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Posted Date: 12 September 2023

doi: 10.20944/preprints202309.0695.v1

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A Comprehensive Monitoring System for Health Status and Behavior of Pigs Under Different Environmental Conditions Using Vision and Audio Technologies

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Abstract: This study aimed to assess the feasibility of employing audio and vision technologies as an integrated monitoring system to monitor the health and behavior of pigs under different environmental conditions and to associate these factors. A total of 81 growing pigs ((Landrace x Largewhite) x Duroc) with distinct weight categories (10.47 ± 2.57 kg and 28.81 ± 5.03 kg) were distributed into two distinct housing conditions: Control (characterized by low NH_3 levels and low stocking density) and Treatment (marked by elevated NH_3 levels and varying stocking densities). Each house was installed with a SoundTalks monitor for automated daily evaluation of respiratory health status (ReHS), and a camera with a microphone to facilitate manual tracking of respiratory symptoms and behavioral patterns. Results showed that the Treatment group encountered significantly high room temperature, NH_3 concentration, and carbon dioxide levels, resulting in compromised growth performance—a phenomenon further exacerbated in high stocking density conditions. Pigs within the treatment exhibited increases ($p < 0.05$) in lateral and total lying behaviors, and incidences of ear and tail injuries, increases screaming frequency, conjunctivitis incidences, coughing frequency, elevated respiration rates, and a decrease in ReHS. The environmental conditions affect the behavior and health of the pigs. Moreover, the behavioral patterns of the pigs are associated with their health conditions. The SoundTalks system did not trigger any warnings during the experimental period. Nevertheless, trend analysis indicated a significant reduction in respiratory health in the treatment. In conclusion, this study underscores the efficacy of merging audio and visual technologies to holistically monitor pig health and behavior, enabling enhanced management strategies. Findings emphasize that monitoring the ReHS trend serves as a pivotal marker for identifying respiratory health problems, complementing the system's innate alarm functions.

Keywords: respiratory health; ammonia; ventilation; smart farming

1. Introduction

A climate-controlled house (CCH) system improved farm productivity by providing animals with a conducive environment for growth and reproduction [1–3]. Despite technological advancement, environmental conditions inside the CCH are not 100% controlled. Factors not limited to building design, model of ventilation equipment, software, sensors accuracy, knowledge and skill of the farmers, slurry pit management, and seasons can influence the environmental conditions of the house [4–10]. The house environment is usually controlled and manipulated based on the ambient temperature through automatic adjustment of the ventilation rate [11]. However, during cold seasons, the room temperature is low, therefore, the ventilation rate is reduced. This leads to exposing animals to toxic gases such as ammonia (NH_3), carbon dioxide (CO_2), carbon monoxide, hydrogen sulfide, and methane, which are detrimental to animal's health and welfare [4,12]. If added with poor manure management, this problem would worsen.

The welfare and health conditions are expressed in the feeding, drinking, social, resting, and vocalization behavior of the animals [13–17]. Alteration of these behaviors could be an indication of discomfort and/or health problems. Therefore, monitoring and detecting these behavioral changes is crucial to deploy early corrective actions to mitigate the potential problem. However, early correction of the cause of discomfort and disease requires an early detection of the abnormalities. This can be possible if farmers are able to monitor the pigs 24 hours throughout their cycle. With this necessity, there is an increasing effort to develop artificial intelligence (AI) for automatic and real-time monitoring of behavior and health conditions of pigs [18–24]. Previous studies used either cameras or microphones for the detection of abnormalities. However, in the study of Lee et al. [25], they demonstrated a good result on cough detection, localization, and visualization using combination of sound and vision techniques. Combining vision and audio technologies will be a more powerful tool. It will provide more comprehensive data on behavioral and physiological conditions of the animals for a more holistic management approach.

AI product that can automatically detect and monitor the respiratory health status of pigs using sound technology is available in the market, the SoundTalks (SoundTalks NV, Leuven, Belgium) [26]. Several studies evaluate its applications in swine farming and show advantages over conventional method of health monitoring [27–30]. Currently, the company changed their system from respiratory distress index to respiratory health status (ReHS). The RDI is the average number of coughs per head within 24 hours and the threshold of the alarm system is based on the history and variations of the RDI of the herd [28]. On the other hand, in the new system, coughing sounds are quantified and converted into metric values from 0 to 100 (the higher the ReHS values, the higher the health condition of the pigs) [31]. There were limitations found on the previous system such as variability of RDI values and the alarm system is population-dependent [26]. Therefore, there is a need to evaluate the new system in the field condition. The objectives of the study were (1) to evaluate the SoundTalks' new system of monitoring the respiratory health status of pigs under different environmental conditions, (2) to evaluate the applications of combined camera and microphone in monitoring growing pigs' health conditions and behavior; and (3) to determine the association between environmental conditions and pigs' health and behavior conditions.

2. Materials and Methods

2.1. Animals and Housing

The experiment was conducted in the swine research facilities of Sunchon National University, South Korea (34.999546 °N, 127.507396 °W) from June 2 to 30, 2023. 81 pigs of different weight categories (smaller pigs: 10.47 ±2.57 kg and bigger pigs: 28.81 ±5.03 kg) were divided and raised in two identical CCH with different environmental conditions. In the control house, the NH_3 level was maintained at no more than 10 ppm. In the treatment house, the ventilation was adjusted to maintain the NH3 level more than 15 ppm. Each house has four pens with a size of 2.35 x 2.9 m per pen. In this study, two pens were utilized in the control house with 13 pigs in each pen (smaller pigs in pen 1 and bigger pigs in pen 2). On the other hand, three pens were utilized in the treatment house. 19 bigger

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pigs, 13 bigger pigs, and 23 smaller pigs were penned to pens 1, 2, and 3, respectively. The pigs had unlimited access to feeds and water throughout the experimental period.

The houses were equipped with high-definition cameras (PNO-A6081R) (Hanwha VisionCo., Ltd., South Korea) with an audio input using VideoMicro (RODE, Australia) (Figure 1). The cameras were installed strategically 2 meters from the floor and were able to capture pen number 2 of each house. Each of these pens had 13 heads of bigger pigs. All the video data was saved and accessed online through Wisenet Recorder Webviewer. The houses were well lit 24 hours throughout the period.

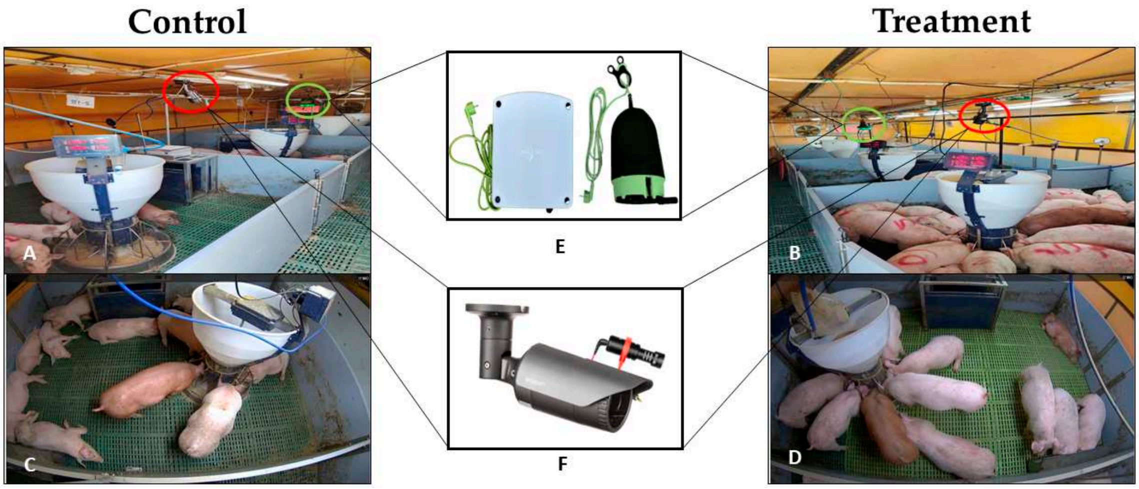

Figure 1. The experimental facilities at Sunchon National University, a) CONTROL group; b) TREATMENT group; c) vision of control group captured using PNO-A6081R camera; d) vision of treatment group captured using PNO-A6081R camera; e) monitor and gateway of SoundTalks (SoundTalks NV, Leuven, Belgium); f) PNO-A6081R camera with VideoMicro.

2.2. Environmental Conditions

The experimental houses were equipped with sensors that can automatically collect room temperature (RM), relative humidity (RH), NH_3, and CO_2, and the data were accessed online through Farm Note (Narae Trend Co., Ltd. Farm Note, South Korea). Manual collection of NH_3 concentration at the animal's level was also conducted using a GASTEC detector tube and pump GV-100 (GASTEC Corporation, Japan). Synchronously, dust particles (PM2.5) were measured using AR830A SMART SENSOR (Shenzhen Smartsensor Trading Co., Ltd., China) once a day.

2.3. Growth Performance

The pigs were individually weighed every week to evaluate their growth weekly. Feeds given were recorded daily and the remaining feeds in the feeder were weighed weekly to get the weekly feed intake.

2.4. Pigs' Behavior

2.4.1. Posture

The behavioral activity of the pigs indicates health conditions and response to environmental conditions. Pigs on lateral lying (LL), sternal lying (SL), total lying (TL), standing, sitting, and resting near waterer (RW) were quantified from 12 sample photos taken from 2:00, 4:00, 6:00, 8:00, 10:00, 12:00, 14:00, 16:00, 18:00, 20:00, 22:00, and 24:00. The manual counting was conducted daily throughout the study period. The data were converted into percentages. The ethogram used for identification of pig behavior is shown in Table 1.

 doi:10.20944/preprints202309.0695.v1

Table 1. Ethogram of pig behavior observed in different environmental conditions.

Behavior	Definition
Lateral lying	The pig is lying on the side with limbs extended
Sternal lying	The pig is lying on its belly with at least two legs folded under the body
Total lying	Summation of lateral and sternal lying
Standing	Standing, walking, or running, the body is elevated and supported by 3 or 4 legs
Sitting	Hindquarters on floor with front legs straight
Resting at waterer	The pig is lying and the head is within a 0.5-meter radius of the water trough
Screaming	High-frequency content calls with a large amplitude often uttered in stressful and painful situations

2.4.2. Biting Behavior

The frequency of screaming sounds was recorded by listening to a 10-minute audio-video data taken at 9:00, 12:00, 15:00, and 18:00 once per week. At the end of the study, all pigs were checked for the presence of wounds on the ears and the tail as signs of biting (Figure 2).

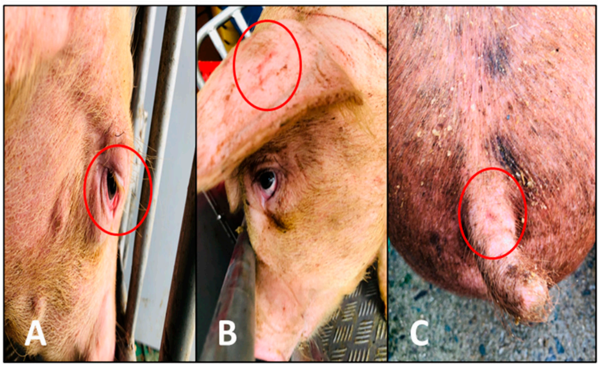

Figure 2. Pigs showing signs of a) conjunctivitis, b) ear-bite wound, and c) tail-bite wound. **.**

2.5. Health Conditions

The respiratory health status of the herds was automatically measured using SoundTalks. SoundTalks automatically detects the coughing sounds of pigs and generates daily respiratory health status (ReHS) value that ranges from 0 to 100 (the higher the ReHS, the healthier the herd is). It has an alarm system that signifies the health conditions of the herd. ReHS values from 60 to 100 signify healthy pigs, otherwise, there is a potential respiratory health problem. One SoundTalks monitor was installed in each house, following the manufacturer's guidelines. All data collected were stored and accessed through their website (https://www.soundtalksweb.com).

Coughing frequency (CF) was manually counted over a 5-minute period in 3-hour intervals, starting from the 2nd day until the 27th day by one trained personnel by listening to the audio-video data. A total of 40 minutes of audio-video recording per day were assessed. The CF per head (CF/h) was derived by dividing CF by the population of pigs in each house.

Using the video data, the pigs' respiration rate (RR) was determined by visual observation of abdominal fluctuation. The counting was conducted at 6-hour intervals per day, twice a week. At the end of the experiment, all pigs were checked for the presence of conjunctivitis.

2.6. Statistical Analysis

IBM SPSS Statistics version 20 and RStudio version 2023.06.1 were used for the statistical analyses. The percentage difference in the growth performance parameters between groups of the same weight range was calculated for comparison.

A statistical test was applied to evaluate whether the environmental, behavioral, and health condition parameters significantly differ between groups. The data were first tested for normality of distribution and homogeneity of variance using Shapiro-Wilk's and Levene's tests, respectively. The two-sample t-test was used for the data with normal distribution and equal variance, otherwise, the Mann-Whitney U test was used. Daily or weekly data were used as experimental units. There is a statistically significant difference if the p-value is less than 0.05. All the dependent variables were matched with the specific dates and Spearman's correlation analysis was conducted to examine their association.

The daily ReHS trend of both groups was tested for stationarity to determine a significant change in respiratory health using Augmented Dickey-Fuller (ADF) and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) tests. The trend is stationary if the p-value is <0.05 in ADF but non-stationary in KPSS. The trend was further tested using the Mann-Kendall test to determine which day significant change or changepoint occurred if the trend is non-stationary.

3. Results

3.1. Environmental Conditions

The results showed that pigs under treatment were exposed to significantly (P<0.001) higher room temperature (30.05 °C vs 24.75 °C), NH_3 (20.14 ppm vs 2.89 ppm), and CO_2 (1,600.93 ppm vs 905.92 ppm) (Table 2). An increasing trend of RT and RH towards the end was observed in the treatment (Figure 3). In contrast, the control's environmental conditions were more consistent. CO_2 concentration increased throughout the growing period in both groups. However, the rate of increase was higher in the treatment. The RH and PM2.5 were statistically similar in both groups. A correlation analysis showed that NH_3 and CO_2 levels are strongly associated with RT (R= 0.848 and 0.950; P < 0.001) (Figure 4).

Table 2. Environmental conditions of the experimental houses.

Parameters		Control	Treatment	SEM	P-value
Temperature (⁰C)	mean, SD min-max	24.75 ±0.37 24.5-25.50	30.05 ±1.37 27.50-32.50	0.381	<0.001
Humidity (%)	mean, SD min-max	76.96 ±4.14 62.00-81.00	79.00 ±4.79 73.00-90.00	0.609	0.095
CO_2 (ppm)	mean, SD min-max	905.92 ±57.20 836.37-1,058.68	1,600.93 ±170.50 1,366.64-1,985.47	49.790	<0.001
NH_3 (ppm)	mean, SD min-max	2.89 ±2.70 0.00-10.00	20.14 ±4.50 10.00-30.00	1.263	<0.001
Dust (mg/m^2)	mean, SD min-max	32.00 ±17.92 50.00-77.00	41.39 ±18.33 16.00-89.00	2.482	0.058

SD = standard deviation; min = minimum; max = maximum; CO_2 = carbon dioxide; NH_3 =ammonia.

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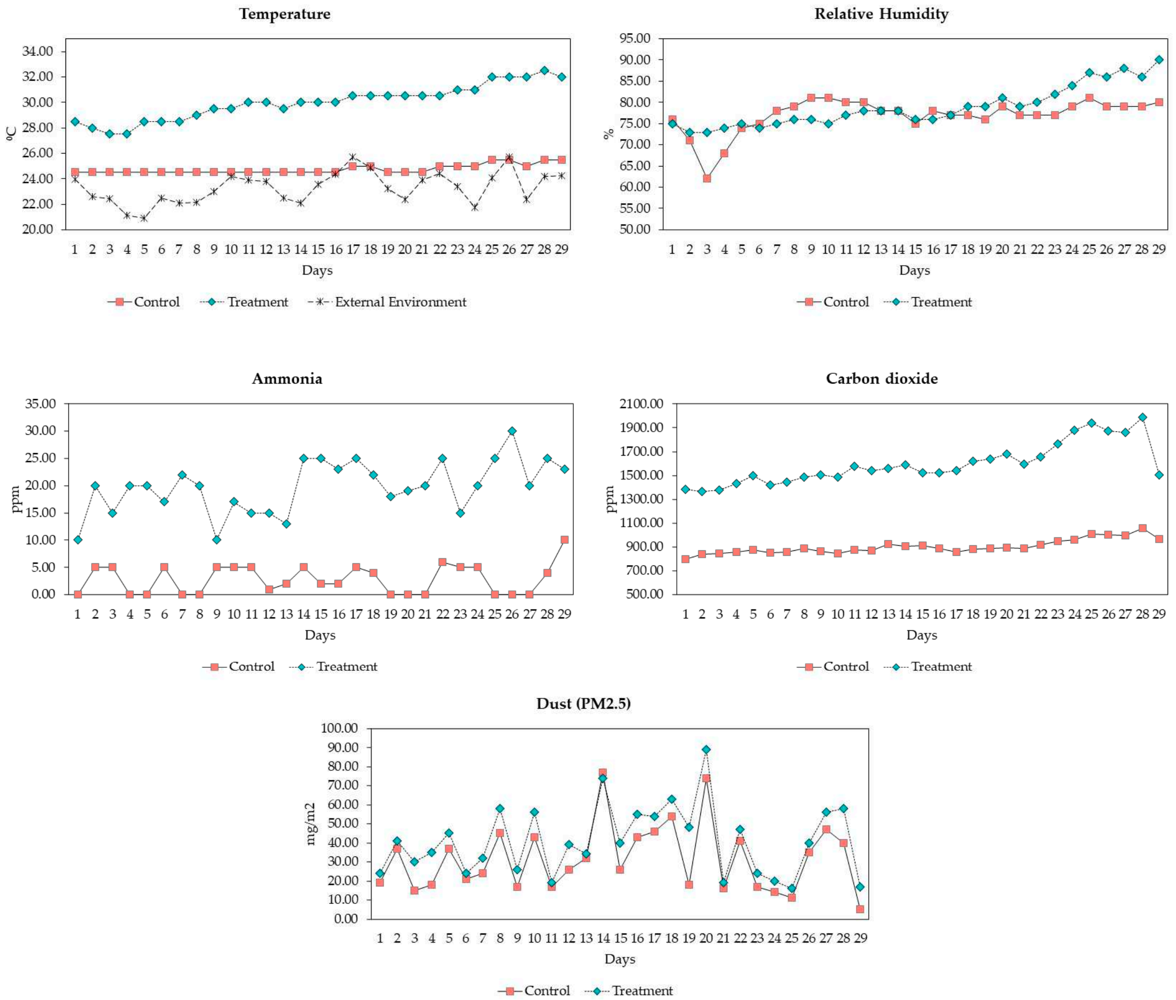

Figure 3. Daily temperature, relative humidity, ammonia, carbon dioxide, and dust concentrations in CONTROL and TREATMENT houses.

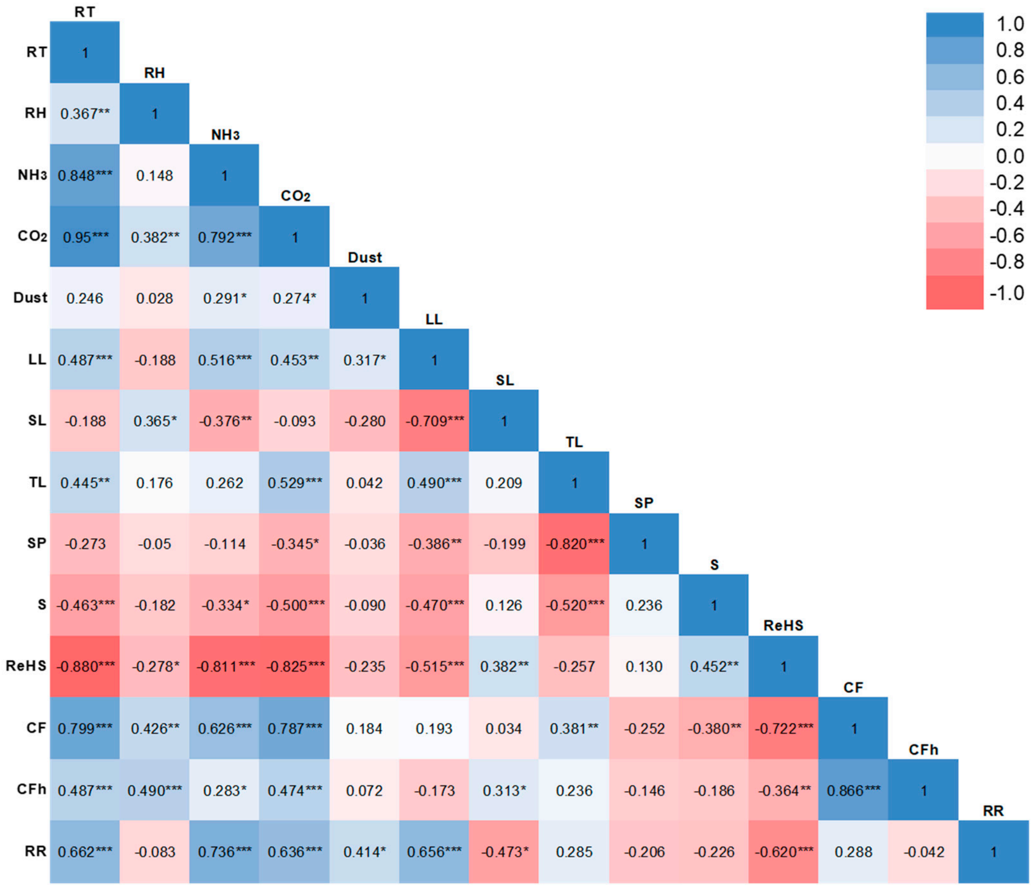

Figure 4. Spearman's correlation analysis between environment, pig's behavior, and respiration health. (* = significant at the 5%; ** = significant at 1%; significant at 0.1%; RT = room temperature; RH = relative humidity; NH3 = ammonia, CO2 = carbon dioxide; Dust = dust particles (PM2.5); LL = lateral lying; SL = sternal lying; TL = total lying; SP = standing; S = sitting; ReHS = respiratory health status; CF = coughing frequency; CFh = coughing frequency/head; RR = respiration rate.).

3.2. Growth Performance

Environmental conditions are detrimental to the growth of the animals. In this study, pigs exposed to a poor environment had lower growth performance parameters than their counterparts grown in a good environment (Table 3). Smaller pigs in the treatment were 24.76%, 36.98%, and 34.60% less in the final weight, body weight gain, and feed intake, respectively, and 7 points higher in feed conversion ratio (FCR) compared to pigs in the control. Bigger pigs had also shown a reduction in performance in the treatment. The growth was further impaired nearly twice with an increasing stocking density in a poor environment. However, smaller pigs in a poor environment and high stocking density had the best FCR which is 7 points better than in the control. Furthermore, the ADG of bigger pigs regardless of environment had a downward trend. While smaller pigs regardless of environment had an increasing ADG trend.

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Table 3. Effects of different environmental conditions and stocking density on the growth performance of growing pigs.

	Bigger Pigs					Smaller Pigs		
	Control	**Treatment**		**Difference**		**Control**	**Treatment**	Difference
N heads	13	13	19			13	23	
SD (m^2/head)	0.45	0.45	0.32			0.45	0.27	
IW (kg)	28.85	28.97	28.56			10.59	10.35	
FW (kg)	55.79	48.32	43.58	-13.40	-21.89	30.05	22.61	-24.76
BWG (kg)	26.94	19.35	15.02	-28.18	-44.26	19.46	12.27	-36.98
ADG (kg/day)	0.962	0.691	0.536	-28.18	-44.26	0.695	0.438	-36.98
FI (kg)	59.32	43.52	31.95	-26.63	-46.15	33.52	21.92	-34.60
FCR (FI/BWG)	2.20	2.25	2.13	2.16	-3.39	1.72	1.79	3.76

N = population in pen; SD = stocking density; IW = initial weight; FW = final weight; BWG = body weight gain; ADG = average daily gain; FI = feed intake; FCR = feed conversion ratio.

3.3. Behavioral Observations

Pigs spend most of their time resting, and this behavior is affected by environmental conditions and health. There was a significant difference (P = 0.019) in TL between the groups (Table 4). Higher TL was observed in treatment with 83.63% compared to 79.43% in the control. Additionally, most of the pigs were resting in a lateral position. However, the percentages of LL and SL were significantly different between groups. The percentage of pigs in control that were lying in a lateral position was lower (42.98% versus 53.98%, P < 0.001). This is negatively associated with the percentage of pigs that were lying in a sternum position. SL in the control was significantly higher compared to the treatment (36.46% versus 29.65%, P = 0.002). However, there was an increasing SL towards the end of growing period in the treatment group (Figure 5). Pigs in standing posture may indicate feeding, drinking, playing, and/or exploring activities. A higher percentage of pigs in the standing posture observed in the control group compared to the treatment group (3.66% versus 2.24%, P = 0.002). But there was no significant difference in terms of the percentage of pigs sitting in all groups. Moreover, more pigs were sleeping near the waterer in the treatment (11.70% vs 16.56%, P = 0.005).

Table 4. Effects of different environmental conditions on behavior and health conditions of growing pigs.

Parameters		**Control**	**Treatment**	**SEM**	**P-value**
Behavior					
Lateral Lying (%)	mean, SD	42.98 ±6.79	53.98 ±6.75	1.257	<0.001
	min-max	28.85-53.21	41.03-66.67		
Sternal Lying (%)	mean, SD	36.46 ±6.93	29.65 ±7.15	1.121	0.002
	min-max	23.72-48.08	20.51-46.79		
Total Lying (%)	mean, SD	79.43 ±6.14	83.63 ±5.80	0.906	0.019
	min-max	64.10-89.10	71.15-92.95		
Standing (%)	mean, SD	3.66 ±1.69	2.24 ±1.24	0.235	0.002
	min-max	0.00-7.69	0.00-4.49		
Sitting (%)	mean, SD	11.62 ±5.66	9.11 ±4.53	0.755	0.097
	min-max	3.85-23.72	1.92-23.72		
Resting at waterer (%)	mean, SD	11.70 ±1.05	16.56 ±1.03	1.151	0.005
	min-max	10.73-12.82	15.38-17.31		
Screaming Frequency	mean, SD	38 ±6.24	65 ±4.58	6.360	0.005
	min-max	31.00-43.00	60.00-69.00		
Health Conditions					
ReHS	mean, SD	98.37 ±1.04	86.04 ±5.93	1.023	<0.001
	min-max	96-99	72-94		
Coughing Frequency	mean, SD	25.07 ±15.85	69.07 ±33.80	4.668	<0.001
	min-max	1-60	10-143		

Coughing Frequency/head	mean, SD	0.96 ±0.61	1.26 ±0.61	0.085	0.086
	min-max	0.04-2.31	0.18-2.60		
Respiration Rate	mean, SD	84.09 ±12.13	106.71 ±7.83	2.886	<0.001
	min-max	60.50-98.00	90.50-116.50		

SD = standard deviation; min = minimum; max = maximum; ReHS = respiratory health status.

The screaming sound can be used as an indicator of a bitten pig. In this current study, the screaming frequency was counted, and it was found that there was higher screaming observed in the treatment (65 vs 38, P = 0.004). At the end of the growing period, ear and tail biting incidence was collected by checking the presence of wounds in the ear and tail to associate with the screaming frequency. Generally, there was a high percentage of animals with wounds in the ear or in the tail, or both in the treatment group (Table 5). Higher ear-biting incidence was observed in smaller pigs in both groups. Additionally, ear and tail-biting incidences were higher with high stocking density.

The correlation analysis showed that there is a high percentage of TL with increasing RT and CO_2 (P < 0.001 and P < 0.002). The LL is positively associated with RT, NH_3, and CO_2 (P < 0.001, <0.001, = 0.001). In contrast, SL is positively associated with RH (P = 0.011) and negatively associated with NH_3 (P = 0.009). The percentage of pigs in standing posture has a negative association with CO_2 (P = 0.016). While the percentage of pigs in sitting posture has a negative association with RT, CO_2, and NH_3 (P = 0.001, <0.001, and = 0.021).

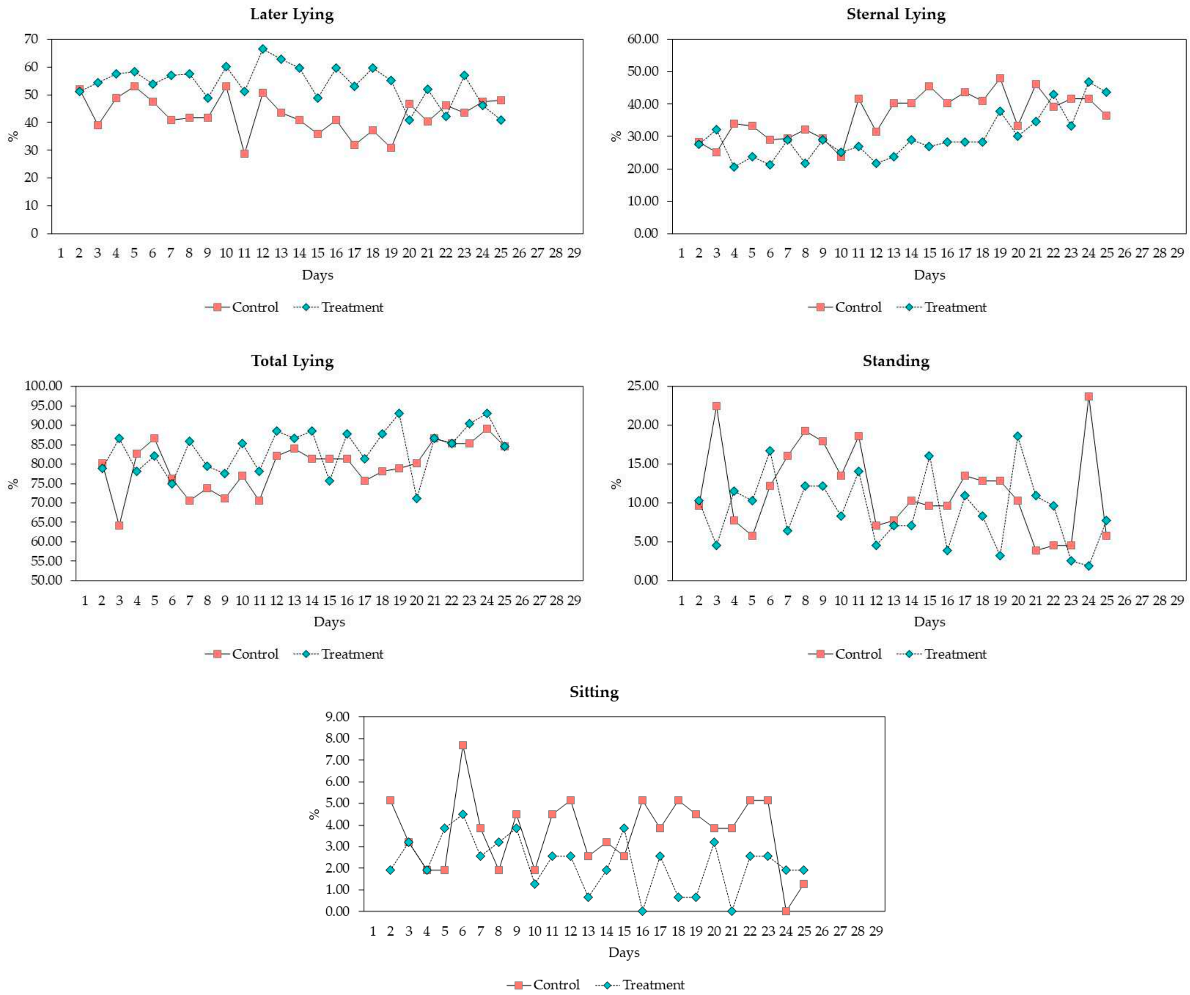

Figure 5. Daily trends of postural patterns of pigs exposed to different environmental conditions.

Table 5. Percentage (%) of pigs with conjunctivitis, ear wound, and tail wound exposed to different environmental conditions**.**

	Control		Treatment		
Weight Class	**S**	**B**	B	B	S
N heads	13	13	19	13	23
SD (m^2/head)	0.45	0.45	0.32	0.45	0.27
Conjunctivitis (%)	46.15	30.77	68.42	76.92	52.17
Ear Wound (%)	7.69	-	42.11	30.77	69.57
Tail Wound (%)	-	-	21.05	7.69	8.70

S = smaller pigs; B = bigger pigs; N = population in pen; SD = stocking density; - = zero.

3.4. Health Conditions

The general respiratory health status of the herds throughout the growing period was healthy based on the SoundTalks system. There was no respiratory health-related alarm since the ReHS values in both groups were more than 60 (Figure 6). However, the treatment group had significantly lower ReHS compared to the control (98.37 versus 86.04; P < 0.001). A decreasing ReHS is associated with an increasing CF (R = -0.722; P < 0.001). There was a significant difference in CF, in which treatment was higher compared to control (25.07 and 69.07; P < 0.001). However, by dividing the CF with the population in the houses to get the CFh, the groups had no difference. Although no significant difference was observed, the ReHS and CFh have moderately negative associations (R = -0.364; P = 0.007). Pigs exposed to a poor environment had significantly increased RR (84.09 and 106.71; P < 0.001). The increasing RR is negatively associated with ReHS (R = -0.620; P < 0.001).

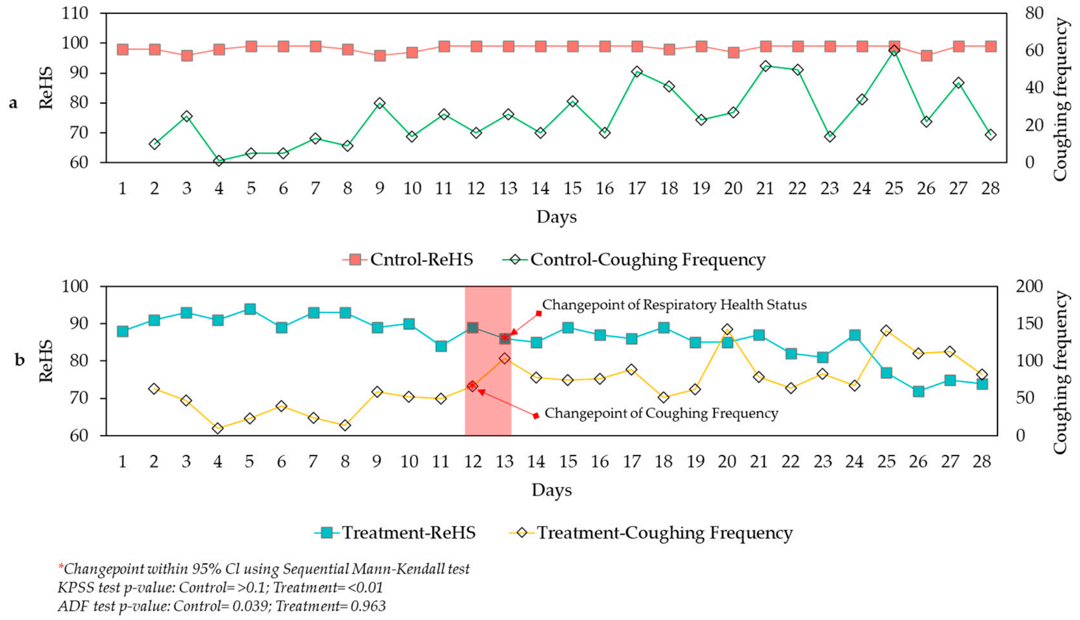

Figure 6. Trend of respiratory health status (ReHS) and coughing frequency of pigs in a) CONTROL and b) TREATMENT groups.

The RT, NH3, and CO_2 have a strong negative association with ReHS (R > 0.800; P < 0.001). While the RH has a moderate negative association with the ReHS (R = -0.278; P < 0.034). Furthermore, the CF, CFh, and RR are increased with increasing environmental parameters (P < 0.05). Additionally, the RR is also associated with the dust level in the house (R = 0.414; P = 0.029).

The LL is negatively associated with ReHS (R = -0.515; P < 0.001). On the other hand, the SL and S are positively associated with the ReHS (P ¬= 0.007, 0.001). With higher CF, pigs will show higher TL (R = 0.381; P = 0.008) and lower activity (S) (R = -0.380; P = 0.008). The CFh is positively associated

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with SL (R = 0.313; P = 0.030). While increasing RR increases LL (R = 0.656; P < 0.001) and decreases SL (R = -0.473; P = 0.011).

Although there was no respiratory health-related alarm from SoundTalks during the growing period. However, the stationarity analyses showed that the trend of ReHS in the treatment was non-stationary (ADF P = 0.963; KPSS P < 0.01) with decreasing direction while the trend in control was stationary (ADF P = 0.039; KPSS P > 0.1). The Mann-Kendall test was conducted to determine which day a change in respiratory health was significant (P < 0.05). The test showed that there was a significant change on day 13. The test also showed a significant increase in CF on day 12.

4. Discussion

The environmental conditions of the experimental houses were manipulated by adjusting the ventilation rate to evaluate the response of pigs in normal and poor environmental conditions. The concentration of NH_3 could be kept below 5 ppm in a well-ventilated pig house [4,32]. This is in accordance with the current study under the control environment with an average NH_3 concentration of 2.89 ppm. This concentration is lower compared to the study of Pessoa et al. [29] and Mielcarek-Bocheńska and Rzeźnik [33] in fattening houses. The variation in concentration might be due to the population size of the herd and the season. The room CO_2 concentration in the control is the same as the study of Zong et al. [34]. Moreover, they reported that the CO_2 concentration in the pit air ranges from 1,228 to 1,556 ppm which is a similar condition to that in the treatment of the current study. However, this level is considered safe as the maximum allowable level for animals is 3000 ppm mentioned by Ni et al. [35]. The CO_2 concentration was increased throughout the growing period, but the rate of increase was higher in the treatment. The increasing trend is associated with the pig's body mass [9,34], in which bigger pigs produced more CO_2 from respiration. Furthermore, the concentrations of CO_2 and NH_3 are highly associated with room temperature. Increasing environmental temperature increases bacterial activity on the pit's organic matter, leading to a high rate of decomposition and ammonification [36–38]. In addition, the population in the treatment house was higher compared to the control (55 vs 26). More CO_2 was produced by the respiration of pigs and by microbial activity in the hindgut and in the decomposing organic matter.

Generally, the house temperature was higher than the external temperature throughout the growing period. The increase in the room temperature could be caused by thermal production during decomposition and the heat produced by the animals [39–41]. With a low ventilation rate, a higher rate of decomposition and the number of animals would be the reasons for the increasing temperature in the treatment. Although RH was not significantly different between groups, an average of 79% RH would worsen the heat stress effect of the RT to pigs.

The reduction of growth performance might be caused by the synergistic effect of high ambient temperature, NH_3, and other gases inside the pig's house. Accordingly, when the animals are exposed to an environment that exceeds their thermoneutral zone, the growth performance of the animals is compromised [42]. This is because animals respond to high ambient temperature by adjusting their feed intake to modify their metabolic heat production [43–45]. Voluntary feed intake is also negatively affected by a very high level of CO_2 (40,00 ppm) [46]. However, in the current study, the treatment's CO_2 concentration was below the safety level but significantly higher than the well-ventilated house. Nevertheless, the CO_2 concentration in the pig house is associated with toxic gases concentration like NH_3. Young pigs (8-week-old) exposed to 0, 50, 100, and 150 ppm of NH_3 showed reduced voluntary feed intake [47]. Even in low levels of NH_3 in the study of Wang et al. [48], decreasing trend was observed in the feed intake with increasing NH_3 levels (from 0, 5, 10, 15, 20, 25 ppm). With reduced feed intake and diversion of nutrients to mitigate heat stress and toxicity, nutrient supply is insufficient to support growth potential of the animal. In this study, the feed intake difference of pig under good and poor environment was at least 26%. This resulted in a lower average daily gain of pigs in the treatment by 28.18%. This result is similar to pigs exposed to 150 ppm of NH_3 [47]. The growth performance was further reduced with increasing stocking density. Several studies demonstrated that limiting space allowance decreases feed intake and average daily gain in growing pigs even in optimum environment conditions [49–51].

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In addition to suboptimal nutrition, the heat stress, the high stocking density, and the high NH_3 induce inflammation, oxidative damage to cells, and reduce gut integrity, weakening the immune system of the animals making them more susceptible to infection and less efficient [49,52–54]. NH_3 irritates the conjunctiva causing conjunctivitis [55], irritates the mucosal layer of the respiratory system and depresses ciliary activity and mucus flow [56] and damaging trachea [57] which predisposing animals to infection. Furthermore, the nasal microbial population is associated with respiratory health. Wang et al. [48] reported that increasing atmospheric NH_3 from 0 up to 25 ppm alters the nasal microbial population of the pigs favoring pathogenic bacteria under the genus Moraxella and Streptococcus, which may lead to respiratory disease.

The manual monitoring of respiratory disease of pigs exposed to poor environmental conditions showed an increase in coughing incidence. This is consistent with previous study of pigs exposed to NH_3 up to 25 ppm [58]. The coughing frequency would increase three times when exposed to 100-150 ppm [59]. The increase in CF is associated with the decrease in pigs' respiratory health status measured by SoundTalks. This finding proves the reliability of the existing technology for automatic monitoring of the respiratory health status of pigs. Increased respiration rate is one subclinical signs of respiratory disease [60]. In the current study, pigs with lower ReHS had higher respiration rate. Respiratory disease reduces the efficiency of the lungs, lowering O_2 and increasing CO_2 levels in the blood [61,62]. To keep the balance, animals increase their respiration rate.

The SoundTalks has been used for several studies for automatic monitoring of respiratory health conditions of pigs exposed to environmental conditions or pathogens associated with respiratory disease [27–30]. However, the previous studies used the respiratory distress index (RDI) as unit of respiratory disease level. Therefore, this study was conducted to explore the new system which is the ReHS. In the current study, there was a significant reduction of ReHS in pigs exposed to poor environmental conditions. However, the alarm system was not triggered to signal potential respiratory disease. The number of coughing sounds or the severity of the respiratory disease might not be enough for the alarm to turn on. There is also a possibility that the differences of ReHS between groups might be due to population size difference since the technology was designed for large pig populations [26]. The result found that the ReHS and the CF have a strong negative association. The CF was divided by the population to determine whether population size affects ReHS value, and it showed no significant difference between groups. However, the treatment groups had higher CF/h. Since population size can influence ReHS, the trends of both groups were tested for stationarity to determine the effect of environmental factors on the respiratory health of the pigs. The trend of ReHS in the pigs exposed to a poor environment was not stationary with decreasing values towards the end of the growing period. It means that the respiratory health of the pigs was deteriorating with increasing exposure to such environment. Chen et al. [63] used Mann-Kendall test for change point detection of COVID-19 cases of the United States outbreak. This was applied in the current study and found that the ReHS in the treatment was significantly changed at day 13 of exposure. On the other hand, significant change of CF was detected on day 12 of exposure. These findings suggest that the alarm system of the existing technology needs to be further evaluated and calibrated. Furthermore, trend analysis has potential applications for the alarm system to detect significant reduction of respiratory health status.

Continuous monitoring of animal behavior can detect subtle signs of disease and/or stress in response to environmental conditions. For example, pigs' activity is decreased and tend to rest more under high ambient temperature. The resting posture of the pigs could also indicate a problem. Pigs lie laterally with limbs extended when ambient temperature is high, and lie in sternal position in low temperature [64,65]. Lying laterally exposes more surface to floor and air, enhancing heat loss [66]. Wallowing is one of the methods of pigs for thermoregulation and there are several studies found a positive relationship of it with air temperature [67–69]. However, in this study, pigs were not provided with wallow. But there was a significant increase in the percentage of pigs resting near a wet area, which is near the water trough. NH_3 level could also influence feeding and foraging activity of pigs which decreases with high NH_3 (Jones et al., 1996). In this study, there was no association between total lying and NH3 concentration. However, NH_3 concentration has a positive association with the lateral lying. Choi et al. [70] also found an increase in lateral lying pigs exposed to 15.35 ppm NH_3 during summer. Exposure to high atmospheric NH_3 increases NH_3 level in the blood [58], leading to NH_3 poisoning in which the secretion of excitatory neurotransmitters is inhibited making the animals less active [71]. Additionally, lying behavior has been linked to the health conditions of the animals. Pigs infected with porcine reproductive and respiratory (PRRS) virus spent more time lying [72] in ventral position [73]. In the current study, pigs in the treatment house had lesser percentage of sternal lying. However, sternal lying increased from day 14 until the end of growing period in the group. And day before that, the ReHS was significantly decreased, implying presence of respiratory disease.

The tail and ear biting behavior of pigs is an important concern for animal welfare. Pigs in poor environmental conditions were uncomfortable, inducing biting behavior leading to a high percentage of pigs with ear and tail wounds. Furthermore, increasing stocking density induces more biting behavior. Several studies has been linked this damaging behavior to high stocking density, poor environmental conditions, nutrient deficiency, sex, and age [74–78]. With increasing concern, there are several efforts have been executing to develop an AI for automatic detection and monitoring of biting behavior using computer vision [18,79–81]. The current study demonstrated a potential application of microphones to monitor tail and ear biting by monitoring screaming sounds of pigs. The cameras can distinguish ear biting, tail biting, degree of biting, biter, and the bitten [75]. However, there are disadvantages in their application, such as limited capture area, and detection failure due to pigs are obstructed by farm equipment or lenses covered with dust or fly feces. These concerns can be addressed by using microphones as they can detect sounds in a wide area and sounds travel through air, therefore, screaming sounds from unseen pigs can still be detected. Combining these two technologies would be advantageous.

5. Conclusions

The study revealed that environmental conditions significantly impact pig growth, behavior, and health. Behavioral patterns were found to be associated with the pigs' health status. Cameras and microphones proved effective in monitoring pig behavior and health. Combining vision and audio technologies offered a holistic approach to management. This study is the first to assess the SoundTalks' ReHS system in different environmental conditions for pigs. The AI system effectively monitored the respiratory health of the herds. However, the study suggests the need to calibrate the SoundTalks alarm system thresholds based on our findings. Furthermore, the study introduced the Mann-Kendall test for detecting change points in pig respiratory health status, complementing the SoundTalks system. This test could be integrated into the alarm system to enable early detection of respiratory diseases.

Author Contributions: Conceptualization, E.B.L., H.-S.M. and C.-J.Y.; Data curation, E.B.L. and H.-S.M.; Formal analysis, E.B.L. and H.-S.M.; Funding acquisition, C.-J.Y.; Investigation, E.B.L., H.-S.M., K.M.B.A., V.C., H.R.P. and Young-Hwa Kim; Methodology, E.B.L., H.-S.M. and C.-J.Y.; Resources, C.-J.Y.; Supervision, C.-J.Y.; Visualization, E.B.L. and H.-S.M.; Writing – original draft, E.B.L. and H.-S.M.; Writing – review & editing, E.B.L., H.-S.M., K.M.B.A., V.C., H.R.P., Young-Hwa Kim and C.-J.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The animal study protocol was approved by the Institutional Review Board or Ethics Committee of Sunchon Nation University (SCNU IACUC-2023-19).

Data Availability Statement: The data presented in this study are available on demand from the corresponding author or first author at yangcj@scnu.ac.kr or eddiemarlagua@gmail.com.

Acknowledgments: The authors would like to acknowledge the Korea Institute of Planning and Evaluation for Technology in Food, Agriculture and Forestry (IPET) and Korea Smart Farm R&D Foundation through the Smart Farm Innovation Technology Development Program, funded by the Ministry of Agriculture, Food and Rural Affairs (MAFRA) and Ministry of Science and ICT(MSIT) and Rural Development Administration(RDA) (421023-04). Also, work was supported by the "Cooperative Research Program for Agriculture Science &

Technology Development (Project title : Development of high-yielding sow feeding and management technology to improve PSY, Project No. PJ016943)" Rural Development Administration.

Conflicts of Interest: The authors declare no conflicts of interest.

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