

JAST (Journal of Animal Science and Technology) TITLE PAGE

Upload this completed form to website with submission

ARTICLE INFORMATION	Fill in information in each box below
Article Type	Research article
Article Title (within 20 words without abbreviations)	Effects of space allowance on productivity, welfare, and blood constituents of group-housed gestating sows
Running Title (within 10 words)	Space allowance in group-housed gestating sows
Author	Yejin Min ¹ , Hyunjung Jung ¹ , Joeun Kim ¹ , Yohan Choi ¹ , Yongdae Jeong ¹ , Hongjun Kim ¹ , Chaibin Lim ¹ , Hyunju Park ¹ , Minho Song ² ,
Affiliation	1 Swine Science Division, National Institute of Animal Science, Rural Development Administration, Cheonan 31000, Republic of Korea 2 Division of Animal and Dairy Science, Chungnam National University, Daejeon 34134, Republic of Korea
ORCID (for more information, please visit https://orcid.org)	Yejin Min (https://orcid.org/0000-0002-3083-1513) Hyunjung Jung (https://orcid.org/0000-0002-7004-2017) Joeun Kim (https://orcid.org/0000-0002-1935-2132) Yohan Choi (https://orcid.org/0000-0003-4710-4731) Yongdae Jeong (https://orcid.org/0000-0002-1985-583X) Hongjun Kim (https://orcid.org/0000-0002-2346-3353) Chaibin Lim (https://orcid.org/0000-0002-9530-1345) Hyunju Park (https://orcid.org/0000-0001-5143-355X) Minho Song (https://orcid.org/0000-0002-4515-5212)
Competing interests	No potential conflict of interest relevant to this article was reported.
Funding sources State funding sources (grants, funding sources, equipment, and supplies). Include name and number of grant if available.	This work was carried out with the support of "Cooperative Research Program for Agriculture Science and Technology Development (Project No. PJ01623002, RS-2021-RD010166)" Rural Development Administration, Republic of Korea.
Acknowledgements	This study was supported by 2026 collaborative research program between university and Rural Development Administration, Republic of Korea.
Availability of data and material	Upon reasonable request, the datasets of this study can be available from the corresponding author.
Authors' contributions Please specify the authors' role using this form.	Conceptualization: Min Y, Song M. Data curation: Min Y, Choi Y. Formal analysis: Min Y, Jung H, Kim H, Lim C. Investigation: Min Y, Kim J, Park H, Jeong Y. Writing - original draft: Min Y. Writing - review & editing: Min Y, Jung H, Kim J, Choi Y, Jeong Y, Kim H, Lim C, Park H, Song M.
Ethics approval and consent to participate	The experimental protocols for this research were reviewed and approved by the Institutional Animal Care and Use Committee at the National Institute of Animal Science (NIAS-2022-190).

CORRESPONDING AUTHOR CONTACT INFORMATION

For the corresponding author (responsible for correspondence, proofreading, and reprints)	Fill in information in each box below
First name, middle initial, last name	Minho Song
Email address – this is where your proofs will be sent	mhsong@cnu.ac.kr
Secondary Email address	
Address	Division of Animal and Dairy Science, Chungnam National University, Daejeon 34134, South Korea
Cell phone number	

Office phone number	+82 42 821 5776
Fax number	

6
7

Abstract

This study aims to evaluate the effects of space allowance during gestation on productivity, welfare, and blood constituents of group-housed primiparous sows. A total of 48 primiparous sows (Landrace × Yorkshire; 220.68 ± 17.29 kg initial body weight, mean $\pm$ SD) were randomly assigned to four space allowance treatments (1.9, 2.1, 2.3, and 2.5 m²; 12 sows per treatment) in a half-stall group housing system from day 42 to day 106 of gestation. The following parameters were measured in sows: reproductive performance, welfare indicators, and blood constituents. Space allowance did not affect sow body weight, backfat thickness, or reproductive performance, including litter size, litter and piglet weights, average daily gain, or survivability. However, the colostrum total solids and protein concentrations were higher ($p < 0.05$) in sows housed at a space allowance of 1.9 m² than those housed at 2.5 m². For the welfare indicators, skin injury scores were higher ($p < 0.05$) in sows allocated 1.9 and 2.1 m² than those allocated 2.5 m² during the first week after mixing, but lameness scores of sows were not different among space allowance treatments. Sow metabolic and stress-related blood indicators, including blood urea nitrogen, creatinine, triglycerides, free fatty acids, glucose, and cortisol concentrations, were not affected by space allowance treatments. In conclusion, space allowances ranging from 1.9 to 2.5 m² per sow did not affect sow productivity or metabolic status, indicating that productivity and metabolic status were maintained at 1.9 m² under commercial half-stall group housing conditions. However, larger space allowance was associated with progressively fewer skin injuries, suggesting that farms with greater facility capacity may improve sow welfare benefits by adopting space allowances toward the upper end of this range (2.3–2.5 m²).

Keywords: Gestating sows, Group housing, Space allowance, Productivity, Colostrum composition, Skin injury

Introduction

The global swine industry is undergoing a major transition from individual gestation stalls to group housing systems for pregnant sows, driven by increasing consumer awareness of animal welfare and strengthening of related legislation [1, 2]. Individual stalls, which are advantageous for individual management and the suppression of inter-sow aggression, have been widely criticized for severely restricting sow movement and preventing the expression of natural behaviors, such as exploration and rooting [3-5]. In response to these welfare concerns, the European Union (EU) mandated group housing for pregnant sows from four weeks post-service until one week before farrowing under Council Directive 2008/120/EC, with full implementation across all member states since 2013 [6, 7]. The EU Directive specifies a minimum unobstructed floor area of 2.25 m² per sow and 1.64 m² per gilt, with a 10% increase for groups of fewer than six animals and a 10% reduction permitted for groups of 40 or more [1, 6, 8].

38 Similarly, the Republic of Korea recently amended its Livestock Industry Act to mandate group housing for pregnant
39 sows from six weeks post-insemination, with all existing farms required to complete the transition by 2030 [9, 10]. However,
40 unlike the EU, Korean legislation has not yet established specific minimum space-allowance standards for group-housed
41 gestating sows, and approximately 1.9 m² per sow is currently considered the practical minimum based on existing farm
42 infrastructure [11]. Given that the EU minimum space allowance of 2.25 m² was established under different production
43 systems and farm structures, the appropriate allowance should be empirically determined under Korean commercial
44 conditions, where half-stall group housing represents the most feasible transition option.

45 Space allowance is one of the most critical factors governing the welfare and health of group-housed gestating sows
46 [5, 12, 13]. Insufficient space exacerbates competition for feed and resting areas and intensifies aggressive interactions,
47 skin injuries, and chronic social stress among sows [14-16]. A space allowance of 1.4 m² per sow has been reported to be
48 inadequate for welfare [5, 15], and increasing floor space from 1.4 to 3.0 m² has been shown to linearly reduce blood
49 cortisol concentrations and improve conception rates from approximately 60% to 75% [15]. Skin injuries and lameness are
50 recognized welfare indicators within established animal welfare assessment protocols, and lameness, in particular, has been
51 associated with reduced productive longevity and increased culling rates in sows [17-19]. Because behavioral observations
52 alone are insufficient to objectively quantify the degree of physiological stress experienced by sows, metabolic and stress-
53 related blood indicators (cortisol, blood urea nitrogen, creatinine, triglycerides, free fatty acids, and glucose) serve as useful
54 objective complements for welfare assessment [2, 20-22].

55 Beyond welfare, space allowances may exert substantial effects on sow productivity via stress-mediated endocrine
56 pathways. Chronic activation of the hypothalamic-pituitary-adrenal axis under space-restricted conditions may elevates
57 glucocorticoid secretion, which can suppress reproductive function by interfering with gonadotropin release and embryo
58 implantation [23, 24]. Although the relationship between space allowance and reproductive performance has yielded
59 inconsistent results across studies [15, 25, 26], the lack of consensus may partly reflect the differences in housing systems,
60 group sizes, and the relatively narrow space ranges examined. Furthermore, the gestational environment may influence
61 colostrum quality at parturition, as maternal stress during late gestation may alter nutrient partitioning and mammary
62 secretory activity, potentially affecting colostrum composition [27, 28]. Colostrum is the primary source of passive
63 immunity and energy for neonatal piglets, and its composition in terms of total solids, protein, fat, and lactose is affected
64 by nutritional, hormonal, and environmental factors during gestation [29-31]. Given that colostrum quality directly
65 determines piglet survival and early immune competence, understanding its relationship with the gestational housing
66 environment is of practical importance for commercial swine production.

Despite the growing body of evidence on space allowance effects, most studies have been conducted under ESF or free-access stall systems with space ranges exceeding 2.25 m², which exceeds the practical constraints of Korean commercial farms currently transitioning to group housing [8, 21, 26, 32]. Within the narrower range of 1.8 to 2.4 m², the effects of incremental changes in space allowance on welfare or productivity outcomes remain insufficiently characterized [5]. In particular, studies evaluating multiple incremental space allowance levels ranging from 1.9 to 2.5 m² in half-stall group housing systems are lacking. Moreover, only a few studies have simultaneously assessed productivity indicators, colostrum composition, skin injuries, lameness, and blood constituents within the same experimental cohort, thus limiting the ability to draw integrated conclusions regarding the space allowance that balances welfare improvement with productive efficiency [11].

Therefore, the present study was conducted to evaluate the effects of four space allowance levels (1.9, 2.1, 2.3, and 2.5 m² per sow) on the productivity and welfare of primiparous gestating sows housed in a half-stall group housing system. Specifically, the objectives were to assess sow body weight and backfat thickness, reproductive performance, colostrum composition, skin injuries, lameness scores, and metabolic and stress-related blood indicators among the four space allowance treatments.

Materials and Methods

All the experimental protocols were reviewed and approved by the Institutional Animal Care and Use Committee of the National Institute of Animal Science (NIAS-2022-190).

Experimental design and animals

A total of 48 primiparous sows (Landrace × Yorkshire; 220.68 ± 17.29 kg initial body weight, mean ± SD) were used in this study. Sows were randomly assigned to one of four space allowance treatments (1.9, 2.1, 2.3, or 2.5 m² per sow), with 12 sows per treatment housed together in a single pen, resulting in four pens in total (one pen per treatment). Each pen was equipped with 12 individual half-stalls (short stalls; 0.65 m width × 1.4 m length per stall) and an adjacent shared group space. The half-stalls had no gates, allowing them to move freely between the feeding area and the shared space. Space allowance was calculated as the total available pen area (sum of the half-stall area and shared group space) divided by the number of sows per pen, and pen dimensions were adjusted to achieve the target space allowance for each treatment. The group-housing period was extended from 42 days after artificial insemination to 106 days of gestation, at which point all sows were relocated to individual farrowing crates (1.8 × 2.4 m²).

96 **Diets and feeding**

97 The ingredients and chemical compositions of the experimental diets used during gestation and lactation are presented
98 in Table 1. Diets were formulated to meet or exceed the nutrient requirements of gestating and lactating sows, as
99 recommended by the National Research Council [33]. During gestation, sows received a restricted allowance of 2.5 kg/day
100 provided in two equal meals at 09:00 and 16:30. During lactation, sows were fed using an automatic feeder (Automatic
101 Feeder of Lactating Sows, Koca), with daily allowances progressively increasing as follows: 2–4 kg/day from days 1–3
102 postpartum; 4–6 kg/day during the first week; 6–8 kg/day during the second week; and 7–10 kg/day from the third week
103 until weaning. Water was provided ad libitum throughout the experiment.

104

105 **Productivity measurements**

106 ***Sow performance***

107 Body weight and back fat thickness were measured at 42 and 106 days of gestation and at weaning. Backfat thickness
108 was measured at the P2 position (5 cm lateral to the midline at the level of the 10th rib) using an ultrasound device (Anyscan
109 BF; SongKang GLC, Korea) [11].

110

111 ***Reproductive performance***

112 Litter size was recorded at birth and categorized as total-born, stillborn, mummified, born alive, cross-fostered, or
113 weaned. The number of piglets per sow was adjusted within one day after farrowing based on piglet birth weight to ensure
114 uniformity across treatment groups. Litter weight was recorded at birth and again at weaning, which occurred at 28 days
115 of age. Weaning-to-estrus intervals were monitored twice daily (09:00 and 16:30 h) following weaning. The gestation
116 length was recorded for each sow.

117

118 ***Colostrum composition***

119 Colostrum samples were collected from sows during active parturition after the delivery of 2–4 piglets. This sampling
120 window was selected to obtain colostrum during the early stage of farrowing while minimizing interference with active
121 parturition. The exact sampling time and the number of piglets born before sampling were not included as covariates in the
122 statistical analysis. Approximately 30 mL of colostrum was collected from the anterior mammary glands by hand massage
123 without oxytocin administration and stored in 50 mL tubes at –20°C until analysis. Before analysis, the samples were
124 thawed at room temperature (20°C). Colostrum composition, including total solids, protein, fat, and lactose, was

determined using a Fourier-transform infrared milk analyzer (CombiScope FTIR 300 HP, Delta Instruments, The Netherlands) [10, 11].

Welfare measurements

Lameness

Lameness was assessed in all sows before group mixing (week 0) and at weeks 1, 3, 5, 7, and 9 of the group housing period. Before assessment, the sows were allowed to walk or trot freely for approximately 30–50 m in an open corridor. Lameness was scored using a four-point scale (0–3) as described by Karlen et al. [34] and applied in previous studies [10, 11]: score 0, normal gait with no apparent posture or movement abnormalities; score 1, occasional signs of discomfort or minor alterations in gait while maintaining support from all four limbs; score 2, one or more limbs occasionally lifted off the ground during movement; and score 3, one or more limbs incapable of bearing weight, accompanied by joint swelling or pain-related vocalization. Lameness was assessed independently by three trained evaluators, and the final score was the mean of their evaluations.

Skin lesions

Skin lesions were assessed in all sows before group mixing (week 0) and at weeks 1, 3, 5, 7, and 9 of the group housing period. The total number of scratches and lesions on the body surface of each sow was recorded by a single trained observer following the method described by Karlen et al. [34]. The observer was not blinded to treatment group, as pen identity and housing configuration were visible during scoring.

Blood collection and analysis

Blood samples (10 mL) were collected from the jugular vein of each sow at 106 d of gestation. The samples were transferred into serum-separating Vacutainer tubes and centrifuged at $3,000 \times g$ for 20 min. Separated serum was stored at -20°C until analysis. Metabolic blood indicators, including blood urea nitrogen (BUN), creatinine, triglycerides, free fatty acids, and glucose, were analyzed using an automated biochemistry analyzer (Dri-Chem 3500i, Fujifilm, Japan). Serum cortisol concentrations were measured using a commercial ELISA kit (Cusabio, USA) according to the manufacturer's instructions.

Statistical analysis

All data were analyzed using the GLM procedure in SAS (version 9.4; SAS Institute Inc., Cary, NC, USA). Space allowance was included as the fixed effect. Because only one pen was assigned to each space allowance treatment, treatment and pen effects were completely confounded, and individual sows within the same pen could not be considered independent experimental replicates of the space allowance treatment. Measurements were collected from individual sows within each pen, and data were analyzed using individual sows as the observational unit, consistent with previous studies conducted under similar group-housing conditions [11, 32]. For skin injury and lameness scores, each assessment time point (weeks 0, 1, 3, 5, 7, and 9) was analyzed independently to examine treatment differences at each week. This approach was used because the primary objective was to compare space allowance treatments at each assessment week rather than to evaluate changes over time. When significant differences were detected among the treatment means, they were separated using Tukey's honestly significant difference test. Significance was declared at $p < 0.05$, and tendencies were considered at $0.05 \leq p < 0.10$. All data are presented as least squares means $\pm$ standard error of the mean.

Results

Productivity

Sow performance

Space allowance did not affect sow body weight or backfat thickness during gestation and lactation (Table 2; $p > 0.05$).

Reproductive performance

Space allowance did not affect reproductive performance, including litter size traits, litter and piglet weights, average daily gain, or survivability (Table 3; $p > 0.05$). Gestation length did not differ among the treatments ($p = 0.100$).

Colostrum composition

Space allowance affected the colostrum composition (Table 4). Total solids concentration was higher in sows housed at a space allowance of 1.9 m² (33.38%) than in those housed at 2.5 m² (24.63%; $p = 0.042$), whereas values at 2.1 m² (28.95%) and 2.3 m² (29.19%) were intermediate and not different from either extreme. The colostrum protein concentration followed the same pattern, being higher at 1.9 m² (17.09%) than at 2.5 m² (12.33%; $p = 0.019$). Colostrum fat tended to differ among the treatments ($p = 0.063$), whereas lactose concentration was not affected by space allowance ($p = 0.210$).

Welfare

Skin injuries

Skin injury scores (Table 5) did not differ among treatments at weeks 0, 3, and 9 ($p > 0.05$). At week 1, sows housed at 1.9 and 2.1 m² had more skin injuries than those at 2.5 m² (31.3 and 31.1 vs. 17.9, respectively; $p = 0.002$), with the 2.3 m² treatment (23.1) showing an intermediate value. A treatment effect was detected at week 5 ($p = 0.049$), although Tukey's multiple comparison test did not identify any significant pairwise differences. At week 5, the pattern across treatments was non-monotonic, with the 2.3 m² treatment showing the numerically lowest score (7.1). Skin injury scores tended to differ among the treatments at week 7 ($p = 0.087$). Across all treatments, skin injury scores peaked at week 1 following grouping and declined progressively thereafter.

Lameness

Space allowance did not affect lameness scores at any assessment time point (Table 6; $p > 0.05$).

Metabolic and stress-related blood indicators

Space allowance did not affect blood metabolic or stress indicators, including blood urea nitrogen, triglycerides, free fatty acids, glucose, and cortisol (Table 7; $p > 0.05$). Serum creatinine levels tended to differ among treatments ($p = 0.076$).

Discussion

Productivity

Space allowance ranging from 1.9 to 2.5 m² did not affect sow body weight or backfat thickness at any measurement point during gestation or lactation, nor did it influence reproductive performance, including litter size, litter and piglet weight, average daily gain, or survivability. These findings are consistent with previous literature, demonstrating largely stable sow body condition and reproductive output across comparable space allowance ranges in group-housed gestating sows. Mack et al. [26] reported no effects of space allowance (1.93, 2.68, or 3.24 m²) on body weight, body condition score, litter size, or piglet birth weight in a free-access stall system, and Remience et al. [8] similarly found no differences in sow body weight gain, backfat change, or litter traits when comparing 2.25 and 3.0 m² under an electronic sow feeder system. Equivalent null effects across broadly consistent ranges of space allowance have been reported under various group housing systems [5, 10, 15, 25, 35]. In a previous study comparing two levels (1.9 vs. 2.3 m²) under a half-stall system, Min et al. [11] reported higher body weight at farrowing crate relocation and greater total litter weight in the 1.9 m² group, suggesting that narrow space allowance may influence certain performance indicators under specific conditions. The absence of such

differences in the present study, which examined four incremental levels across a wider range (1.9–2.5 m²) with 12 sows per pen, may reflect the influence of group size, pen composition, or the broader range of space allowance tested. Collectively, these findings suggest that within the commercially relevant range of 1.9 to 2.5 m² under a half-stall housing system, incremental increases in space allowance were not associated with reduced sow body condition or reproductive output in the present study.

In contrast, space allowance significantly affected colostrum composition in the present study (Table 4), with sows housed at 1.9 m² producing colostrum with higher total solids (33.38%) and protein concentrations (17.09%) than those at 2.5 m² (24.63% and 12.33%, respectively; $p < 0.05$). Colostrum fat content tended to differ among treatments ($p = 0.063$), whereas lactose concentration was unaffected ($p > 0.05$). The direction of this effect—higher nutrient concentrations at a narrower space allowance—is not consistent with a stress-mediated interpretation, as chronic gestational stress is expected to impair mammary secretory activity and colostrum quality rather than enhance them [27, 28]. Furthermore, the absence of treatment-related differences in serum cortisol concentrations in the present study (discussed below) provides additional evidence against a stress-driven mechanism.

Colostrum composition is inversely related to colostrum yield, as lactose-driven osmotic water influx during the periparturient period dilutes pre-formed immunoglobulins and protein fractions even when their absolute quantities remain unchanged [29, 31]. A colostrum dilution effect is one plausible explanation, whereby the observed compositional differences may reflect differences in colostrum yield between space allowance groups—potentially associated with differences in hormonal milieu or mammary gland development during gestation—resulting in lower proportional concentrations of total solids and protein in wider-space sows [29, 31]. However, as colostrum yield and immunoglobulin concentrations were not measured in the present study, this interpretation is necessarily speculative, and the precise mechanism underlying the observed compositional differences could not be determined from the available data. Alternative nutrient- or hormone-mediated mechanisms cannot be excluded based on the present data. Future studies incorporating direct measurements of colostrum yield are warranted to clarify whether the observed differences in total solids and protein concentrations reflect meaningful changes in nutrient and passive immune transfer to neonatal piglets [29, 31, 36].

Welfare

Space allowance substantially influenced the skin injury scores, whereas lameness was unaffected throughout the experimental period. These divergent outcomes suggest that the welfare consequences of space allowance in a half-stall group housing system are primarily expressed through social aggression and its dermal consequences, rather than through locomotor impairment.

Skin injury scores were the highest in week 1 following group mixing across all treatments and then declined progressively throughout the housing period. Although aggressive or agonistic behavior was not directly measured in the present study, this pattern is consistent with the well-documented behavioral response of group-housed sows to social mixing, in which agonistic interactions peak within the first 24 to 48 h as individuals compete to establish a dominance hierarchy and then diminish as social rank stabilizes over subsequent days to weeks [8, 16, 25]. The transient peak at week 1 observed in the present study, followed by progressive stabilization, may reflect the capacity of sows to adapt behaviorally and physiologically to group environments once the social order is established [4, 5].

Space allowance significantly affected skin injury scores at week 1, with sows allotted 1.9 and 2.1 m² sustaining more injuries than those allotted 2.5 m² (31.3 and 31.1 vs. 17.9, respectively; $p = 0.002$), while the 2.3 m² group (23.1) was intermediate. A treatment effect was also detected at week 5 ($p = 0.049$); although Tukey's post hoc test detected no significant pairwise differences, a tendency was observed at week 7 ($p = 0.087$). The observed differences in skin injury scores are consistent with the general finding that reduced space allowance increases the frequency and severity of skin lesions in group-housed sows by limiting the escape distance available to subordinate individuals and intensifying competition for feeding and resting areas [5, 14]. A narrower space allowance has also been associated with increased agonistic interactions and elevated cortisol concentrations during the mixing period, even in cases in which the total injury counts did not differ significantly among treatments [15]. The present findings extend the space allowance–skin injury relationship into the 1.9–2.5 m² range under a half-stall system and are consistent with the previously reported advantage of 2.3 m² over 1.9 m² in reducing overall skin lesion frequency under comparable conditions [11].

This pattern suggests a possible threshold effect in the welfare benefit of increasing space allowance, whereby the improvement between 2.1 and 2.3 m² may be meaningful but insufficient to reach statistical separation from either extreme within the sample size of the present study. The half-stall structure used in this study provided partial physical protection at the feeding station, which likely moderated the magnitude of space-related aggression compared with that observed in open-pen floor-feeding systems [2, 5, 13, 37]. The protective function of the stall partition reduces direct confrontation during feeding. However, because the rear of the sow remains exposed, displacement from the feeding station and vulnerability to attacks from behind are not fully eliminated, and the effects of floor space on inter-sow aggression remain evident [10, 35].

Space allowance did not affect lameness scores at any assessment time point, consistent with previous reports examining comparable space-allowance ranges. The overall low prevalence and severity of lameness observed in this cohort may have limited the statistical power to detect differences among space allowance treatments. Mack et al. [26] found no differences in lameness among space allowance levels of 1.93, 2.68, and 3.24 m² in a free-access stall system,

and DeDecker et al. [38] similarly reported no significant effect of space allowance (1.7 vs. 2.3 m²) on lameness score. Min et al. [11] also observed no effect of space allowance (1.9 vs. 2.3 m²) on lameness under a half-stall system, and Pluym et al. [17] found no association between housing system type and lameness prevalence across Belgian group-housing farms. In contrast, Pluym et al. [39] reported that enlarging space allowance from 1.7 to 3.0 m² reduced the risk of lameness development, and Hallowell and Pierdon [19] identified a significant association between available floor area and lameness-related culling in US commercial farms. The discrepancy across studies may be because of confounding factors, such as flooring type, group stability, and housing system design, which may independently affect claw and limb health to a greater extent than space allowance alone within the range examined in the present study [7, 39].

Metabolic and stress-related blood indicators

Space allowance did not significantly affect any of the metabolic or stress-related blood indicators measured at the end of the experimental period, including BUN, creatinine, triglyceride, free fatty acid, glucose, and cortisol concentrations ($p > 0.05$). This absence of treatment effects is consistent with the lack of differences observed in sow productivity (see Productivity above) and suggests that space allowance within the 1.9 to 2.5 m² range did not affect the measured metabolic and stress-related indicators at day 106 of gestation.

The lack of a cortisol response is consistent with previous reports showing that differences within a comparable or even narrower range failed to elicit detectable changes in circulating or salivary cortisol concentrations. Mack et al. [26] found no effect of space allowance (1.93, 2.68, or 3.24 m²) on cortisol concentration in a free-access stall system, and Remience et al. [8] similarly reported no difference in salivary cortisol between sows housed at the EU minimum (2.25 m²) and a wider allowance (3.0 m²) under an electronic sow feeder system. Comparable null effects have also been reported when sows were mixed after pregnancy confirmation, the group size varied, and urinary cortisol was assessed as an alternative measure of adrenal activity [20, 21, 40]. In contrast, cortisol differences have been detected when space allowance was reduced to more restrictive levels (1.0–1.4 m²) or when individually stalled sows were compared with group-housed sows, suggesting that the cortisol response to space restriction may follow a threshold pattern, becoming detectable only below a certain minimum allowance rather than varying linearly across the moderate range examined in the present study [15, 41].

The absence of sustained cortisol elevation at the study endpoint is also consistent with the transient nature of the stress response to social mixing. Circulating and salivary cortisol concentrations typically peak within 2 h of mixing and return to baseline within 24–48 h as dominance hierarchies stabilize, while behavioral and physiological adaptations to the group environment continue to develop over the following days [8, 13, 16]. Given that blood samples in the present study

were collected on day 106 of gestation, more than nine weeks after the initial group formation on day 42, the sampling time point was well beyond the acute mixing-stress window, which likely explains the absence of detectable treatment differences in cortisol, despite the skin injury differences observed earlier in the study period (see Welfare above).

The remaining indicators reflect protein, lipid, and carbohydrate metabolism and show no evidence of nutritional or metabolic compromise associated with space allowance. BUN did not differ among treatments, and serum creatinine showed a tendency to differ among treatments ($p = 0.076$), which is unlikely to reflect a biologically meaningful change in renal function or protein metabolism, given that the values remained within the normal physiological range. Triglyceride and free fatty acid concentrations, which indicate lipid storage status and the degree of fat mobilization under a negative energy balance, were also unaffected, suggesting that the energy balance during late gestation did not differ significantly among the treatments [2, 36]. This is consistent with previous findings of no treatment effects on serum or colostrum triglyceride concentrations in individually housed and group-housed sows [10, 42]. Glucose concentration, which can be elevated by cortisol-mediated gluconeogenesis under stress, did not differ among treatments, providing further indirect support for the absence of stress-related metabolic responses [2].

Taken together, the uniform absence of treatment effects across this panel of metabolic and stress-related blood indicators reinforces the interpretation presented in the productivity section that the higher colostrum total solids and protein concentrations observed at 1.9 m² are unlikely to reflect a stress-mediated mechanism. Instead, it more plausibly arises from a colostrum dilution effect in which greater colostrum volume in wider-space sows resulted in lower proportional concentrations of total solids and protein, although this remains speculative in the absence of colostrum yield data.

Implications for space allowance in commercial practice

Our findings indicate that, within the 1.9 to 2.5 m² range under a half-stall housing system, space allowance did not affect sow productivity, reproductive performance, lameness, or metabolic and stress-related blood indicators, whereas skin injury scores were consistently higher at 1.9 and 2.1 m² than at 2.5 m², with 2.3 m² occupying an intermediate position. This pattern, in which welfare benefits accrue with increasing space while productivity remains stable, is broadly consistent with previous reports across a range of group housing systems and space-allowance intervals [5, 8, 15, 26].

From regulatory and commercial perspectives, the minimum space allowance that can be practically achieved during the conversion of existing individual-stall facilities to group housing in South Korea is estimated at 1.9 m² per sow [11]. The present results suggest that this minimum, while not compromising productivity or metabolic status, is associated with a greater incidence of skin injuries than wider space allowances, consistent with previous comparisons of 1.9 and 2.3 m²

under comparable half-stall conditions [11]. Therefore, increasing space allowance toward 2.3 to 2.5 m² represents a practical means of improving sow welfare without an accompanying cost to productivity in the present study. This range also falls within the broader 1.8 to 2.4 m² interval that previous literature has identified as a transitional allowance that preserves production performance while extending behavioral freedom relative to individual stalls [5, 19].

However, expanding space allowance is not without economic costs. Increasing floor space per sow increases facility construction and infrastructure costs in proportion to the additional area required, and the associated increase in fixed costs, including depreciation and opportunity costs of land and capital, can account for a substantial share of the total production cost [43]. Nonetheless, the magnitude of this cost increase appears modest relative to total production expenses: converting from individual stalls (1.4 m²) to group housing in the 2.0 to 2.3 m² range has been estimated to raise total production costs by approximately 0.7 to 1.2%, a difference that can be offset by even small improvements in reproductive performance, such as a 1% increase in the number of weaned piglets per sow [43]. This cost estimate was derived from a general economic analysis of the stall-to-group-housing transition and was not specific to the half-stall system evaluated in the present study. Group housing systems compliant with welfare regulations have also been shown to maintain investment returns comparable to those of stall-based systems, indicating that the transition is economically viable in the longer term [43].

Taken together with the present results, these findings suggest that a space allowances of 2.3 to 2.5 m² may be associated with some welfare benefits in half-stall group housing of gestating sows under conditions representative of South Korean commercial farms. This range reduces skin injury relative to the practical minimum of 1.9 m² without measurable cost to productivity, reproductive performance, or metabolic and stress-related blood indicators, while remaining within a space allowance interval that has consistently been associated with manageable infrastructure cost increases in economic analyses of the stall-to-group-housing transition [11, 43]. Although further increases in space allowance beyond 2.5 m² (e.g., 2.5–3.6 m²) have been associated with additional welfare benefits in some studies, particularly with respect to the expression of exploratory behavior and reduction of aggression in small groups, the marginal welfare gain relative to the additional facility cost should be evaluated against the specific constraints of commercial swine operations before recommending allowances beyond this range [4, 14, 44]. As only one pen was assigned per treatment, the treatment effects should be interpreted with caution, as they represent responses observed under commercial-scale pen conditions rather than fully replicated experimental units.

Conclusions

Space allowance within 1.9 to 2.5 m² did not affect sow body weight, backfat thickness, reproductive performance, lameness, or metabolic and stress-related blood indicators in primiparous sows housed under a half-stall group housing system from day 42 to day 106 of gestation. However, skin injury scores were consistently higher at 1.9 and 2.1 m² than at 2.5 m², with 2.3 m² occupying an intermediate position, and colostrum total solids and protein concentrations were higher at 1.9 m² than at 2.5 m², although the mechanism underlying this difference could not be determined in the present study. These results indicate that increasing space allowance within the 1.9 to 2.5 m² range reduces skin injury while productivity and metabolic status remain stable, whereas the concurrent difference in colostrum composition warrants further investigation. Given the practical minimum space allowance of approximately 1.9 m² achievable during the conversion of existing stall facilities in South Korea, these findings indicate that sow productivity and metabolic status were maintained at 1.9 m². Nevertheless, because skin injury scores decreased with increasing space allowance, allocating space toward the upper end of the tested range (2.3–2.5 m²) may be considered as an additional welfare-oriented option for farms with the facility capacity to do so, without compromising productivity.

Acknowledgments

This study was supported by the Cooperative Research Program for Agriculture, Science, and Technology Development (Project No. PJ01623002, RS-2021-RD010166), Rural Development Administration, Republic of Korea.

References

1. Schubbert A, Spoolder HA, Pedersen LJ. Review on group housing and mixing of sows. EURCAW-Pigs. 2020.
2. Jang J-C, Oh S-H. Management factors affecting gestating sows' welfare in group housing systems—A review. *Animal Bioscience*. 2022;35(12):1817.
3. Broom DM, Mendl MT, Zanella AJ. A comparison of the welfare of sows in different housing conditions. *Animal science*. 1995;61(2):369–85.
4. Spoolder H, Geudeke M, Van der Peet-Schwering C, Soede N. Group housing of sows in early pregnancy: A review of success and risk factors. *Livestock Science*. 2009;125(1):1–14.
5. Verdon M, Hansen CF, Rault J-L, Jongman E, Hansen LU, Plush K, et al. Effects of group housing on sow welfare: A review. *Journal of Animal Science*. 2015;93(5):1999–2017.
6. Union E. Council Directive 2008/120/EC of 18 December 2008 laying down minimum standards for the protection of pigs. Brussels, Belgium: European Commission, 2008.

7. Maes D, Pluym L, Peltoniemi O. Impact of group housing of pregnant sows on health. *Porcine Health Management*. 2016;2(1):17.
8. Remience V, Wavreille J, Canart B, Meunier-Salaün M-C, Prunier A, Bartiaux-Thill N, et al. Effects of space allowance on the welfare of dry sows kept in dynamic groups and fed with an electronic sow feeder. *Applied Animal Behaviour Science*. 2008;112(3-4):284–96.
9. Korea S. Livestock Industry Act of 25 February 2020 amending Chapter Permission for Livestock Farming Business/Article 14/Act No 30477. Sejong, Korea: Ministry of Agriculture, Food and Rural Affairs, 2020.
10. Min Y, Choi Y, Kim J, Kim D, Jeong Y, Kim Y, et al. Comparison of the productivity of primiparous sows housed in individual stalls and group housing systems. *Animals*. 2020;10(11):1940.
11. Min Y, Kyoung H, Choi Y, Kim D, Jeong Y, Kim Y, et al. Effects of space allowance during gestation and socialization training during growing period on the productivity and welfare of primiparous sows. *J Anim Sci Technol*. 2025;67(5):1139–51.
12. Whittaker AL, Van Wettere WH, Hughes PE. Space requirements to optimize welfare and performance in group housed pigs—a review. *Am J Anim Vet Sci*. 2012;7(2):48–54.
13. Bench C, Rioja-Lang F, Hayne S, Gonyou H. Group gestation sow housing with individual feeding—II: How space allowance, group size and composition, and flooring affect sow welfare. *Livestock Science*. 2013;152(2-3):218–27.
14. Weng R, Edwards S, English P. Behaviour, social interactions and lesion scores of group-housed sows in relation to floor space allowance. *Applied Animal Behaviour Science*. 1998;59(4):307–16.
15. Hemsworth PH, Rice M, Nash J, Giri K, Butler KL, Tilbrook AJ, et al. Effects of group size and floor space allowance on grouped sows: aggression, stress, skin injuries, and reproductive performance. *Journal of Animal Science*. 2013;91(10):4953–64.
16. Stevens B, Karlen GM, Morrison R, Gonyou HW, Butler KL, Kerswell KJ, et al. Effects of stage of gestation at mixing on aggression, injuries and stress in sows. *Applied Animal Behaviour Science*. 2015;165:40–6.
17. Pluym L, Nuffel AV, Dewulf J, Cools A, Vangroenweghe F, Hoorebeke SV, et al. Prevalence and risk factors of claw lesions and lameness in pregnant sows in two types of group housing. 2011.
18. Heinonen M, Peltoniemi O, Valros A. Impact of lameness and claw lesions in sows on welfare, health and production. *Livestock Science*. 2013;156(1-3):2–9.
19. Hallowell A, Pierdon M. Effects of lameness on productivity and longevity for sows in pen gestation. *Journal of Swine Health and Production*. 2022;30(4):223–9.
20. Pol F, Courboulay V, Cotte J-P, Martrenchar A, Hay M, Mormède P. Urinary cortisol as an additional tool to assess the welfare of pregnant sows kept in two types of housing. *Veterinary research*. 2002;33(1):13–22.

21. Salak-Johnson J, DeDecker A, Horsman M, Rodriguez-Zas S. Space allowance for gestating sows in pens: Behavior and immunity. *Journal of animal science*. 2012;90(9):3232–42.
22. Grimberg-Henrici C, Büttner K, Ladewig R, Burfeind O, Krieter J. Cortisol levels and health indicators of sows and their piglets living in a group-housing and a single-housing system. *Livestock Science*. 2018;216:51–60.
23. Peltoniemi O, Björkman S, Maes D. Reproduction of group-housed sows. *Porcine Health Management*. 2016;2(1):15.
24. Salak-Johnson JL. Social status and housing factors affect reproductive performance of pregnant sows in groups. *Molecular reproduction and development*. 2017;84(9):905–13.
25. Seguin M, Barney D, Widowski T. Assessment of a group-housing system for gestating sows: Effects of space allowance and pen size on the incidence of superficial skin lesions, changes in body condition, and farrowing performance. *Journal of Swine Health and Production*. 2006;14(2):89–96.
26. Mack L, Lay Jr D, Eicher S, Johnson AK, Richert B, Pajor E. Group space allowance has little effect on sow health, productivity, or welfare in a free-access stall system. *Journal of animal science*. 2014;92(6):2554–67.
27. Farmer C, Quesnel H. Nutritional, hormonal, and environmental effects on colostrum in sows. *Journal of animal science*. 2009;87(suppl_13):56–64.
28. Hasan S, Orro T, Valros A, Junnikkala S, Peltoniemi O, Oliviero C. Factors affecting sow colostrum yield and composition, and their impact on piglet growth and health. *Livestock Science*. 2019;227:60–7.
29. Declerck I, Dewulf J, Piepers S, Decaluwé R, Maes D. Sow and litter factors influencing colostrum yield and nutritional composition. *Journal of animal science*. 2015;93(3):1309–17.
30. Hurley W. Composition of sow colostrum and milk. *The gestating and lactating sow: Wageningen Academic*; 2015. p. 193–229.
31. Amatucci L, Luise D, Correa F, Bosi P, Trevisi P. Importance of breed, parity and sow colostrum components on litter performance and health. *Animals*. 2022;12(10):1230.
32. Salak-Johnson J, Niekamp S, Rodriguez-Zas S, Ellis M, Curtis S. Space allowance for dry, pregnant sows in pens: Body condition, skin lesions, and performance. *Journal of Animal Science*. 2007;85(7):1758–69.
33. NRC. Nutrient requirements of swine. 11th rev. ed. Washington, DC: National Academies Press; 2012.
34. Karlen GA, Hemsworth PH, Gonyou HW, Fabrega E, Strom AD, Smits RJ. The welfare of gestating sows in conventional stalls and large groups on deep litter. *Applied Animal Behaviour Science*. 2007;105(1-3):87–101.

35. Chapinal N, de la Torre JR, Cerisuelo A, Gasa J, Baucells M, Coma J, et al. Evaluation of welfare and productivity in pregnant sows kept in stalls or in 2 different group housing systems. *Journal of Veterinary Behavior*. 2010;5(2):82–93.
36. Nuntapaitoon M. Colostrum and milk in sow. *Milk Protein-New Research Approaches*. 2022.
37. Bench C, Rioja-Lang F, Hayne S, Gonyou H. Group gestation housing with individual feeding—I: How feeding regime, resource allocation, and genetic factors affect sow welfare. *Livestock Science*. 2013;152(2-3):208–17.
38. DeDecker A, Hanson A, Walker P, Salak-Johnson J. Space allowance and high fiber diet impact performance and behavior of group-kept gestating sows. *Journal of animal science*. 2014;92(4):1666–74.
39. Pluym LM, Maes D, Van Weyenberg S, Van Nuffel A. Risk factors for development of lameness in gestating sows within the first days after moving to group housing. *The Veterinary Journal*. 2017;220:28–33.
40. Morgan L, Klement E, Novak S, Eliahoo E, Younis A, Sutton GA, et al. Effects of group housing on reproductive performance, lameness, injuries and saliva cortisol in gestating sows. *Preventive veterinary medicine*. 2018;160:10–7.
41. Liu X, Song P, Yan H, Zhang L, Wang L, Zhao F, et al. A comparison of the behavior, physiology, and offspring resilience of gestating sows when raised in a group housing system and individual stalls. *Animals*. 2021;11(7):2076.
42. Zhou Q, Sun Q, Wang G, Zhou B, Lu M, Marchant-Forde J, et al. Group housing during gestation affects the behaviour of sows and the physiological indices of offspring at weaning. *Animal*. 2014;8(7):1162–9.
43. Alves LKS, Raineri C, Pairis-Garcia MD, Garbossa CAP. Economic perspective of expanded space allowance for group-housed gestating sows: aligning profitability and welfare compliance. *Livestock Science*. 2025;105858.
44. Sylvén KR, Wallgren T, Almerheim P, Selling LE, Jacobson M, Wallgren P. A comparison of two systems for group housing of gestating sows-effects on productivity, removal, and treatments. *Porcine health management*. 2025;11(1):1.

496

497

Tables

498 **Table 1.** Ingredient and chemical composition of the experimental diets (as-fed basis)

Ingredient, %	Gestation	Lactation
Corn	58.80	59.47
Lupine seed	6.00	-
Wheat bran	11.00	8.00
Soybean hull	4.00	-
Soybean meal	9.00	21.10
Rapeseed meal	3.00	3.00
Animal fat	2.50	3.60
Molasses	1.80	0.50
L-Lysine	0.33	0.57
Threonine	0.02	0.15
Tryptophan	0.10	0.05
Mono-dicalcium phosphate	1.50	1.20
Limestone	1.38	1.67
Salt	0.40	0.40
Vitamin and mineral premix ¹	0.15	0.15
Phytase	0.02	0.02
Total	100.00	100.00
Chemical composition, %		
Digestible energy (kcal/kg)	3,300	3,480
Crude protein	14.31	17.31
Calcium	0.93	0.96
Phosphorus	0.67	0.64
Lysine	0.79	1.05
Methionine	0.22	0.33
Threonine	0.53	0.78

499 ¹Supplied per kilogram of diet: vitamin A, 9600.00 IU; vitamin D₃, 1800.00 IU; vitamin E, 24 mg; vitamin K₃, 1.5 mg;
500 vitamin B₁, 1.5 mg; vitamin B₂, 12 mg; vitamin B₆, 2.4 mg; vitamin B₁₂, 0.045 mg; pantothenic acid, 24 mg; niacin, 45 mg;
501 biotin, 0.09 mg; folic acid, 0.39 mg; Fe, 150 mg; Cu, 96 mg; Zn, 72 mg; Mn, 46.5 mg; I, 0.9 mg; Se, 0.3 mg.

Table 2. Effects of space allowance on sow performance

Items	Space allowance, m ²				SEM ¹	<i>p</i> -value
	1.9	2.1	2.3	2.5		
Number of sows	12	12	12	12	-	-
BW, kg ²						
Gestation						
At d 42	221.42	220.92	218.64	221.58	5.18	0.978
At d 106	274.00	263.42	264.55	272.42	5.97	0.521
Lactation						
At weaning	234.00	231.50	232.80	242.55	7.28	0.742
BFT, mm ³						
Gestation						
At d 42	22.00	19.21	21.08	21.33	0.93	0.177
At d 106	23.88	21.46	22.73	23.83	0.85	0.187
Lactation						
At weaning	17.04	16.45	17.55	18.45	0.89	0.444

¹ SEM, standard error of means. ² BW, body weight. ³ BFT, backfat thickness.

Table 3. Effects of space allowance on reproductive performance in sows.

Items	Space allowance, m ²				SEM ¹	p-value
	1.9	2.1	2.3	2.5		
Litter size, no. of piglets						
Total born	14.25	13.27	11.27	12.22	1.07	0.241
Stillbirth	1.42	1.64	0.70	1.11	1.06	0.426
Mummy	0.25	0.36	0.36	0.44	0.22	0.938
Dead ²	0.58	0.55	0.18	0.33	0.24	0.613
Born alive	12.58	11.27	10.27	10.78	1.06	0.426
Cross-fostering	11.92	10.27	11.18	10.78	0.70	0.419
Weaned	10.92	9.45	10.64	10.00	0.65	0.422
Litter weight, kg						
Total born	19.41	18.77	16.73	17.24	1.23	0.413
Born alive	17.62	16.64	16.01	15.52	1.28	0.696
Cross-fostering	16.47	15.58	17.34	15.88	0.98	0.657
Weaned	91.65	83.88	96.49	94.06	5.47	0.461
Piglet weight, kg						
Total born	1.43	1.45	1.61	1.50	0.07	0.324
Born alive	1.45	1.47	1.61	1.51	0.08	0.406
Cross-fostering	1.40	1.59	1.56	1.51	0.09	0.431
Weaned	8.40	9.08	9.25	9.56	0.38	0.184
Average daily gain, g/pig ³	249.99	267.40	274.80	287.55	11.77	0.176
Survivability, % ³	92.01	93.29	95.01	93.04	2.58	0.879
Gestation length, day	115.08	116.09	115.64	116.67	0.42	0.100

¹ SEM, standard error of means. ² Number of piglets born alive but found dead within 24 h after farrowing; stillborn and mummified piglets were excluded.

Table 4. Effects of space allowance on colostrum composition in sows

Items	Space allowance, m ²				SEM ¹	<i>p</i> -value
	1.9	2.1	2.3	2.5		
Number of sows	12	12	12	12	-	-
Total solids, %	33.38 ^a	28.95 ^{ab}	29.19 ^{ab}	24.63 ^b	1.73	0.042
Protein, %	17.09 ^a	15.89 ^{ab}	14.73 ^{ab}	12.33 ^b	0.84	0.019
Fat, %	4.19	2.77	4.55	3.07	0.49	0.063
Lactose, %	3.50	2.42	2.53	1.44	0.45	0.210

¹ SEM, standard error of means.505
506

Table 5. Effects of space allowance on skin injury scores in sows

Treatment duration	Space allowance, m ²				SEM ¹	<i>p</i> -value
	1.9	2.1	2.3	2.5		
At week 0	0.8	0.6	1.0	0.7	0.3	0.773
At week 1	31.3 ^a	31.1 ^a	23.1 ^{ab}	17.9 ^b	2.7	0.002
At week 3	14.3	12.2	10.5	9.8	1.7	0.250
At week 5	11.7	10.9	7.1	8.9	1.2	0.049
At week 7	9.3	13.6	13.5	8.6	1.7	0.087
At week 9	10.7	12.4	9.8	9.2	1.5	0.468

¹SEM, standard error of means.^{abc} Values with different superscripts in the same row differ significantly ($p < 0.05$).

507

508

Table 6. Effects of space allowance on lameness score in sows

509

510

Treatment duration	Space allowance, m ²				SEM ¹	<i>p</i> -value
	1.9	2.1	2.3	2.5		
At week 0	0.2	0.0	0.2	0.1	0.1	0.506
At week 1	0.1	0.3	0.1	0.0	0.1	0.249
At week 3	0.2	0.1	0.4	0.3	0.2	0.468
At week 5	0.3	0.3	0.6	0.1	0.2	0.265
At week 7	0.3	0.3	0.7	0.1	0.2	0.139
At week 9	0.3	0.3	0.3	0.2	0.1	0.878

¹SEM, standard error of means.

Table 7. Effects of space allowance on metabolic and stress-related blood indicators in SOWS

Items	Space allowance, m ²				SEM ¹	<i>p</i> -value
	1.9	2.1	2.3	2.5		
BUN, mg/dL	6.3	6.2	5.8	5.5	0.47	0.556
Creatinine, mg/dL	2.5	2.4	2.4	2.2	0.10	0.076
Triglyceride, mg/dL	16.2	15.8	14.7	21.8	2.50	0.232
Free fatty acid, μEq/L	852.0	713.8	848.0	895.4	100.9	0.590
Glucose, mg/dL	81.6	84.4	88.8	89.3	2.98	0.233
Cortisol, μg/dL	4.5	6.3	4.6	6.0	0.66	0.147

¹ SEM, standard error of means; BUN, blood urea nitrogen.

511

512

513

514