaning that for measurements in warm carcasses, the buffers were stored at 30 °C before calibration, and for measurements in cold carcasses, calibration was performed in buffers at a temperature of 5 °C.

Carcasses then continued their journey through the cooling tunnel, 45 min from sticking. The cooling process lasted 75 min at −20 °C, followed by equalization at 4 °C until the next day.

On the day after slaughter (approximately 22 h post-mortem), the pH was measured in the longissimus lumborum muscle at the level of the L1 vertebra (pH 22). The carcasses were then cut, and the left loins were marked individually and sent via refrigerated truck to the Danish Technological Institute (approximately a 3-h drive), where they were stored in a refrigerated room until 48 h post-slaughter. The next day, each loin was sliced in its center to perform the different meat quality analyses.

Drip loss was measured 48 h after slaughter following the methods from Rasmussen and Andersson (1996). A 20 mm slice was cut at a right angle to the muscle fiber direction. Within a few seconds, two samples were bored in the fiber direction in the middle of the piece of meat steak using a Ø 25 mm circular knife and stored in a special plastic container for 24 h at 4 °C, before weighing and calculation.

2.6.3. Colour

Colour was measured in fresh meat samples 48 h after slaughter using a Minolta CR400 with D65 illumination and a Ø 8 mm aperture. The CIELab parameters determined were L^* (lightness), a^* (redness), and b^* (yellowness). One slice of 2.0 cm was cut across the grain from the longissimus thoracis muscle between T7 and T9. The slice was placed in the refrigerator at 4 °C for 30 min. Colour was measured by placing the colorimeter directly on the surface of the meat, in four different positions on the exposed surface of the slice.

2.6.4. Texture and cooking loss

Texture analyses were only performed in Batch 2. Approximately 24 h after slaughter, two slices, each 3.5 cm thick, were cut between T9 and T13, kept at 4 °C for 72 h, and then vacuum-packed, frozen, and stored at < −20 °C for up to a maximum of 3 months. Before the analysis, the samples were thawed in the dark at 4 °C for 24 h.

Samples were grilled on a plate grill (Neumarker, Hemer, Germany) preheated to 200 °C. The internal temperature of each slice was monitored by inserting a thermometer (Testo 925, Lenzkirch, Germany) into the center of the piece. When the center reached 40 °C, the sample was turned over until it reached 68 °C and was then removed from the grill and allowed to stabilize until the internal temperature reached 70 °C. The cooking loss was calculated as the percentage weight difference between the fresh fillet and the cooked loin, with losses expressed relative to the initial weight.

A Slice Shear Force (SSF) kit (AMSA, 2016) was used to cut each of the two samples, first making a cut across the width of the muscle at a point approximately 2.0 cm from the lateral end. Then, a cut parallel to the first cut of the loin, 5.0 cm from the first cut, was made. Two parallel cuts were then made, spaced 1 cm apart, through the length of the 5-cm-long steak portion, forming an angle of 45 degrees to the longitudinal axis of the longissimus and parallel to the muscle fibers. Two slices (samples) were taken per muscle, one slice per steak. The slices were sheared using a flat, blunt-point blade with a thickness of 1.1684 mm and a half-round bevelled cutting edge, attached to a TA-XT2i texturometer (Stable Micro Systems, United Kingdom) using a crosshead speed of 2.00 mm/s. The shear value was recorded at the maximum peak force of shearing (expressed in N).

2.6.5. Protein and fat content

Proximate composition was determined by the methods of AOAC protein (AOAC 981-10, 1983) and intramuscular fat (ISO, 1973).

2.7. Statistical analyses

Due to an outbreak of tail biting in Batch 1 and an outbreak of pneumonia in Batch 2, a total of 70 animals across both batches had to be removed from the experiment due to health concerns (see detailed numbers in Table 1). In Batch 1, most of the pigs were removed between week 2 and 5 due to severe tail damage or severe biting behaviour. In Batch 2, most of the pigs were removed between week 1 and 4 due to severe cases of pneumonia. In addition, some pigs were removed

Table 1
– Number of pigs included in the datasets for different analyses in each batch of the study.

		Control	Enrichment	Roughage	Space 9	Space 6	Total
B1	n pigs start	108	108	108	54	36	414
	n pigs at slaughter	99	89	103	50	36	377
	n pigs selected	36	36	36	36	36	180
	n samples from slaughter data (carcass weight / meat%)	27	24	25	21	26	123
	n samples from slaughter line (°C /pH)	25	22	24	19	25	115
	n samples sent to analysis	28	24	25	22	26	125
	Females	14	12	14	11	14	65
	Castrates	14	12	11	11	12	60
B 2	n pigs start	107	106	107	54	36	410
	n pigs at slaughter	101	97	93	50	36	377
	n pigs selected	36	36	36	36	36	180
	n samples from slaughter data (carcass weight / meat%)	20	20	20	20	16	96
	n samples from slaughter line (°C /pH)	20	19	20	20	16	95
	n samples sent to analysis	20	20	20	20	16	96
	Females	10	10	10	10	8	48
	Castrates	10	10	10	10	8	48

B1 = Batch 1; B2 = Batch 2.

throughout the study due to severe lameness. The pigs removed were excluded from all analyses.

Data on all pigs slaughtered (n = 744) were used to analyse the weight data collected during the experiment.

Additionally, issues with the collection of samples at the slaughterhouse led to the removal of some samples from certain parts of the experiment (see detailed numbers in Table 1). In general, the samples were lost for two main reasons: (1) the carcasses were taken out of the slaughter line to be controlled, which prevented data collection as planned or (2) despite the tattoo, some carcasses could not be identified and linked an experimental pig.

In total, information on carcass weight and meat percentage were provided on 219 samples by the slaughterhouse (due to some of the tattoos being poorly visible).

A total of 210 samples were taken by experimenters at the slaughter line (data on temperature and pH; losses due to carcasses being taken out of the slaughter line).

A few experimental piece of pork meat were retrieved in the cooling chamber, therefore 221 samples were sent to be analysed. Among the meat samples collected and brought to analysis, 3 samples from the control group could not be analysed for driploss.

All statistical analyses were conducted in R version 4.3.2 (R Core Team, 2023). Two datasets were analysed.

Based on these parameters, the prevalence of meat categorized as PSE or DFD was additionally calculated as follows (according to the definitions suggested by Joo et al. (1999) for PSE1 and Põldvere et al. (2015) for PSE2):

PSE_1: Drip loss >6 % and L-value (lightness) > 50.

PSE_2: $pH_{45} < 5.8$ and $pH_{22} < 5.3$.

DFD: $pH_{22} > 6$.

All models included the effects of treatment (roughage provision vs. enrichment provision vs. space allowance with 9 pigs in the pen vs. space allowance with 6 pigs in the pen vs. control), batch (1 vs. 2) and their interaction, and slaughter day (1 vs. 2) as fixed effect, with pen nested in batch as random effect.

Weight at arrival was analysed in a mixed model with a Gamma distribution using a log link. Slaughter weight, carcass weight, meat percentage, drip loss, pH 45, pH 22, redness, yellowness, and fat percentage were analysed in a general linear mixed model using the "glmmTMB" package (Brooks et al., 2017), with a Gaussian distribution. Growth, slaughter weight, temperature, and lightness were analysed with a similar model, but the data were squared-transformed to meet model assumptions, as the initial model residuals showed a significant deviation In addition, the models for growth and weight at slaughter included weight at arrival as a covariate. Texture (as measured by shear force) and cooking loss were only measured in Batch 2 and were therefore analysed in a similar mixed model but without the effects of batch and the interaction between batch and treatment. The risk of PSE1, PSE2, and DFD was analysed as binary data in a mixed model with a binomial distribution.

For all models, model assumptions were tested using the 'DHARMa' package (Hartig, 2022). If the model showed significant effects of one or more of the fixed effects ($p < 0.05$), post-hoc analyses were conducted using the 'emmeans' package (Lenth, 2024).

Results are presented as model estimates ± standard error (SE).

3. Results

3.1. Average daily weight gain throughout the fattening period

As intended, the weight of the pigs at the start of the experiment did not differ statistically among treatments (Table 2), but pigs from Batch 1 were slightly lighter than pigs from Batch 2 (27.2 ± 0.4 and 32.1 ± 0.4 kg, respectively, $P < 0.01$).

When considering the average daily weight gain (ADG), the interaction between batch and treatment was not significant. The effect of treatment alone was significant (P = 0.04), with the pairwise

Table 2
Weight at arrival (kg), ADG (kg/day) and weight at slaughter (kg) during the fattening period per fixed effect.

	Weight at arrival (kg)	ADG (kg/day)*	Weight at slaughter (kg) *
Control (n = 200)	29.4 ± 0.6	1.18 (1.40 ± 0.03)^{b}	122 (14,785 ± 218)
Enrichment (n = 186)	29.2 ± 0.6	1.20 (1.44 ± 0.03)^{ab}	123 (15,086 ± 225)
Roughage (n = 196)	28.3 ± 0.6	1.19 (1.41 ± 0.03)^{ab}	122 (14,887 ± 222)
Space 9 (n = 100)	30.3 ± 0.7	1.21 (1.47 ± 0.03)^{ab}	124 (15,427 ± 275)
Space 6 (n = 72)	30.5 ± 0.8	1.23 (1.52 ± 0.04)^{a}	125 (15,746 ± 313)
P	n.s.	0.04	n.s.
Batch 1 (n = 377)	27.2 ± 0.4	1.20 (1.43 ± 0.02)	130 (16,840 ± 163)^{a}
Batch 2 (n = 377)	32.1 ± 0.4	1.21 (1.47 ± 0.02)	116 (13,521 ± 164)^{b}
P	<0.01	n.s.	<0.01

Results are presented as model estimates ± standard error. ADG; Average daily weight gain *Back transformed estimates are presented, with model estimates ± standard errors in brackets. ^{ab} Different letters indicate significant differences among treatments.

comparisons only showing a difference between the Control treatment (1.18 ± 0.02 kg/day) and the Space 6 treatment (1.20 ± 0.02 kg/day, $P < 0.05$; back transformed estimates). Pigs with a higher weight at arrival showed significantly greater ADG ($P < 0.01$).

Neither the interaction between treatment and batch nor treatment alone affected the weight prior to slaughter. Batch effects were significant ($P < 0.01$), with a higher weight recorded in Batch 1 (130 ± 13 kg) than Batch 2 (116 ± 13 kg, back transformed estimates). Weight at arrival also affected slaughter weight ($P < 0.01$). Lastly, pigs slaughtered on the first slaughter day of each batch had a higher slaughter weight than pigs slaughtered on the second slaughter day (120 ± 13 vs. 127 ± 13 kg/day, $P < 0.01$, back transformed estimates). This result was to be expected considering that the pens closest to the target 120 kg at slaughter were selected first for slaughter.

3.2. Carcass weight and meat percentage

The model showed a significant effect of the interaction between treatment and batch on carcass weight ($P = 0.03$; see Table 3). The pairwise comparisons showed a significant difference between pigs from the Space 9 treatment in Batch 1 (100.8 ± 1.8 kg) and pigs from the Enrichment treatment in Batch 1 (91.8 ± 1.7 kg, $P < 0.01$) as well as between pigs from the Space 9 treatment in Batch 1 and pigs from the Control (92.2 ± 1.8 kg, $P = 0.01$), Enrichment (89.7 ± 1.9 kg, $P < 0.01$), Roughage (90.2 ± 1.8 kg, $P < 0.01$), Space 9 (89.0 ± 1.82 kg, $P < 0.01$) and Space 6 (91.1 ± 2.0, $P = 0.01$) treatments in Batch 2.

The slaughter day also impacted the carcass weight, with heavier carcasses being recording on day 2 (94.8 ± 0.8 kg) than on day 1 (91.1 ± 0.8 kg, $P < 0.01$).

The interaction between treatment and batch did not affect the meat percentage on the carcass, but batch did, with higher a higher meat percentage in Batch 1 (58.8 ± 0.2 %) than in Batch 2 (57.9 ± 0.2 %, $P < 0.01$).

3.3. Temperature, pH, drip loss and cooking loss

Neither temperature at 45 min post slaughter ($Temp_{45}$) nor pH at 45 min (pH_{45}) or at 22 h post slaughter (pH_{22}) was significantly impacted by the interaction between treatment and batch nor by treatments alone (Table 4). However, slaughter day affected temperature at 45 min post slaughter ($P = 0.03$) with lower temperatures recorded on the first slaughter day (38.3 °C, back transformed estimates) than the second (38.6 °C, back transformed estimates). Batch affected pH at 45 min post slaughter ($P < 0.01$), with a lower pH recorded in Batch 1 (6.6 ± 0.02) than in Batch 2 (6.7 ± 0.02). In addition, pH 22 h post-slaughter was affected by both batch and slaughter day, with a higher pH recorded in Batch 1 (5.7 ± 0.1) than in Batch 2 (5.6 ± 0.1, $P < 0.01$) and a lower pH observed on the first day of slaughter (5.6 ± 0.1) compared to the second day (5.7 ± 0.1, $P < 0.01$).

The interaction between treatment and batch did not significantly impact drip loss (Table 5), but an effect of treatment alone was recorded ($P = 0.05$), with higher drip loss measured in meat from the Roughage treatment (5.82 ± 0.21 %) compared to the meat from the Space 9 treatment (4.93 ± 0.22 %, $P = 0.03$). Again, batch effects were significant ($P < 0.01$) with higher drip loss measured in Batch 1 (5.62 ± 0.13 %) than in Batch 2 (5.05 ± 0.14 %).

Cooking loss (only analysed for Batch 2) was not affected by neither treatments nor slaughter day (Table 5).

3.4. Colour

The interaction between batch and treatment was not significant for neither aspect of meat colour (Table 6). However, the treatments

Table 3
Carcass weight (kg) and meat percentage (%) on the carcass per treatment and batch.

		Carcass weight (kg)	Meat percentage (%)
Batch 1	Control ($n = 27$)	93.9 ± 1.6^{ab}	58.6 ± 0.4
	Enrichment ($n = 24$)	91.8 ± 1.7^{a}	59.5 ± 0.5
	Roughage ($n = 25$)	93.9 ± 1.6^{ab}	59.0 ± 0.5
	Space 9 ($n = 21$)	100.8 ± 1.8^{b}	57.7 ± 0.5
	Space 6 ($n = 26$)	96.8 ± 1.6^{ab}	59.0 ± 0.05
Batch 2	Control ($n = 20$)	92.2 ± 1.8^{a}	58.0 ± 0.5
	Enrichment (n = 20)	89.7 ± 1.9^{a}	58.0 ± 0.5
	Roughage (n = 20)	90.2 ± 1.8^{a}	58.2 ± 0.5
	Space 9 (n = 20)	89.0 ± 1.8^{a}	57.8 ± 0.5
	Space 6 (n = 16)	91.1 ± 2.0^{a}	57.4 ± 0.6
P		0.03	n.s

Results are presented as model estimates ± standard errors. ^{ab} Different letters indicate significant differences among treatments.

Table 4
Meat temperature 45 min post-slaughter ($Temp_{45}$, °C), pH at 45 min (pH_{45}), and pH 22 h (pH_{22}) post-slaughter per treatment and batch.

	$Temp_{45}$ (°C)*	pH_{45}	pH_{22}
Control ($n = 45$)	38.3 (1469 ± 9)	6.7 ± 0.1	5.7 ± 0.1
Enrichment ($n = 41$)	38.5 (1479 ± 10)	6.7 ± 0.1	5.7 ± 0.1
Roughage ($n = 44$)	38.4 (1473 ± 10)	6.6 ± 0.1	5.7 ± 0.1
Space 9 ($n = 39$)	38.5 (1486 ± 10)	6.7 ± 0.1	5.7 ± 0.1
Space 6 ($n = 41$)	38.6 (1487 ± 10)	6.6 ± 0.1	5.7 ± 0.1
P	n.s.	n.s.	n.s.
Batch 1 ($n = 115$)	38.5 (1482 ± 6)	6.6 ± 0.1	5.7 ± 0.1
Batch 2 ($n = 95$)	38.4 (1476 ± 6)	6.7 ± 0.1	5.6 ± 0.1
P	n.s.	<0.01	<0.01

Results are presented as model estimates ± standard errors. *Back transformed estimates are presented, with model estimates ± standard errors in brackets. ^{ab} Different letters indicate significant differences among treatments.

Table 5
Drip loss (%) and cooking loss (%) per treatment and batch.

	Drip loss (%)	Cooking loss (%)
Control	5.41 ± 0.21^{ab} ($n = 45$)	17.6 ± 0.6 ($n = 20$)
Enrichment	5.20 ± 0.21^{ab} ($n = 44$)	18.0 ± 0.6 (n = 20)
Roughage	5.82 ± 0.21^{a} (n = 45)	18.6 ± 0.6 (n = 20)
Space 9	4.93 ± 0.22^{b} ($n = 42$)	16.7 ± 0.6 (n = 20)
Space 6	5.31 ± 0.23^{ab} (n = 42)	17.6 ± 0.7 ($n = 16$)
P	0.05	n.s.
Batch 1	5.62 ± 0.13 ($n = 122$)	–
Batch 2	5.05 ± 0.14 ($n = 96$)	–
P	<0.01	–

Results are presented as model estimates ± standard errors. ^{ab} Different letters indicate significant differences among treatments.

Table 6
Colour measures (lightness, redness and yellowness) per treatment and batch.

	Lightness* (L^*)	Redness (a^*)	Yellowness (b^*)
Control ($n = 48$)	54.5 (2965 ± 34) [b]	5.0 ± 0.1	4.6 ± 0.1[ab]
Enrichment (n = 44)	54.6 (2982 ± 35) [b]	5.1 ± 0.1	4.9 ± 0.1[b]
Roughage (n = 45)	55.2 (3042 ± 35) [b]	4.9 ± 0.1	4.7 ± 0.1 [ab]
Space 9 (n = 42)	53.1 (2815 ± 36) [a]	5.1 ± 0.1	4.4 ± 0.1[a]
Space 6 ($n = 42$)	54.1 (2927 ± 37) [ab]	5.2 ± 0.1	4.6 ± 0.1[ab]
P	<0.01	n.s.	<0.01
Batch 1 ($n = 125$)	56.7 (3210 ± 21)	5.2 ± 0.1	5.2 ± 0.1
Batch 2 (n = 96)	51.8 (2683 ± 24)	4.9 ± 0.1	4.1 ± 0.1
P	<0.01	0.01	<0.01

Results are presented as model estimates ± standard errors. *Back transformed estimates are presented, with model estimates ± standard errors in brackets. [ab] Different letters indicate significant differences among treatments.

affected the lightness of the meat (L^*, $P < 0.01$), with darker meat observed for Space 9 (53.1, back transformed estimate) as compared to Control (54.5, back transformed estimate, $P < 0.01$), Enrichment (54.6, back transformed estimate, $P < 0.01$) and Roughage (55.2, back transformed estimate, $P < 0.01$). Similarly, treatments affected the yellowness of the meat (b^*, $P = 0.04$), with less yellow meat observed for Space 9 (4.4 ± 0.1) as compared to Enrichment (4.9 ± 0.1, $P = 0.03$).

In addition, batch effects were significant, with lighter ($P < 0.01$), redder (a^*, $P = 0.01$), more yellow ($P < 0.01$) meat recorded in Batch 1 (56.7, back transformed estimate, 5.2 ± 0.1 and 5.2 ± 0.1, respectively) compared to Batch 2 (51.8, back transformed estimate, 4.9 ± 0.1 and 4.1 ± 0.1, respectively). Lighter, more yellow meat was also recorded on slaughter day one compared to slaughter day two (55.1, back transformed estimate, and 4.8 ± 0.1 vs. 53.4, back transformed estimate and 4.5 ± 0.1, respectively, $P < 0.01$).

3.5. Texture

Texture was only recorded in Batch 2 and did not differ significantly among treatments nor between slaughter days (Table 7).

3.6. Fat and protein content

The fat content of the meat was not affected by the interaction between batch and treatment, nor by the treatments alone (Table 7). However, batch had an effect ($P < 0.01$), with fatter meat observed in Batch 2 (4.4 ± 0.1 %) as compared to Batch 1 (3.7 ± 0.1 %). Protein content did not differ among treatments, batches or slaughter days.

Table 7
Shear Force (N) and fat content (%) of the meat per treatment and batch.

	Shear force (N)	Fat content (%)	Protein content (%)
Control	117.2 ± 3.9 (n = 20)	4.2 ± 0.2 ($n = 48$)	21.8 ± 0.1 (n = 48)
Enrichment	115.8 ± 4.3 (n = 20)	3.9 ± 0.2 (n = 44)	21.8 ± 0.1 (n = 44)
Roughage	125.6 ± 4.0 (n = 20)	4.0 ± 0.2 (n = 45)	21.8 ± 0.1 (n = 45)
Space 9	126.9 ± 4.1 (n = 20)	4.2 ± 0.2 (n = 42)	22.0 ± 0.1 (n = 42)
Space 6	118.4 ± 4.5 (n = 16)	4.0 ± 0.2 (n = 42)	21.9 ± 0.1 (n = 42)
P	n.s.	n.s.	n.s.
Batch 1	–	3.7 ± 0.1 (n = 125)	21.9 ± 0.1 ($n = 125$)
Batch 2	–	4.4 ± 0.1 ($n = 96$)	21.8 ± 0.1 (n = 96)
P	–	<0.01	n.s.

Results are presented as model estimates ± standard errors.

3.7. Risk of PSE and DFD

Using Joo et al.'s (1999) definition of PSE (Driploss >6 % and L^* (lightness) > 50, PSE_1), PSE meat was recorded in approximately 29 % of the samples (Table 8). However, the model revealed no significant difference between treatments nor treatments in interaction with batch. Batch effects were nevertheless significant, with a higher risk of PSE measured in Batch 1 than in Batch 2 (odds ratio 2.71, 95 % CI [1.32: 55], $P = 0.01$, Table 9).

Using the definition of PSE presented as PSE_2 ($pH_{45} < 5.8$ and $pH_{22} < 5.3$), no case of PSE was recorded. Similarly, using $pH_{22} > 6$ as a definition of DFD, none of the meat analysed were categorized as such.

4. Discussion

In line with previous studies, our results showed a limited impact of the extensification factors on the meat quality of pigs raised in indoor conventional husbandry. Neither the provision of enrichment nor roughage impacted meat quality, and increased space allowance only had a minor effect on meat colour.

Nonetheless, the study showed an effect of space allowance on growth and carcass weight, with increased growth and carcass weight recorded in pigs housed with the highest space allowance compared to the control. The same effect was not recorded on slaughter weight, but this could be explained by the fact that pigs from the Space 6 treatment reached the target slaughter weight of 120 kg prior to other treatments and were therefore often sent to slaughter at the earliest slaughter date, while the remaining pigs stayed in the experiment for another week prior to be sent to slaughter, and therefore had the opportunity to grow further. Overall, 66 % of the pigs from the Space 6 treatment reached the target slaughter weight on the first slaughter date, compared to 42 % in the other treatments. In addition, although feed intake was not recorded, it is noticeable that pigs in the Space 6 treatment received on average 3 kg of finisher feed per day more than the pigs from the control group on the last week prior to slaughter in Batch 2 (see Supplementary Table 2), which suggests that they had a higher feed intake and resulting growth. This outcome is not in line with previous studies that showed no effect of space allowance on growth (Camp Montoro et al., 2021; Camp Montoro et al., 2022). However, when rearing heavier pigs, a positive effect of increased space on growth and performance seems to be observed (Nannoni et al., 2019; Rossi et al., 2008). The relationship between space and growth appears to depend on slaughter weight, with increased growth mainly occurring in the last weeks of the fattening period. In our study, the average slaughter weight was above 120 kg, and thus this effect may have had the opportunity to develop.

Additionally, some effects of the space treatments were observed in specific meat attributes. Pigs raised with 1.4 m^2 per animal (Space 9)

Table 8
Probability of developing PSE_1 per treatment and batch.

	PSE_1	PSE_2	DFD
Control	24.93 ± 0.07	0	0
Enrichment	23.97 ± 0.07	0	0
Roughage	38.82 ± 0.09	0	0
Space 9	18.84 ± 0.07	0	0
Space 6	22.32 ± 0.08	0	0
P	n.s.	–	–
Batch 1	36.01 ± 0.05	0	0
Batch 2	17.20 ± 0.04	0	0
P	<0.01	–	

Results are presented in model estimates ± standard errors.

Table 9
Odds ratios of developing PSE_1 per treatment and batch.

	Control	Enrichment	Roughage	Space 9
Control (n = 48)	–	–	–	–
Enrichment (n = 44)	1.11 [0.27: 4.61]	–	–	–
Roughage (n = 45)	0.52 [0.14:2.24]	0.50 [0.11:2.16]	–	–
Space 9 (n = 42)	1.51 [0.31:7.41]	1.36 [0.26:7.05]	2.7 [0.56:13.34]	–
Space 6 (n = 42)	1.22 [0.26:5.83]	1.10 [0.22:5.47]	2.21 [0.44:11.1]	0.81 [0.14:4.77]
Batch 1 / Batch 2 (n = 125) (n = 96)	2.71 [1.32: 5.55]			

Results are presented as odds ratio, 95 % confidence interval [lower limit:upper limit].

had a darker meat compared to the roughage, enrichment and control treatments in which pigs were housed with a conventional space density (0.7 m^2 per animal). Meat from the Space 9 treatment was also less yellow than that of the enrichment treatment. From these results, it could be hypothesized that increased space allowance alone may affect meat colour. This hypothesis is somehow in line with a previous study showing a positive effect of space allowance on meat quality, though that study demonstrated effects on pH, tenderness and water holding capacity rather than colour (Liorancas et al., 2006). The same effect was however not observed in pigs allowed 2.1 m^2 per animal (Space 6), which seems inconsistent with this hypothesis. One explanation could be that pigs from the Space 6 treatment developed a significant higher risk of stomach ulcers, potentially due to their high intake of highly concentrated feed (Coutant et al., 2025). This phenomenon may have potentially affected the resulting meat attributes for that treatment and hampered the effects of increased space allowance alone. Pigs in the Space 9 treatment also showed a lower driploss than the pigs provided with roughage, which could also suggest a higher chemical quality of the meat in the Space 9 treatment. Yet, it is again unclear why this difference was observed. If resulting from the increase in space (as suggested from Liorancas et al., 2006), the samples from Space 9 would have been expected to similarly differ from the other treatments involving a conventional space density. If resulting from the roughage intake, the roughage pigs would have been expected to also differ from the other treatments fed exclusively concentrated feed. Nevertheless, the difference between the two treatments was not consistent across meat parameters, which seems to suggest that the overall quality of the meat did not differ.

Overall, the lack of relationship between extensification and meat quality could be explained by several factors. First, it is possible that our extensification treatments, characterized by the addition of point objects or roughage, did not sufficiently address the pigs' behavioural needs to elicit a welfare change significant enough to affect meat quality. Previous studies suggest that changes in meat quality often result from more drastic modifications to the husbandry system, such as switching to free-range or outdoor rearing, conditions that create a much more complex form of enrichment and diet (Lebret & Čandek-Potokar, 2022). Future studies could therefore further investigate the benefit of extensification factors taken in combination (considerable increase in space allowance along with provision of environmental enrichment and roughage supplementation). Second, it is possible that, despite potential benefits of the extensification factors, the stress associated with transport and slaughter may have had a greater impact on meat quality than the rearing conditions did during the fattening period. Pre-slaughter stress, induced during transport, lairage, and stunning, has indeed been correlated with post-mortem muscle acidification, which is associated with a reduction in meat quality (Faucitano, 2018).

When comparing the general meat quality observed in this study to the average meat quality in Denmark as documented by Aaslyng and Hviid (2020), it is apparent that the meat from our experiment differed to some extent from the national norm. Notably, the probability of pale, soft exudative meat (PSE), as defined by Joo et al. (1999), reached 29 % in our sample, compared to only 2 % in Aaslyng and Hviid's study, with a peak of 36 % in the first batch of the experiment. A high degree of PSE could result from a high level of pre-slaughter stress; however, the short trip between the farm and the slaughterhouse and the relatively fast slaughter of the animals would indicate the opposite. Furthermore, as described in Rosenvold and Andersen (2003), a high level of pre-slaughter stress is expected to result in lower levels of meat pH at 45 min post-mortem. With comparable pH levels post-mortem recorded in our study and Aaslyng and Hviid's, pre-slaughter stress seems unlikely to explain this difference. We hypothesize that the unforeseen issues in the daily rearing conditions—namely tail biting in Batch 1 and pneumonia outbreaks in Batch 2—could have impacted stress during rearing and ultimately affected meat properties. Although the precise relationship between these stressors and meat quality remains to be determined, this hypothesis aligns with previous studies showing a connection between tail damage and weakened meat quality, as measured by increased muscle temperature, drip loss, and lighter meat colour (Valros et al., 2013).

Overall, our results showed large differences between the two experimental batches for several meat quality parameters. These differences may be attributed to multiple factors that were confounded with batches. First, the pigs originated from different herds. Although they had the same genetics, differences in early life experiences may have influenced their development. Additionally, the outbreaks of tail biting and pneumonia in Batch 1 and Batch 2, respectively, differences in age at slaughter, and varying amounts of weaner diet, finisher diet, and straw provided per batch likely played a role. Lastly, batches were also confounded with the seasons (spring for Batch 1 and autumn for Batch 2). A previous study has shown an effect of season on meat quality parameters (Čobanović et al., 2020). Although the largest differences were observed between summer and winter, this study showed a significant reduction in drip loss, lightness, and redness in the autumn compared to spring. Furthermore, the likelihood of PSE was reduced from 43 % in the spring to 10 % in the autumn. Our outcomes are consistent with these results, with reduced pH at 22 h post-slaughter, drip loss, lightness, and redness observed in Batch 2 (autumn) compared to Batch 1 (spring). The probability of PSE was additionally reduced from 36 % in Batch 1 (spring) to 17 % in Batch 2 (autumn). As explained in Čobanović et al. (2020), these differences may be due to temperature and the related thermal comfort of the pigs during rearing and transport. Our results suggest that season, potentially in combination with specific events during the rearing period, may modulate meat quality to a significantly greater degree than the housing and management changes tested in this experiment.

Nevertheless, it is important to consider that not all aspects of meat quality were analysed in this study. For instance, fatty acid composition is an important parameter for the nutritional quality of pork, which is increasingly valued by consumers (Wood & Enser, 2017). It could be hypothesized that this factor could have potentially differed among treatments, especially for the pigs having been provided with extra roughage (Hansen et al., 2006). Yet, the effects of the tested extensification factors on fatty acid composition will need to be clarified in a future study. Furthermore, while extensification did not result in major alterations to meat quality, consumer sensory analyses and the impact of knowledge of these extensification factors on the perception of meat quality remain to be investigated.

Moreover, the extensification treatments may have affected other important aspects of pig production. Besides the effect of space allowance on growth and carcass weights mentioned earlier, it is worth noting that no pigs from the Space 6 treatment (2.1 m^2 per animal) had to be removed from the experiment during the outbreaks of tail biting and pneumonia. Although this observation should be interpreted cautiously, it could suggest an effect of space allowance on pig resilience. This

outcome would align with previous studies showing a positive effect of increased space allowance (achieved by decreasing group size) on immune function and/or disease transmission between individuals (Chidgey, 2023; Turner et al., 2000). Similarly, the impact of extensification treatments (provided individually or in combination) on animal welfare and behaviour, including feeding, social, and thermoregulatory behaviours, deserves further attention.

5. Conclusion

Providing indoor enrichment or additional roughage as extensification strategies did not affect the quality of meat in finisher pigs, while increasing space allowance only had minor effects on meat colour. However, increasing space allowance by a factor of three did show some benefits in terms of growth and carcass weight. Further studies are needed to investigate the combined effects of these factors on both meat quality and growth in indoor husbandry. Additionally, more research is required to explore how extensification factors influence other aspects of husbandry, such as animal welfare, health, and farm economy, in a more holistic way. This will help to better understand the overall benefits and potential drawbacks of these strategies.

Consent form

The study did not involve any human subject.

CRediT authorship contribution statement

Mathilde Coutant: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Marlene Schou Grønbeck:** Writing – review & editing, Methodology, Investigation. **Marchen Hviid:** Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Lene J. Pedersen:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Mona L. V. Larsen:** Writing – review & editing, Supervision, Methodology, Investigation, Data curation, Conceptualization.

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.meatsci.2025.109916.

Data availability

Data will be made available on request.

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