Alternative housing systems for pigs: Influences on growth, composition, and pork quality

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Alternative housing systems for pigs: Influences on growth, composition, and pork quality[1]

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ABSTRACT: Effects of pig birth (first 3-wk period) and rearing environments on growth and muscle quality characteristics of loins were evaluated in three experiments over seasons in west Texas and central Missouri. Housing systems included indoor slatted-floor buildings, indoor deep-bedded buildings, outdoor housing on dirt, and outdoor housing on alfalfa pasture. Experiments were conducted during the growing/finishing phases and pigs were slaughtered at the same age. Loins were collected, vacuum-packaged, and stored for 14 d at 2°C. Pigs born and finished in an outdoor environment during the summer months (Exp. 1) had a greater ADG (0.92 vs 0.82 ± 0.06 kg/d, $P < 0.05$) and had heavier carcass weights (87.9 vs 78.4 ± 2.4 kg, $P < 0.05$) than pigs born and finished in an indoor environment with a slatted-floor finishing building. Carcasses from the outdoor-reared group measured a larger ($P < 0.05$) loineye area and were fatter ($P < 0.01$) at the first rib, last rib, and last lumbar vertebra measurements than carcasses from the indoor-reared group. Loin chops from outdoor-reared pigs had darker color scores in the retail display case throughout the 4-d period, measured lower L* values on d 1, and had more discoloration and browning on d 4 than loin chops from the indoor-reared group. During the winter months (Exp. 2), no difference was detected in ADG, carcass measurements, sensory characteristics, or shear force values from indoor-born pigs placed in either an outdoor or indoor finishing environment. Pigs finished on deep bedding (Exp. 3) had heavier carcass weights and more backfat ($P < 0.01$) than pigs finished on slats, but no differences were detected in sensory panel or shear force results. Overall, carcass measurements, pH, drip loss, sensory panel, and shear force values were similar among the groups finished in different housing systems. Outdoor or deep-bedded systems may increase growth rates of pigs if suitable land area and resources are available, but pork quality of loins will be similar for pigs finished in either conventional or alternative systems.

Key Words: Environment, Housing, Pigs, Pork Quality

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Introduction

A growing interest has been shown in alternative pig production systems because of the low capital cost of outdoor systems, which varies from 40 to 70% of the cost for conventional indoor systems (Thornton, 1988). Concerns for animal welfare and awareness of niche marketing opportunities have increased interest in the production of free-range animals (McGlone, 2001). Outdoor housing on pasture or dirt pens accounts for less than 5% of the pigs finished in the United States; an additional 9% are housed in an open building with outside access (NAHMS, 2001). Success of outdoor pig finishing systems may depend on the details of the housing design, management, and location, including soil type and climatic conditions (Edwards and Turner, 1999). Effects of pig birth environment on performance and carcass measures have not been reported until recently (Gentry et al., 2002). In this work, outdoor-born pigs had a higher ADG than indoor-born pigs.

Deep-bedded swine housing systems (hoop-style and converted poultry buildings) have been considered as an alternative to traditional slatted-floor indoor systems (Honeyman et al., 2000). These systems often use large group sizes and are operated as an "all in-all out" sys-

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tem. Pigs are raised on some type of bedding (corn stalks, straw, fescue hulls, etc.) rather than concrete slats.

Few researchers have examined the effects of outdoor housing systems on pig growth and meat quality characteristics. The overall objectives of these experiments were to examine the effects of alternative pig housing systems on growth and meat quality measures using both controlled university trials and field studies. The objectives of Exp. 1 and 2 were to determine the effects of outdoor finishing on a dirt lot or alfalfa pasture on pig growth, pork quality, and retail display characteristics. The objective of Exp. 3 was to evaluate the effects of pig rearing environment (bedded vs slatted flooring) on growth and meat quality.

Materials and Methods

Animal Selection and Slaughter. Experiments 1 and 2 were designed as controlled experiments at the Texas Tech University farm. Experiment 3 was a field trial in a commercial setting. Animals were housed in accordance with the *Guide for the Care and Use of Agriculture Animals in Agricultural Research and Teaching* (FASS, 1999), and the Texas Tech University Animal Care and Use Committee approved the project.

Experiment 1. Animals were randomly selected from the Texas Tech University farm system of indoor-born (sows in farrowing crates) and outdoor-born (sows outdoors with individual huts for farrowing) pigs that were weaned on the same day. The farm is located in the Southern high plains and the climate is considered semi-arid. The location is about 40 km northeast of Lubbock (latitude 33° 45′ N; longitude 101° 47′ W; elevation 993 m) and the mean annual precipitation is 46.5 cm. Production systems were described by Johnson et al. (2001). The pigs' dams had gestated indoors or outdoors. This birth environment refers to the system in which sows gestated and lactated and in which the pigs suckled. Outdoor sows were maintained entirely in an outdoor setting. Groups were stratified by sex and both barrows and gilts were used in this study. All pigs were of Newsham genetics from the same genetic lines (Newsham female line mated to UL sire line) that were halothane-negative. Newsham is a white-line breeding female containing Yorkshire, Landrace, and Duroc breeds. The Newsham sire is a crossbred dark-skinned sire (Line UL). Pigs were from a herd that has a high health status and is PRRS-negative. Indoor-born pigs were housed in groups of 8 to 10 pigs/pen in an indoor nursery that was maintained at 26.7°C until they reached 30 kg. Outdoor-born pigs were housed in one group (162 pigs) in an outdoor nursery after weaning. The outdoor pen was 24 × 14.4 m and two huts were provided for shelter (9 × 15 m; Port-a-Hut, Storm Lake, IA). Wheat straw bedding was provided in the huts. The average air temperature during the nursery period was 10.2°C and the relative humidity was 54.8%.

This experiment began in mid-April and pigs were slaughtered in July. Average initial weight of the pigs was 30 kg. The average air temperature for the outdoor pigs during this trial was 21°C (range: 3 to 38°C) and the average relative humidity was 60%. The air temperature was within normal ranges during this study period. Indoor pigs were placed in a temperature-controlled building where temperatures did not fall below 18°C. When the temperature reached 29°C or higher in the finishing barn, misters are turned on. In this first preliminary experiment, 40 outdoor-born pigs were placed in an outdoor pen (approximately 2.0 m^2/pig) on dirt with two huts (9 × 15 m; Port-a-Hut) for shelter and a wallow. Wheat straw was placed in the huts for bedding. Outdoor-finished pigs had twice as much space allowance per pig as the indoor-finished pigs. Indoor pens were 4.2 × 7.2 m and the flooring consisted of concrete slats. Twenty indoor-born pigs were placed in one of two adjacent pens (approximately 1.0 m^2/pig) in the finishing barn. For each of the pens, one three-hole feeder (Smidley feeders, Marting Manufacturers, Yazoo City, MS) and one nipple waterer was provided for 20 pigs. Both groups (indoor-finished and outdoor-finished) were given ad libitum access to an identical growing and finishing diet that included milo and soybean meal formulated to meet NRC (1998) requirements. Pigs were weighed at d 0, 43, and 94 and the final live weight averaged approximately 114 kg at the end of the experiment. All pigs were processed on d 95 at a commercial packing plant (Guymon, OK) by electrical stunning and chilled in a blast cooler on the same day.

Experiment 2. Pigs were randomly selected from a group of indoor-born pigs at the Texas Tech University Farm and were placed on trial at approximately 52 kg. Pigs were born indoors in farrowing crates, weaned at approximately 21 d, and kept in an indoor nursery for 5 wk. After the nursery period, pigs were moved to the indoor finishing facility and kept on concrete-slatted flooring. Littermates were placed in each of the two finishing environments: indoors on concrete-slatted flooring (1.2 m^2 of space per pig) or outdoors on an alfalfa pasture (212 m^2 of space per pig). One hut (9 × 15 m; Port-a-Hut) was placed in each of the four pens for shelter. Wheat straw was placed in each of the huts for bedding. The experiment began in mid-October and finished in early January. The average air temperature for the outdoor pigs during this trial was 10°C (range: –9 to 30°C) and the average relative humidity was 57%. Air temperatures were within normal ranges during this study period. Indoor pigs were placed in a temperature-controlled building where temperatures did not fall below 18°C. Four pens per finishing environment were used and six barrows were placed in each pen (n = 48). All pens had one three-hole feeder (Smidley feeders) and one nipple waterer. All pigs were of the same Newsham genetic lines as previously described in Exp. 1 and halothane-negative. Pigs were given ad libitum access to an identical growing and finishing diet (milo/soybean meal) formulated to meet NRC (1998) requirements. Pigs were weighed at d 0, 28, 56, and 87. Two pigs per pen were randomly selected for one of two slaughter dates at the Texas Tech University Meat Laboratory. Pigs from each of the two treatments were slaughtered on each of the two slaughter dates. At processing, pigs from each of the treatments were the same age. Pigs were transported for 30 min and then rested overnight before slaughter. Pigs were processed under normal commercial practices after electrical stunning (300 V, 2 A).

Experiment 3. Animals were born in an indoor facility, weaned at 3 wk, and then finished at one of two field sites. The first site consisted of an indoor finishing facility with concrete-slatted flooring and was located in western Kansas. Pigs were housed in groups of 25 and the space allowance was 7.5 m^2/pig. A wet/dry tube feeder and a nipple waterer were provided in each pen. At the second site in central Missouri, pigs were finished in a converted poultry house on fescue hull bedding, which is a by-product when harvesting fescue seeds. The building was large and open with natural ventilation on both ends and curtain sides. Pigs (n = 1,500) were housed in this facility and the space allowance was 12 m^2/pig. Dry feeders were located at one end of the building and nipple waterers were located on the right side of the pen. All pigs in this experiment originated from the same indoor swine facility and were weaned on the same day. Both of these two sites were located within three h of the processing facility. They were born indoors in farrowing crates and consisted of PIC USA genetics (Camborough-22 females mated to Hampshire × Duroc meat type sires) that were halothane negative. At weaning, pigs were randomly sent to either the indoor finishing facility or the bedded facility and pigs were in their respective finishing environments from weaning until processing. Both groups were given ad libitum access to the same corn/soybean meal growing and finishing rations that met NRC (1998) requirements. Pigs from each farm were transported 2 to 3 h to the processing plant and were held overnight for rest. Two truckloads from each farm (n = 4 truckloads, 180 pigs per truck) were processed. Pigs from each truckload derived from the same weekly batch and were the same age at processing. Pigs were processed after electrical stunning and carcasses were held in a spray-chill cooler overnight.

Foot pad and toe lesions were scored on a random group of 50 pigs per truckload for a total of 100 pigs from each finishing environment during processing. A trained observer stood on the line to score foot lesions as the hanging carcass passed during processing. The foot lesions were given a score of 1 = clear, 2 = mild, or 3 = severe lesions of the toe, food pad or both. When both the toe and foot pad had significant (over 25%) wound area, the lesion was considered severe. Lung lesions also were assessed on 100 pigs per finishing environment. A trained observed scored lungs for the percentage of damage (nonfunctional tissue) and lungs with lesions of 50% or more were considered severe. Lungs were given a score of 1 = clear of lesions, 2 = mild lesions, or 3 = severe lesions.

An additional experiment was conducted in the same manner as Exp. 3 only using outdoor-born pigs that were placed into the two finishing environments. However, the pigs placed in the bedded facility became severely sick with an enteric parasite infection (whip worms) upon arrival and had reduced performance. For this reason, results from the fourth experiment are not included in this article.

Temperature and pH Decline. Temperature and pH of the carcasses were measured at the 10th and 11th rib interface at 1, 6, and 24 h postmortem. Temperature was measured with a Hantover Model TM99A-H Digital Thermometer with a 10-cm stem (Hantover, Atlanta, GA). The pH decline was monitored using an Orion Model 230A Digital Ionalyzer (Orion Research, Cambridge, MA) with a puncture electrode.

Sample Collection and Color Evaluation. Carcasses were measured for backfat thickness at the first rib, last rib, and last lumbar vertebra. Ham muscle scores were assigned to each carcass using a scale of 1 = thin, 2 = average, and 3 = thick. After 24 h of chilling, the carcasses were fabricated into wholesale cuts. Loins were cut into boneless loins (IMPS No. 413) for Exp. 1 and 2 and loins were purchased as whole, bone-in loins (IMPS No. 410) for Exp. 3. Loins were vacuum-packaged in plastic Cryovac bags and stored at 2°C until 14 d postmortem. Color was evaluated instrumentally at 14 d postmortem on the longissimus muscle at the 10th rib for Commission Internationale de l'Eclairage (CIE) L* (muscle lightness), a* (muscle redness), and b* (muscle yellowness) values using a Minolta Spectrophotometer Meter model CM-2002 (Minolta Camera Co., LTD, Osaka, Japan), with a D_{65} illuminant with a 1-cm-diameter aperture in Exp. 1 and 3. Three readings per loin were taken and scores were calculated by averaging the three readings. A Hunter Miniscan XE Plus colorimeter (Hunter Laboratories, Model MSXP-4500L, Reston, VA) was used to measure CIE L*, a*, and b* in Exp. 2. Each instrument was calibrated following the manufacturer's instructions. Visual color, marbling, and firmness scores were assigned to each loin by two trained personnel (NPPC, 1999). Color was scored on a 6-point scale with 6 = dark purplish-red, 3 = reddish-pink and 1 = pale pinkish-gray to white. Marbling scores were assigned on a 10-point scale with 10 = moderately abundant or greater and 1 = devoid. Firmness was scored on a 5-point scale with 5 = very firm and dry, 3 = slightly firm and moist, and 1 = very soft and very watery. A loin drip loss core sample (2.5 × 2.5 cm) was obtained at 14 d postmortem. Samples were weighed, placed in a drip loss tube (meat juice containers, C. Christensen Laboratory, Denmark), and held at 2°C for 24 h. Samples were reweighed at 24 h to determine percentage of drip loss. Loins were cut into 2.5-cm-thick chops at d 14 postmortem for Warner-Bratzler shear (**WBS**) force evaluation, sensory attributes, and proximate analyses. Chops were vacuum-packed and frozen at −40°C for 1 to 2 mo until further analysis.

Sensory and Shear Force Analyses. Chops (n = 2 for sensory evaluation and two for WBS) were cut from each loin. All chops were thawed overnight in a refrigerator to an internal temperature of 2 to 5°C. Chops were cooked on a belt grill (Model TBG-60 Magigrill, Magi-Kitch'n, Quakertown, PA) to an internal temperature of 71°C (AMSA, 1995). The belt grill settings (top and bottom heat = 163°C, preheat = disconnected, height = 0.33 cm, and cook time = 5.4 min) were set to produce an internal temperature of 71°C. The final internal temperature was recorded with a needle thermocouple meat thermometer (Model #91100, Cole-Parmer, Vernon Hills, IL). The chops for WBS were cooled to room temperature, wrapped with polyvinyl chloride film to prevent dehydration, and stored overnight at 2°C. Three 1.3-cm-diameter cores were removed parallel to the muscle fiber orientation from each chop. Each core was sheared once through the center with a United Testing Machine (Model # SSTM-500 with a tension attachment; United Calibration, Huntington Beach, CA). The crosshead speed was 20 cm/min, as suggested from previous literature (AMSA, 1995; Wheeler et al., 1997). Shear force values for each animal were determined by averaging values from the six cores (n = 3 per chop). Muscle from the other two cooked chops was cut into 1.3- × 1.3- × 2.5-cm pieces for sensory evaluation. Samples were served warm (approximately 50°C) to a six- to eight-member panel selected and trained according to Cross et al. (1978). Panelists evaluated the samples on an 8-point scale for juiciness, tenderness, flavor intensity, pork flavor, and overall mouthfeel (8 = extremely juicy, tender, intense, and characteristic pork mouthfeel; 1 = extremely dry, tough, bland, unsavory, and uncharacteristic mouthfeel, respectively). The samples were served under red lights to mask color differences. The panelists were served water and apple juice to rinse their palates between samples. Individual panelist scores were averaged and mean scores from each sample were used for the statistical analysis.

Retail Display. Retail display characteristics were evaluated in Exp. 1 and 2. One loin chop from each animal was placed on a tray and overwrapped with Reynolds 914 saran wrap for display in a retail case for 4 d at 4°C. The display case was equipped with two overhanging lights, each containing two bulbs of Sylvania 40W, GroLux, Model A858, and ceiling lights (Phillips 34W, Watt-Saver, Model G), which produced a light reading of 55 footcandles at the meat level. The chops were placed randomly in a coffin-style retail display case (Model DGC6, Tyler Refrigeration, Niles, MI) and continuously illuminated during the 4-d display period. CIE L*, a*, and b* values were taken initially and at 24-h intervals. A trained, six-member panel evaluated the chops each day for color (8 = extremely bright grayish-pink and 1 = extremely dark grayish-pink), color uniformity (5 = extreme two-toning and 1 = uniform), surface discoloration (7 = 100% discolored and 1 = 0% discolored), and browning (6 = dark brown and 1 = none) according to AMSA (1991).

Statistical Analyses. Data were analyzed using SAS (SAS Inst. Inc., Cary, NC). Growth and carcass data were analyzed as a completely randomized design using GLM procedures of SAS. In Exp. 1 and 3, the animal was the experimental unit. In Exp. 2, the pen effect was included in the model. In Exp. 2, slaughter date was included in the initial analysis but had no significant effect on the measured traits and was dropped from the final analysis. In Exp. 1, initial weight was included as a covariate in the analysis for the determination of final live weight and ADG. Sex was also included in the model for Exp. 1; however, treatment differences due to sex were minimal. In two of the experiments, hot carcass weight (Exp. 1) or cold carcass weight (Exp. 3) was used as a covariate to minimize effects of carcass weight differences among the treatments on pork quality measures. Retail display data were analyzed as repeated measures over time. Least squares means were separated by the protected Predicted Difference test within GLM. In Exp. 3, foot lesions and lung lesions were analyzed using a chi-square analysis.

Results

Experiment 1. Pigs born and reared outdoors had a higher ($P = 0.001$) ADG than pigs born and reared indoors (Table 1). Outdoor-born pigs were significantly heavier at weaning than indoor-born pigs; therefore, initial weight was included as a covariate in the analysis to account for differences in weight at the beginning of the experiment. Pigs finished outdoors gained 0.1 kg/d more ($P < 0.05$) than the pigs finished indoors and were 13.7 kg heavier at the end of the trial. Barrows were heavier at d 43 (67.7 vs 63.5 kg ± 1.1 kg; $P = 0.009$), and d 94 (114.8 vs 106.2 ± 1.4 kg; $P = 0.001$) and had a higher ADG (0.90 vs 0.81 ± 0.01 kg/d; $P < 0.001$) than gilts. No other differences between performance measures of barrows and gilts were detected.

Pigs born and raised outdoors were similar in muscle characteristics but had more muscle development and less fat deposition than pigs born and reared indoors. No differences were detected in pH measurements of loineye muscle at 1, 6, or 24 h postmortem between the pigs housed indoors or outdoors. Pigs finished indoors had more ($P < 0.01$) backfat at the first rib, last rib, and last lumbar vertebra than pigs finished outdoors when hot carcass weight was included as a covariate in the analysis. Pigs finished outdoors had a larger ($P = 0.03$) loineye area than the pigs finished indoors when weight was held constant in the analysis. No differences were detected in carcass length or ham muscle scores between the two groups (data not shown). Loins from pigs reared indoors had higher ($P = 0.04$) marbling scores than loins from pigs reared outdoors. Visual color and firmness scores and CIE L*, a*, and b* values were not different between the treatments. No differences in

Table 1. Growth and carcass characteristics of pigs born and finished outdoors or indoors during the summer months (Exp. 1)

Measure	Outdoor	Indoor	SEM	*P*-value
No. of pigs	40	40	—	—
Growth trait, kg[a]				
Initial wt (d 0)	31.9	27.7	1.27	0.001
Final live wt (d 94)	115.3	105.8	3.16	0.001
ADG	0.91	0.81	0.03	0.001
Hot carcass wt	87.9	78.4	2.43	0.001
Carcass measurements[b]				
1-h pH[c]	6.6	6.8	0.06	0.22
24-h pH[c]	5.6	5.5	0.03	0.31
First rib backfat, cm	4.4	5.2	0.07	0.003
Last rib backfat, cm	3.1	3.7	0.05	0.004
Last lumbar backfat, cm	2.5	3.0	0.04	0.004
Loineye area, cm^2	45.0	40.9	0.18	0.03
Color score[d]	3.6	3.5	0.15	0.65
Marbling score[e]	2.7	3.6	0.25	0.04
Firmness score[f]	2.8	2.8	0.12	0.88
L*[g]	47.2	48.1	0.64	0.38
a*[g]	3.7	3.2	0.33	0.33
b*[g]	11.4	11.1	0.32	0.55

[a]Initial weight was included as a covariate for growth measurements.
[b]Hot carcass weight was included as a covariate for carcass measurements.
[c]pH was measured at the 9th and 10th rib of the longissimus muscle.
[d]Color scores range from 1 to 6, 1 = pale, pinkish-gray and 6 = dark, purplish-red.
[e]Marbling scores range from 1 to 10, 1 = devoid and 10 = moderately abundant or greater.
[f]Firmness scores range from 1 to 5, 1 = very soft and watery, 5 = very firm and dry.
[g]Measured on the longissimus muscle at the 10th and 11th rib.

backfat or loineye area measurement between barrows and gilts were found.

Initial juiciness scores for loin chops from the pigs finished indoors were higher ($P < 0.05$) than scores for loin chops from the pigs finished outdoors (Table 2).

Table 2. Sensory and shear force of loin chops from pigs born and finished outdoors or indoors during the summer months (Exp. 1)

Measure	Outdoor	Indoor	SEM	*P*-value
No. of loins	30	33	—	—
Initial juiciness[a]	5.4	6.0	0.14	0.03
Sustained juiciness[a]	5.8	5.9	0.16	0.53
Initial tenderness[a]	6.0	6.1	0.15	0.48
Sustained tenderness[a]	6.2	6.4	0.15	0.43
Pork flavor intensity[a]	6.2	6.3	0.08	0.54
Pork flavor[a]	6.4	6.4	0.08	0.82
Overall mouthfeel[a]	5.9	6.2	0.14	0.22
Off-flavor[b]	1.0	1.1	0.02	0.04
Shear force, kg	2.3	2.2	0.09	0.45

[a]Sensory panel scores for initial and sustained juiciness, initial and sustained tenderness, flavor intensity, pork flavor, and overall mouthfeel range from 1 to 8, with 1 = extremely dry, tough, bland, unsavory, and uncharacteristic mouthfeel and 8 = extremely juicy, tender, intense, and characteristic pork mouthfeel.
[b]Scores for off flavor are 1 = no off-flavor and 5 = extreme off-flavor.

Table 3. Retail display (4 d) characteristics of loin chops from pigs born and finished outdoors or indoors during the summer months (Exp. 1)

				P-value	
Attribute	Outdoor	Indoor	SEM	Trt within day	Trt × day
Color[a]	5.6	6.1	0.07	< 0.001	0.98
Uniformity[b]	1.7	1.6	0.03	0.28	0.48
Discoloration[c]	2.0	1.7	0.06	< 0.001	0.002
Day 1	1.0	1.0	0.12	0.91	
Day 2	1.1	1.0	0.12	0.47	
Day 3	2.0	1.8	0.12	0.15	
Day 4	4.0	3.1	0.12	0.001	
Browning[d]	1.6	1.5	0.03	0.21	0.009
Day 1	1.0	1.0	0.07	0.98	
Day 2	1.1	1.0	0.07	0.39	
Day 3	1.8	1.7	0.07	0.15	
Day 4	2.5	2.3	0.07	0.004	
L*	51.7	52.6	0.37	0.10	0.18
a*	3.3	3.3	0.10	0.58	0.93
b*	9.7	9.7	0.15	0.90	0.71

[a]Color scores range from 1 to 8 (1 = extremely dark grayish-pink; 8 = extremely bright grayish-pink).
[c]Uniformity scores range from 1 to 5 (1 = uniform, 5 = extreme two-toning).
[d]Discoloration scores range from 1 to 7 (1 = 0% discoloration, 7 = 100% discoloration).
[e]Scores for browning range from 1 to 6 (1 = none, 6 = dark brown).

Differences in sustained juiciness were not detected. Loin chops from the indoor-reared pigs had a higher ($P < 0.05$) mean for off-flavor than chops from the outdoor-reared pigs.

Visual evaluations indicated that loin muscle from pigs finished outdoors deteriorated faster during retail display (Table 3). Loin chops from the indoor-housed and outdoor-housed pigs were similar in visual color and uniformity. Loin chops from the pigs finished in the two differing environments were also similar in instrumental color measurements (L*, a*, and b* values). Significant treatment × day interactions were observed for discoloration and browning. The outdoor-housed pigs had loins with higher ($P < 0.05$) discoloration and browning scores on d 4 of display than loins from indoor-housed pigs.

Experiment 2. Growth rates and carcass measurements were similar between the groups finished indoors and outdoors (Table 4). Pigs finished outdoors had similar backfat and loineye area measurements compared to their littermates finished indoors on slats.

No differences were detected in 1-, 6-, or 24-h pH measurements between the loins of indoor-housed and outdoor-housed pigs. Loins from pigs finished indoors had a higher ($P = 0.02$) drip loss than loins from pigs housed outdoors, but means for visual color, pH, L*, a*, or b* values were similar between the groups finished either indoors or outdoors. However, these results were not consistent with pH values and subjective or objective color scores of the loins. No differences in loin color, marbling, or firmness were detected for the indoor and outdoor pigs.

Table 4. Growth and carcass characteristics of indoor-born pigs finished outdoors on alfalfa pasture or indoors on concrete slats during the winter months (Exp. 2)

Measure	Outdoor	Indoor	SEM	*P*-value
Growth traits, kg				
No. of pigs	24	24		
Initial wt (d 0)	52.1	51.3	2.94	0.68
Final live wt (d 87)	105.9	108.8	4.01	0.30
ADG	0.77	0.82	0.29	0.79
Hot carcass wt	77.7	81.6	3.53	0.13
Carcass measurement				
No. of sides	15	16		
1-h pH[a]	5.9	6.0	0.07	0.32
24-h pH[a]	5.7	5.7	0.02	0.95
First rib backfat, cm	3.2	3.5	0.08	0.29
Last rib backfat, cm	2.2	2.3	0.04	0.63
Last lumbar backfat, cm	1.5	1.7	0.06	0.44
Loineye area, cm^2	40.0	38.0	0.13	0.13
Loin drip loss, %	1.7	0.7	0.22	0.02
Color score[b]	2.8	3.2	0.14	0.09
Marbling score[c]	2.3	2.6	0.16	0.30
Firmness score[d]	2.8	3.2	0.15	0.06
L*[e]	56.3	54.1	0.90	0.13
a*[e]	9.9	10.7	0.41	0.21
b*[e]	17.5	17.1	0.36	0.48

[a]pH was measured at the 9th and 10th rib on the longissimus muscle.
[b]Color scores range from 1 to 6, 1 = pale, pinkish-gray and 6 = dark, purplish-red.
[c]Marbling scores range from 1 to 10, 1 = devoid and 10 = moderately abundant or greater.
[d]Firmness scores range from 1 to 5, 1 = very soft and watery, 5 = very firm and dry.
[e]Values were measured on the longissimus muscle at the 10th and 11th rib.

Pigs housed in these differing environments produced loins with similar juiciness, tenderness, and flavor scores. No statistical differences were detected in any of the evaluations by the sensory panel (data not shown).

Visual and instrumental color scores of loins from the pigs finished indoors and outdoors were similar during the retail display period (data not shown). No significant differences were noted for uniformity, discoloration or browning throughout the 4-d period.

Experiment 3. Severe foot lesions were more prevalent on the pigs housed on bedding but pigs housed on concrete slats had a higher overall incidence of foot/toe lesions. Pigs housed on bedding had more severe foot pad and toe lesions (31 vs 9% of pigs with severe foot lesions, $P < 0.01$) than pigs housed on concrete slats; however, pigs housed on slats had more overall lesions (55 vs 32% of pigs with foot lesions) than pigs housed on bedding (Table 5). Overall, the percentage of clear and lesioned lungs was similar for the pigs finished in the two housing systems. However, the percentage of severe lung lesions was about twice as high among pigs in slatted-floor facilities.

Indoor-born pigs finished on bedding had heavier carcasses than pigs finished on slatted flooring. Pigs finished on bedding had 0.5 cm more backfat at the last

Table 5. Percentage of foot pad/toe lesions and lung lesions on indoor-born pigs housed on bedding or concrete slats (Exp. 3)

			Chi^2 for comparison	
Measure	Bedding, %	Slats, %	Clear vs all	All vs severe
No. of pigs	100	100		
Feet			10.76**	18.17**
Clear	68	45		
All lesions	32	55		
Severe[a]	31	9		
Lungs			1.59	3.71†
Clear	68	76		
All lesions	32	24		
Severe[b]	6	13		

[a]Percentage of lesioned pigs' feet; for example, 31% of the 32% of all foot lesions were severe for pigs on bedding.
[b]Percentage of lesioned lungs; for example 6% of the 32% of all lung lesions were severe for pigs on bedding.
†$P < 0.10$.
**$P < 0.05$.

rib measurement than pigs finished on slats (Table 6; $P < 0.001$).

No differences were detected in loin drip loss or color scores between the pigs finished on bedding and slats, indicating that the lower 1- and 6-h pH values did not cause an overall reduction in loin muscle quality. Pigs

Table 6. Carcass characteristics of indoor-born pigs housed on bedding or concrete slats (Exp. 3)[a]

	Type of flooring			
Measure	Bedding	Slats	SEM	*P*-value
No. of pigs	46	58		
1-h pH[b]	5.6	6.1	0.04	0.001
6-h pH[b]	5.5	5.6	0.03	0.05
24-h pH[b]	5.5	5.5	0.03	0.21
Cold carcass wt, kg	104.2	96.6	3.47	0.001
First rib backfat, cm	4.8	4.2	0.04	0.001
Last rib backfat, cm	3.2	2.7	0.03	0.001
Last lumbar backfat, cm	2.7	2.4	0.04	0.01
Carcass length, cm	88.2	89.6	0.18	0.04
Ham muscle score	2.2	2.3	0.06	0.42
Loineye area, cm^2	43.9	42.1	0.19	0.30
Loin drip loss, %	0.8	0.9	0.13	0.53
Color score[c]	3.2	3.0	0.14	0.37
Marbling score[d]	2.7	2.4	0.16	0.22
Firmness score[e]	2.7	2.3	0.14	0.02
L*[f]	46.0	46.2	0.70	0.83
a*[f]	5.6	5.7	0.30	0.79
b*[f]	12.2	12.0	0.44	0.74

[a]Chilled carcass weight was included as a covariate in the analysis.
[b]pH was measured at the 9th and 10th rib on the longissimus muscle.
[c]Color scores range from 1 to 6, 1 = pale, pinkish-gray and 6 = dark, purplish- red.
[d]Marbling scores range from 1 to 10, 1 = devoid and 10 = moderately abundant or greater.
[e]Firmness scores range from 1 to 5, 1 = very soft and watery and 5 = very firm and dry.
[f]Values were measured on the longissimus muscle at the 10th and 11th rib.

Table 7. Sensory attributes and shear force of loin chops from indoor-born pigs housed on bedding or concrete slats (Exp. 3)

	Type of flooring			
Measure	Bedding	Slats	SEM	*P*-value
No. of loins	39	47		
Initial juiciness[a]	5.9	6.1	0.09	0.24
Sustained juiciness[a]	6.0	6.2	0.09	0.32
Initial tenderness[a]	5.7	5.8	0.13	0.76
Sustained tenderness[a]	5.9	6.1	0.12	0.44
Pork flavor intensity[a]	6.1	6.1	0.07	0.61
Pork flavor[a]	6.2	6.2	0.08	0.60
Overall mouthfeel[a]	6.0	5.9	0.11	0.51
Off-flavor[b]	1.0	1.0	0.04	0.70
Shear force, kg	3.0	3.0	0.10	0.96

[a]Sensory panel scores for initial and sustained juiciness, initial and sustained tenderness, flavor intensity, pork flavor, and overall mouthfeel range from 1 to 8 with 1 = extremely dry, tough, bland, unsavory, and uncharacteristic mouthfeel and 8 = extremely juicy, tender, intense, and characteristic pork mouthfeel.

[b]Scores for off-flavor are 1 = no off-flavor and 5 = extreme off-flavor.

finished on bedding had lower 1- and 6-h pH measurements ($P < 0.05$) than pigs finished on slats, but no differences were detected in 24-h pH values. Loins from the pigs finished on bedding had higher firmness scores ($P < 0.05$) than loins from the pigs finished on slats. Visual scores for color and marbling were not different between the groups. No differences were detected in L*, a*, or b* values of loins from the pigs finished on bedding or slats.

Sensory panel scores were consistent among the treatment groups and, therefore, no significant differences were detected in any of the categories evaluated (Table 7).

Discussion

Experiments 1 and 2. Pig growth patterns were dependent on environmental factors as indicated by the differences in growth rates during trials conducted over warm and cool seasons. Pig birth environment (first 21 d of life) may play a critical role in growth rates as well. It is yet to be determined which component (pig birth or finishing environment or the interaction) is more important in affecting growth rates and performance of the outdoor-reared pigs. However, we recently determined that outdoor-born pigs have an advantage in growth rates compared to indoor-born pigs, regardless of whether they are placed indoors or outdoors for finishing (Gentry et al., 2002). The pigs finished outdoors during the winter months (Exp. 2) had ADG similar to those of their indoor-finished counterparts. Pigs finished outdoors during warm months (Exp. 1) had higher ADG than the indoor group. In Exp. 2, only indoor-born pigs were placed in the indoor and outdoor finishing environments, and therefore it is difficult to compare results between these two experiments. Advantages in ADG for pigs in outdoor finishing systems may be seasonal and pig birth environment may play a critical role in growth and performance. Experiment 1 evaluated both indoor-born and outdoor-born pigs, whereas Exp. 2 only evaluated indoor-born pigs. Therefore, it is difficult to determine the exact effect of pig birth environment on performance and meat quality over seasons from these two experiments. Our data show no advantages in growth rates or pork quality of indoor-born pigs finished outdoors during the winter months. We did find a significant advantage in growth rates of outdoor-housed pigs in the summer months compared to conventional indoor systems in this semi-arid climate. Previous literature from other researchers has not examined the effect of pig birth environment on growth rates and subsequent meat quality.

Researchers have reported conflicting results regarding the growth rates of pigs finished in outdoor or alternative systems. Results from these experiments conflict with Enfält et al. (1997), who reported that indoor-finished pigs had higher ADG than outdoor-finished pigs during winter months. However, climatic conditions are less extreme in the west Texas region compared to northern parts of Europe and may account for these differences in growth patterns. In addition, Sather et al. (1997) reported that indoor-finished pigs grew faster over both the summer and winter seasons in Canada. The indoor-finished pigs reached market weight 16 ± 0.61 d faster than the pigs finished in outdoor lots. Variable results have been reported on the effects of outdoor finishing environments on pig growth rates; however, many factors, including genetics, the physical environment, climatic conditions, and management levels, influence pig performance.

Carcass composition of pigs finished in outdoor and alternative finishing systems has been variable in previous literature. In Exp. 1, the indoor-born/reared pigs were fatter than the outdoor-born/reared pigs. However, no differences were detected in backfat measurements of the indoor-born pigs reared indoors or outdoors in Exp. 2. Our results from Exp. 1 agree with Warriss et al. (1983) and Enfält et al. (1997), who found that outdoor-reared pigs had less backfat than pigs reared intensively indoors. In contrast, Beattie et al. (2000) found that pigs from enriched environments (3.5 m^2/pig) had significantly greater levels of backfat and heavier carcass weights than pigs finished in a barren environment; however, this experiment did not included outdoor-born pigs. Other researchers have found that environmental enrichment for indoor-housed pigs resulted in no change in productivity (Pearce and Paterson, 1993; Blackshaw et al., 1997). Differences in backfat response that have been reported thus far may be related to the nature of the enrichment, the length of exposure to the enrichment, the genotype, or the developmental environment in the pig finishing systems that were evaluated.

Van der Wal (1991) determined that free-range pigs with straw bedding had growth and carcass composition similar to that of littermates finished indoors on partially-slatted floors. Others agree that if pigs were reared outdoors in cold conditions with plentiful exercise, carcasses might have less fat because nutrients would be diverted from fat deposition to thermoregulation (Warriss et al., 1983; Sather et al., 1997).

Outdoor pigs have had reduced postmortem pH and water-holding capacity of muscle in other experiments (Warriss et al., 1983; Enfält et al., 1997). Sather et al. (1997) reported that initial pH of free-range-reared pigs was lower, indicating a potential for reduced meat quality. Barton-Gade and Blaabjerg (1989) reported pigs finished in a free-range environment had lower 24-h pH measurements and an increased incidence of PSE meat than confinement-reared pigs. In our Exp. 2, loin drip loss values were higher for the outdoor-finished group; however, no differences in pH, color, or firmness scores were found. Likewise, van der Wal (1991) found no differences in subjective color scores or L*, a*, or b* values comparing conventional indoor and free-range-housed pigs.

Sensory attributes of pork from pigs finished in outdoor or alternative systems have not been consistent in previous literature. Enfält et al. (1997) reported reduced tenderness and juiciness of outdoor-reared pigs during the cold months. Van der Wal (1991) and Barton-Gade and Blaabjerg (1989) reported no differences in pork eating qualities of outdoor-reared pigs. Jonsäll et al. (2001) investigated the effects of indoor finishing (solid floor with straw bedding) and outdoor finishing (large field) on the sensory quality of ham. Results showed few differences in eating quality of ham from the pigs reared in these two diverse environments. Ham from pigs reared outdoors was less juicy and acidulous than ham from the indoor-reared pigs (Jonsäll et al., 2001). Overall, differences in sensory attributes among the treatments in all of our experiments were minimal. We found no major advantages or disadvantages in pork eating qualities for indoor- and outdoor-finished pigs in Exp. 2. In Exp. 1, the indoor-finished pigs had higher initial juiciness scores, which could be attributed to the higher visual marbling scores that were found in loins from the indoor group.

The presence of off-flavors in meat may be attributed to the housing system in which the pigs are raised. Off-flavor of meat was significantly different between the indoor- and outdoor-finished pigs in Exp. 1 conducted during the spring and summer months. The loin chops from the indoor group had a higher off-flavor score than their contemporaries raised outdoors; however, the numerical difference in off-flavor scores was small and thus may not be detected by the consumer. The outdoor pen had natural ventilation that may allow fewer off-flavors to be tasted in the loins from the pigs finished outdoors. Hansen et al. (1994) reported that pigs lying in a mixture of feces and urine in pens at high stocking rates (0.6 m^2/pig) for at least 1 wk had higher levels of skatole and indole levels in subcutaneous backfat than pigs kept in clean pens at low stocking rates (0.8 m^2/pig). In addition, skatole levels were significantly higher in the summer months than the winter months (Hansen et al., 1994). A lower off-flavor score for the outdoor-born group in this study may be attributed, at least in part, to the lower stocking rates of the pigs during the birth and finishing periods and natural ventilation in the outdoor pen.

The effects of pig rearing environments on retail case life of pork products has not been previously reported. Differences in retail display characteristics were found in Exp. 1. Loins from the outdoor-finished group had higher discoloration and browning scores on d 4, indicating a reduction in shelf life in the retail case.

Experiment 3. Few studies have compared deep-bedded finishing systems with conventional indoor finishing systems. Larson et al. (1999) examined the use of hoop structures (open-ended quonsets with bedding) for finishing pigs compared to an unbedded confinement system and determined that pigs finished in hoops had a higher ADG and lower feed efficiency ($P < 0.01$) than pigs finished in confinement. In our experiment, the pigs finished on bedding had heavier carcass weights and more backfat than the pigs finished on slats ($P < 0.05$). Our results indicated that pigs finished on bedding may need to be marketed at an earlier age or fed differently to avoid discounts for carcass percentage muscle and fat and to have desired carcass weights.

Under natural conditions, the pig's feet are intended to be tough and hard and the ground soft and forgiving; however, the opposite is more often the case (Smith et al., 1998). Among production system features, floor type is an important determinant of lameness in pigs. Housing pigs on concrete has resulted in a number of conditions on pig's feet, including abrasions, erosions, and lesions that can lead to lameness and pain. Research comparing foot lesions and lung lesions of pigs finished on different floor types has been limited. Mouttotou et al. (1999) showed that pigs kept on bedded floors, with either sparse or deep straw, had a lower prevalence of sole and heel erosions and a higher prevalence of toe erosions than pigs kept on bare, solid concrete floors. Partially slatted floors resulted in pigs with an increased prevalence of heel erosions (Mouttotou et al., 1999). However, pigs finished on bedding in our experiment had fewer foot lesions but a greater percentage of severe foot pad lesions. The higher percentage of severe foot lesions may have been caused by the bedding material. Although the overall incidence of foot lesions was lower on bedding, because the bedding was wet in some areas, we hypothesize that, once a foot lesion was started, it more often resulted in more severe foot lesions.

In our experiment, pigs finished on slatted flooring had loins with a higher 1-h pH measurement than the pigs finished on bedding, indicating a possible advantage in water-holding capacity, but no differences in 24-h pH or drip loss between the two groups were detected. The group finished on bedding was heavier at finishing and had more backfat than pigs finished on slatted floors. These results lead us to speculate that pigs finished in alternative or outdoor systems may need to be marketed at an earlier age than their counterparts finished on slats to avoid carcass value reductions because of increased backfat, because pigs finished on bedding reached market weight earlier. Loins from the bedded group had higher scores for firmness than loins from the pigs on slats but no differences were detected in color or drip loss. The higher firmness scores could be caused by higher levels of intramuscular fat within the loineye or the increased backfat that was present on the carcasses from the pigs finished on bedding. Studies are needed to examine pigs in these diverse housing systems in which the end weight is held constant rather than holding time on feed constant as we did.

Few studies have investigated the effects of pig finishing system (bedding vs slats) on pig meat quality. No differences in sensory panel or shear force values were detected in Exp. 3. Loins from each of the two finishing environments evaluated were acceptable in juiciness, tenderness, and flavor. Maw et al. (2001) investigated 23 farms in Scotland to test for differences in eating quality of bacon. They determined that floor-type was a factor that influenced bacon quality. Pigs reared on straw had bacon with superior eating quality to bacon from pigs reared on slatted flooring or solid flooring without bedding. One factor that may influence these differences in bacon quality is group size. Pig finished on bedding usually are housed in large groups, compared to the conventional slatted-floor facilities that house approximately 20 to 25 pigs per pen. The exact cause of these differences in eating quality is yet to be fully determined and should be further investigated.

Implications

Pigs finished in alternative and outdoor systems had carcass and pork quality characteristics similar to those of pigs finished in conventional indoor systems on slatted flooring. In mild climates, pigs housed outdoors may grow faster than pigs housed indoors during warm months. Pig birth environment may play an important role in growth and performance throughout the finishing period. Alternative pig housing systems, such as bedded facilities or outdoor finishing, can be successful under proper management. Seasonal differences in growth may exist with pigs finished outdoors. Further research comparing pigs born outdoors and indoors should be conducted to examine differences in growth, meat quality, and pig welfare that may exist in conventional and alternative finishing systems.

Literature Cited

AMSA. 1991. Guidelines for Meat Color Evaluation. 44th Recip. Meat Conf. National Live Stock and Meat Board, Chicago, IL.

AMSA. 1995. Research Guidelines for Cookery, Sensory Evaluation and Instrumental Tenderness Measurements of Fresh Meat. American Meat Science Assoc., Chicago, IL.

Barton-Gade, P., and L. O. Blaagjerg. 1989. Preliminary observations on the behavior and meat quality of free range pigs. In: Proc. 35th Int. Cong. Meat Sci. Technol., Copenhagen, Denmark. pp 1002–1005.

Beattie, V. E., N. E. O'Connell, and B. W. Moss. 2000. Influence of environmental enrichment on the behavior, performance, and meat quality of domestic pigs. Livestock Prod. Sci. 65:71–79.

Blackshaw, J. K., F. J. Thomas, and J.-A. Lee. 1997. The effect of a fixed or free toy on the growth rate and aggressive behavior of weaned pigs and the influence of hierarchy on initial investigation of the toys. Appl. Anim. Behav. Sci. 53:203–212.

Cross, H. R., R. Moen, and M. Stanfield. 1978. Training and testing of judges for sensory analysis of meat quality. Food Technol. 32:48–54.

Edwards, S. A., and S. P. Turner. 1999. Housing and management of pigs in large social groups. In: Proc. Pig Vet. Soc., Market Bosworth, U.K.

Enfält, A. C., K. Lundstrom, I. Hansson, N. Lundeheim, and P. E. Nystrom. 1997. Effects of outdoor rearing and sire breed (Duroc or Yorkshire) on carcass composition and sensory and technological meat quality. Meat Sci. 45:1–15.

FASS. 1999. Guide for the Care and Use of Agricultural Animals in Agricultural Research and Teaching. 1st ed. Federation of Animal Science Societies, Savoy, IL.

Gentry, J. G., J. J. McGlone, M. F. Miller, and J. R. Blanton, Jr. 2002. Diverse birth and rearing environment effects on pig growth and meat quality. J. Anim. Sci. (In press).

Hansen, L. L., A. E. Larsen, B. B. Jensen, J. Hansen-Møller, and P. Barton-Gade. 1994. Influence of stocking rate and faeces deposition in the pen at different temperatures on skatole concentration (boar taint) in subcutaneous fat. Anim. Prod. 59:99–110.

Honeyman, M. S., M. E. Larson, A. D. Penner, and J. D. Harmon. 2000. Two year summary of the performance of finishing pigs in hoop structures and confinement during winter and summer. Iowa State Univ. Res. Rep., Ames. pp 164–169.

Larson, M. E., M. S. Honeyman, and A. D. Penner. 1999. Performance of finishing pigs in hoop structures and confinement during summer and winter. Tech. Rep. ASL-R 1682. Iowa State Univ., Ames. pp 102–104.

Johnson, A. K., J. L. Morrow-Tesch, and J. J. McGlone. 2001. Behavior and performance of lactating sows and piglets reared indoors and outdoors. J. Anim. Sci. 79:2571–2579.

Jonsäll, A., L. Johansson, and K. Lundstrm. 2001. Sensory quality and cooking loss of ham muscle (M. biceps femoris) from pigs reared indoors and outdoors. Meat Sci. 57:245–250.

Maw, S. J., V. R. Fowler, M. Hamilton, and A. M. Petchey. 2001. Effect of husbandry and housing of pigs on the organoleptic properties of bacon. Livest. Prod. Sci. 68:119–130.

McGlone, J. J. 2001. Farm animal welfare in the context of other society issues: toward sustainable systems. Livst. Prod. Sci. 72:75–81.

Mouttotou, N., F. M. Hatchell, and L. E. Green. 1999. Foot lesions in finishing pigs and their associations with the type of floor. Vet. Rec. 144:629–632.

NAHMS. 2001. Part I: Reference of swine health and management in the United States, 2000, National Animal Health Monitoring System. #N338.0801. Fort Collins, CO.

NPPC. 1999. Composition and quality assessment procedures. National Pork Producers Council, Des Moines, IA.

NRC. 1998. Nutrient Requirements of Swine. 10th ed. National Academy Press, Washington, DC.

Pearce, G. P., and A. M. Paterson. 1993. The effect of space restriction and provision of toys during rearing on the behavior, productivity, and physiology of male pigs. Appl. Anim. Behav. Sci. 36:11–28.

Sather, A. P., S. D. M. Jones, A. L. Schaefer, J. Colyn, and W. M. Roberston. 1997. Feedlot performance, carcass composition and meat quality of free-range reared pigs. Can. J. Anim. Sci. 77:225–232.

Smith, W. J., D. J. Taylor, and R. H. C. Penny. 1998. Diseases and Disorders of the Pig. Iowa State University Press, Ames.

Thornton, K. 1988. Outdoor Pig Production. Farming Press, Ipswich, U.K.

Van der Wal, P. G. 1991. Free range pigs: carcass characteristics and meat quality. In: Proc. 35th Int. Cong. Meat Sci. Technol., Copenhagen, Denmark. pp 202–205.

Warriss, P. D., S. C. Kestin, and J. M. Robinson. 1983. A note on the influence of rearing environment on meat quality in pigs. Meat Sci. 9:271–279.

Wheeler, T. L., S. D. Shackelford, L. P. Johnson, M. F. Miller, R. K. Miller, and M. Koohmaraie. 1997. A comparison of Warner-Bratzler shear force assessment within and among institutions. J. Anim. Sci. 75:2423–2432.