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Abstract

Heat stress during late gestation and lactation compromises sow welfare, metabolic stability, and litter performance. This study evaluated the physiological, behavioral, and inflammatory responses of sows exposed to different cooling systems under elevated ambient temperature. Forty multiparous Landrace × Yorkshire sows (223.6 ± 25.8 kg) were assigned to a 2 × 2 factorial arrangement consisting of no cooling (CON), fan (FN), drip cooling (DC), and fan plus drip cooling (FN + DC). The average temperature–humidity index (THI) during the experimental period was 76, indicating heat stress condition. Cooling systems were associated with reductions in respiratory rate and rectal temperature during specific periods of late gestation ($p < 0.05$), with the more pronounced responses observed in FN + DC compared with CON. Hair cortisol concentrations were lower in FN and FN + DC than in CON ($p < 0.05$), whereas DC did not differ from CON. Behavioral indicators of thermal discomfort, including drinking frequency, standing time, and postural changes, were reduced in fan-based ($p < 0.05$), accompanied by increased lying behavior. Sow body weight, backfat thickness, feed intake, and reproductive parameters were not affected by treatments. However, fan-based cooling was associated with a higher number of weaned piglets and litter weight at weaning ($p < 0.05$). Among inflammatory markers, TNF-α concentration was reduced by fan-based systems ($p < 0.05$), whereas IL-1β and IL-6 concentrations were not affected. Overall, cooling systems, particularly fan-based strategies, were associated with improvements in selected physiological, behavioral, and productive indicators under heat stress conditions, although these responses were not consistent across all variables or time points.

Keywords (3 to 6): heat stress, hair cortisol, heat management, thermoregulation, sow welfare.

Introduction

Heat stress represents one of the most critical environmental constraints in modern swine production systems, particularly under intensified production conditions and rising global temperatures [1,2]. Late-gestation and lactating sows are especially susceptible due to elevated metabolic heat production associated with rapid fetal growth and milk synthesis [3,4]. When ambient temperature exceeds the upper critical threshold, thermoregulatory capacity becomes compromised, resulting in increased respiratory rate, elevated rectal temperature, reduced voluntary feed intake, and altered endocrine and metabolic responses [5-8]. These physiological disturbances impair reproductive efficiency and may negatively affect litter performance [3,9].

Beyond production losses, HS activates the hypothalamic–pituitary–adrenal (HPA) axis and increases circulating glucocorticoid concentrations, reflecting activation of systemic stress pathways [10-12]. Chronic exposure to elevated temperatures has also been associated with immune dysregulation and increased production of pro-inflammatory cytokines, potentially compromising maternal resilience during late gestation [4,13]. This stage is particularly critical because maternal metabolic instability may influence fetal development and postnatal growth performance [4,14,15]. Therefore, mitigation strategies during late gestation are essential not only to preserve sow welfare but also to safeguard offspring outcomes.

Several cooling strategies have been adopted in commercial systems to reduce thermal load, including enhanced ventilation, evaporative cooling, floor cooling, and drip applications [16-18]. Airflow-based systems promote convective heat loss by increasing air velocity around the animal, whereas drip cooling enhances evaporative heat dissipation through direct skin wetting [4,19]. Although these approaches are widely used, their comparative effectiveness under moderate heat stress conditions remains inconsistent across studies [19,20]. Moreover, limited information is available regarding their influence on chronic stress indicators, such as hair cortisol, and inflammatory biomarkers during late gestation [12,21].

In addition, the potential additive benefits of combining airflow and drip cooling systems have not been fully elucidated. Determining whether combined systems provide meaningful physiological or productive advantages beyond single-system application is essential for optimizing cost-effective thermal mitigation strategies in commercial herds [17,22]. Therefore, this study aimed to evaluate the individual and combined effects of fan and drip cooling systems on physiological responses, behavior, inflammatory status, and productive performance of sows during late gestation and lactation under elevated ambient temperature conditions.

Materials and Methods

Animals, housing, and experimental design

The experiment was conducted at the Teaching and Research Farm of Kangwon National University (Chuncheon, Kangwon-do, South Korea). The protocol for this study received approval by the Institutional Animal Care and Use Committee of Kangwon National University (Ethical code: 230524-1). A total of forty multiparous Landrace × Yorkshire sows (223.57 ± 25.80 kg) were enrolled from day 90 of gestation until weaning. Animals were randomly assigned to a completely randomized design in a 2 × 2 factorial arrangement with two fixed factors: fan (absence or presence) and drip cooling (absence or presence), resulting in four treatments: no cooling system (CON), fan (FN), drip cooling (DC) and fan + drip cooling (FN + DC). Each treatment included 10 sows, and the sow was considered the experimental unit. During the experimental period, sows were housed individually in pens measuring 2.00 × 0.60 m, consisting of a sow stall and piglet creep areas located on both sides of the stall. Pens were equipped with a solid concrete floor, a feeder, and two nipple drinkers (one for the sow and one for piglets). Sows were fed twice daily a corn–soybean meal diet (Table 1) formulated to meet or exceed NRC [23] requirements. Feed allowance was 2.9 kg/day during late gestation (days 90 to farrowing) and 3.0 kg/day during lactation. Water was provided *ad libitum* throughout the study.

Environmental and Physiological Measurements

Ambient temperature (T, °C) and relative humidity (RH, %) were recorded using data loggers (TM-305U, TENMARS, Taipei, Taiwan) positioned 1.2 m above floor level. Measurements were recorded at 10 min intervals during three periods of the day (10:00, 15:00, and 17:00 h). These data were used to calculate the temperature–humidity index (THI) according to the equation proposed by Dikmen et al. [24]:

$$THI = (1.8 \times T + 32) - [(0.55 - 0.0055 \times RH) \times (1.8 \times T - 26)]$$

Simultaneously, physiological responses were assessed twice daily at 11:30 and 13:00 h. Rectal temperature (RT) was measured using a veterinary digital thermometer (SK-1260, Sato, Tokyo, Japan) inserted approximately 7 cm into the rectum for 10 s [25]. Respiratory rate (RR), expressed as breaths per minute, was determined by visual observation and counting of flank movements for 60 s [26].

Sow and litter performance

Body weight (BW) and backfat thickness (BF) were measured on days 90 and 112 of gestation and at weaning. Backfat thickness was measured at 6.5 cm from the 10th rib using an ultrasound device (Agroscan A16, Angouleme, France) as described by Thiel-Cooper et al. [27]. Average daily feed intake (ADFI) during lactation was calculated by subtracting feed refusals from feed offered. Farrowing duration (h) and weaning-to-estrus interval (d) were recorded. Litter performance included total born, born alive, number of piglets weaned, piglet survivability (%), individual piglet weight at birth and weaning, and total litter weight at birth and weaning.

Behavioral observations

Behavior was monitored using overhead digital cameras (FIX Extreme Action Camera, China), with one camera installed per stall. Sows were recorded for 6 h per day (3 h in the morning and 3 h in the afternoon) from day 90 of gestation until day 21 of lactation. Video footage was analyzed using scan sampling methods to evaluate behaviors including drinking, standing, feeding, sitting, lying, and positional changes. Behavioral ethograms were adapted according to Tatemoto et al. [28].

Cortisol concentrations

Hair samples were collected at weaning by shaving the region between the neck and shoulder blades and subsequent analyses were conducted according to the procedures described by Tajudeen et al. [20]. Samples were washed three times with 2.5 mL isopropanol to remove external contaminants, dried in a forced-air oven at 35°C, and stored in aluminum foil until analysis. Cortisol extraction was performed using methanol, and concentrations were quantified using an ELISA kit (ADI-900-071, Enzo Life Sciences, Farmingdale, NY, USA) according to the manufacturer's instructions.

Inflammatory biomarkers

Blood was collected from the jugular vein using 10-mL disposable syringes into serum separator tubes. Samples were centrifuged at 1,000 × g for 10 min at 4°C. Serum was aliquoted into polypropylene tubes and stored at −20°C until analysis. Serum concentrations of TNF-α (MBS705977), IL-1β (MBS2021728), and IL-6 (MBS701700) were determined using ELISA kits (MyBioSource, Inc., San Diego, CA, USA) according to the manufacturer's instructions.

Statistical analysis

Data were analyzed using SAS (version 9.3; SAS Institute Inc., Cary, NC, USA). The experiment was conducted as a 2 × 2 factorial arrangement with two fixed factors: fan (presence or absence) and drip cooling (presence or absence), including their interaction. For performance, behavioral, cortisol, and inflammatory variables, data were analyzed using the MIXED procedure of SAS, with sow considered the experimental unit. Respiratory rate and rectal temperature were analyzed as repeated measures over time using the MIXED procedure with sow as the subject and day as the repeated factor. Differences were considered significant at $p \leq 0.05$, whereas values between 0.05 and 0.10 were considered a tendency.

Results

Temperature and humidity index and physiological measurements

The average ambient temperature, and THI during the late gestation are presented in Figure 1. Throughout the experimental period, the temperature ranged from 24°C to 29°C, with the highest value recorded on day 107 and the lowest on days 100 and 106. RH averaged 70.8%, peaking at 74.6% on day 107. The daily average THI varied between 72 and 80, with a mean of 76. At 90 days of gestation, no significant differences between the treatments were observed in RR (Figure 2). However, from days 107 to 110, CON exhibited higher ($p < 0.05$) RR, compared to other treatments. Notably, FN + DC treatment demonstrated the most favorable outcomes compared with CON and other cooling treatments. RT differed significantly among treatments from day 101 to 103 of gestation ($p < 0.05$), with CON showing the highest values, followed by FN, DC, and FN + DC (Figure 3). Notably, FN + DC led to the lowest RT among the treatments.

Sow and litter performance

No significant differences were observed for BW and BF on day 90 and 112 of gestation, as well as during the weaning period or loss during lactation. ADFI, farrowing duration, and weaning-to-estrus interval were also not significantly different among treatments during lactation (Table 2). Litter performance results (Table 3) showed no significant differences in total born, live-born, or piglet survival, however, the number of weaned piglets was higher ($p < 0.05$) in the FN treatment. Piglet birth and weaning weights, as well as litter weight at birth, did not differ between treatments, however, litter weight at weaning was higher ($p < 0.05$) in the FN treatment.

Behavior and cortisol concentrations

Significant differences ($p < 0.05$) were observed for drinking, standing, position changes, and lying behaviors (Table 4). Sitting and feeding behaviors were not affected by the treatments. Cortisol concentrations were significantly lower ($p < 0.05$) in the FN and FN + DC compared to CON treatment (Figure 4). CON group showed the highest cortisol concentration among the treatments, whereas FN and FN + DC treatments showed the lowest concentrations without significant differences between them. The DC treatment did not differ significantly from other treatments.

Inflammatory response

Among the inflammatory markers, the concentration of TNF-α was significantly ($p < 0.05$) affected by FN treatment compared to CON treatment with the lowest concentration observed in FN + DC treatment (Figure 5a). The group under DC treatment showed an intermediate value, which was not significantly different from the other cooling systems or CON treatment. No significant differences were observed for IL-1β or IL-6 concentrations between the treatments (Figure 5b, 5c).

Discussion

Heat stress represents one of the major environmental challenges affecting sow productivity and welfare, particularly during late gestation when metabolic heat production increases due to fetal growth and preparation for lactation [7,8,29]. In the present study, ambient temperature and relative humidity resulted in elevated THI values, indicating that the sows were exposed to thermal conditions above their thermoneutral zone. According to Wegner et al. [9], THI values above 74 can impair reproductive and growth performance in sows. Therefore, the environmental conditions observed in this study confirm that the animals experienced heat stress, supporting the evaluation of cooling systems as mitigation strategies [18,22].

Consistent with the environmental challenge, RR and RT responded to the cooling treatments, validating their importance as physiological indicators of thermal stress in pigs [32]. RR increased under higher ambient temperatures, reflecting activation of evaporative heat dissipation through panting, a primary thermoregulatory mechanism in swine [19,22,31]. However, the effects of cooling systems on RR were not consistently observed throughout the entire experimental period. Significant differences between treatments were detected during specific days of late gestation (days 107-110), indicating that the magnitude of the cooling response may depend on temporal fluctuations in environmental conditions or physiological status. Whitin these periods, the combined cooling system (FN + DC) resulted in lower RR compared with the CON, whereas FN and DC showed intermediate responses without consistent differences between them. These findings suggest that both airflow and evaporative cooling may contribute to heat dissipation, although their effectiveness appears to be context-dependent rather than uniform across time.

Similarly, RT values reflected the efficiency of the treatments in maintaining internal heat balance. Differences in RT were observed during days 103 to 103 of gestation, with lower values observed in DC and FN + DC treatments compared with CON. This pattern indicates that cooling interventions may influence thermoregulation under specific environmental or physiological conditions rather than throughout the entire period. The reduction observed in RT may be related to evaporative heat loss from the skin surface, as water applied to the skin surface evaporates and absorbs latent heat from the body, facilitating heat dissipation and lowering body temperature [32,33]. When combined with airflow, this process may be enhanced due to increased evaporation efficiency. Similar results have been reported by Romanini et al. [19] who observed improved thermoregulation in lactating sows exposed to combined ventilation and evaporative cooling systems.

Beyond the immediate physiological responses reflected by RR and RT, cortisol was analyzed to assess the impact of the treatments on the sows' welfare. Hair cortisol is a reliable biomarker of chronic stress, as it reflects cumulative hormonal exposure over extended periods rather than acute fluctuations [21]. In the present study, the highest cortisol concentrations were observed in the CON group, indicating heightened chronic stress in unmitigated thermal environments. In contrast, FN sows exhibited the lowest hair cortisol levels, potentially due to enhanced convective heat loss driven by higher air velocity [18,19,34]. Consequently, FN may provide a more stable microclimate, reducing both physiological strain and chronic stress responses.

Complementing these physiological findings, behavioral data showed that sows in the FN and FN + DC groups spent more time lying, with a reduction in drinking frequency, standing, and positional changes compared to the CON. These behavioral patterns are consistent with strategies to reduce metabolic heat production and facilitate heat dissipation [18,35]. Specifically, the decrease in standing behavior suggests lower endogenous heat expenditure, as standing requires greater muscular activity [17,35]. Conversely, the increased incidence of positional changes observed in the DC group likely represent attempts to maximize body surface exposure to water droplets and enhance evaporative efficiency. Therefore, behavioral responses can be interpreted as adaptive strategies that may vary depending on environmental conditions and the specific cooling system applied. These adjustments are consistent with previous reports of pigs modifying posture to optimize the thermoregulatory mechanisms [20,26].

Heat stress is known to impair sow productivity by reducing voluntary feed intake and inducing negative energy balance [36]. However, in the present study, cooling treatments did not significantly influence sow body weight, backfat thickness, or ADFI. These results suggest that the level of heat stress experienced during the experimental period may not have been sufficiently severe to result in severe metabolic alterations in sow performance. Despite the absence of significant effects on sow performance, fan-based cooling was associated with an increased number of weaned piglets and greater litter weight at weaning compared with CON. However, the number of total born, live-born, and piglet survival, were not significantly affected. These findings indicate that improved maternal thermal comfort may positively influence piglet survival and growth [9,37]. Heat stress during late gestation and lactation has been associated with impaired placental function, reduced milk production, and decreased piglet viability [4,14,38]. Therefore, mitigating thermal stress may indirectly support improved litter performance by preserving maternal physiological homeostasis.

Inflammatory responses represent another important consequence of heat stress. Exposure to elevated temperatures can stimulate immune activation and increase circulating concentrations of pro-inflammatory cytokines such as TNF-α, IL-1β, and IL-6 [10,12,13]. In the present study, fan-based cooling reduced TNF-α concentrations compared with the control treatment, suggesting that improved thermal conditions may attenuate inflammatory activation in heat-stressed sows. In contrast, IL-1β and IL-6 concentrations were not significantly affected by cooling treatments. The absence of changes in IL-1β and IL-6 may be related to the moderate level of heat stress or to differences in sensitivity among cytokines to environmental challenges [12,31].

Overall, the results demonstrate that cooling systems can influence physiological, behavioral, and selected productive responses in late-gestation sows exposed to elevated ambient temperature. However, these effects were not consistently observed across all variables or time points, indicating that the responses to cooling strategies are variable and context dependent. The combined FN + DC system showed greater reductions in thermoregulatory indicators during specific periods, whereas fan-based cooling appeared to be associated with lower chronic stress indicators and selected improvements in litter outcomes. Taken together, these findings highlight the potential of practical cooling strategies to mitigate some effects of heat stress, while also emphasizing that their impact may vary depending on environmental conditions and duration of exposure.

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Tables

Table 1. Formula and chemical composition of experimental basal diets (as-fed basis)

Item	
Ingredient (%)	
Corn	48.89
Whey powder	4.00
Dehulled soybean meal	7.79
Soy oil	3.76
Wheat bran	20.13
Distillers dried grains with soluble	12.00
Salt	0.50
Tricalcium phosphate	1.14
Limestone	1.05
DL-Methionine (98%)	0.02
L-Lysine (78.8%)	0.21
L-Tryptophan (10%)	0.11
L-Threonine (98.5%)	0.05
Choline-chloride (50%)	0.10
Vitamin premix[1]	0.10
Mineral premix[2]	0.10
Phytase	0.05
Total	100.00
Chemical composition (%)	
Metabolizable energy (Kcal/kg)	3,140
Crude protein	14.00
Calcium	0.82
Available phosphorus	0.38
Crude fiber	4.50
Standardized ileal digestible Lysine	0.58
Standardized ileal digestible Methionine	0.22
Standardized ileal digestible Methionine + Cysteine	0.42
Standardized ileal digestible Threonine	0.42
Standardized ileal digestible Tryptophan	0.13

[1]Supplied per kilogram of vitamin premix: 12,000,000 IU vitamin A, 2,400,000 IU vitamin D_3, 132,000 IU vitamin E, 1,500 mg vitamin K_3, 3,000 mg vitamin B_1, 11,250 mg vitamin B_2, 3,000 mg vitamin B_6, 45 mg vitamin B_{12}, 36,000 mg pantothenic acid, 30,000 mg niacin, 600 mg biotin, 4,000 mg folic acid.

[2]Supplied per kilogram of mineral premix: 80,000 mg Fe, 170 mg Co, 8,500 mg Cu, 25,000 mg Mn, 95,000 mg Zn, 140 mg I, 150 mg Se.

Table 2. Effects of different cooling systems on sows performance under high ambient temperature

Cooling system	CON	FN	DC	FN + DC	SEM	p-value		
						DC	FN	DC × F
BW, kg								
D 90	222.27	225.27	219.57	227.17	12.08	0.963	0.539	0.789
D 112	238.42	242.28	236.28	242.73	11.94	0.921	0.545	0.879
Weaning	202.89	206.47	200.84	206.80	11.96	0.920	0.576	0.889
Loss during lactation	35.53	35.81	35.44	35.93	0.56	0.970	0.337	0.792
BF, mm								
D 90	21.14	21.40	21.19	21.32	0.32	0.964	0.398	0.770
D 112	21.39	21.67	21.48	21.57	0.33	0.983	0.431	0.707
Weaning	15.45	15.57	15.48	15.47	0.28	0.876	0.794	0.730
Loss during lactation	5.95	6.10	5.99	6.11	0.19	0.848	0.341	0.893
ADFI, kg/d								
During lactation, kg	5.57	5.55	5.60	5.54	0.11	0.877	0.603	0.814
Farrowing duration, h	4.52	4.81	4.71	4.68	0.27	0.876	0.500	0.407
Weaning to estrus interval, d	5.80	5.50	5.60	6.00	0.54	0.679	0.897	0.365

CON, control; FN, fan; DC, drip cooling; FN+DC, fan + drip cooling; BW, body weight; BF, backfat thickness; ADFI, average daily feed intake. [a,b] Means within a variable with no common superscript differ significantly ($p < 0.05$).

Table 3. Effects of different cooling systems on litter performance under high ambient temperature

Cooling system	CON	FN	DC	FN + DC	SEM	p-value		
						DC	FN	DC × F
Litter size, n								
Total born	14.00	14.30	14.10	14.20	1.16	0.966	0.809	0.904
Born alive	12.00	13.10	12.80	13.60	0.88	0.302	0.135	0.811
Weaned	10.70[b]	12.10[a]	11.70[ab]	12.40[a]	0.68	0.186	0.036	0.472
Survivability of piglets, %	89.49	93.22	91.49	91.97	2.96	0.859	0.322	0.442
Piglet weight, kg								
At birth	1.34	1.33	1.33	1.31	0.05	0.760	0.664	0.971
At weaning	6.18	5.96	6.09	5.97	0.21	0.795	0.259	0.755
Litter weight, kg								
At birth	15.99	17.27	16.93	17.69	0.91	0.294	0.122	0.687
At weaning	65.82[b]	71.71[a]	70.65[a]	73.60[a]	2.88	0.107	0.036	0.473

CON, control; FN, fan; DC, drip cooling; FN+DC, fan + drip cooling. [a,b] Means within a variable with no common superscript differ significantly ($p < 0.05$).

Table 4. Effects of different cooling systems on behavior characteristics under high ambient temperature

Cooling systems	CON	FN	DC	FN + DC	SEM	p-value		
						DC	FN	DC × F
Drinking, %	10.10[a]	8.59[b]	9.54[a]	8.29[b]	0.40	0.135	<0.001	0.652
Standing, %	15.74[a]	11.56[b]	14.73[a]	11.43[b]	0.50	0.113	<0.001	0.223
Position change, times	8.29[a]	6.22[b]	7.93[a]	6.11[b]	0.37	0.380	<0.001	0.640
Lying, %	75.23[b]	80.84[a]	76.73[b]	81.14[a]	0.68	0.070	<0.001	0.222
Sitting, %	9.88	9.95	10.52	9.53	0.44	0.778	0.409	0.110
Feeding, %	0.60	0.63	0.55	0.67	0.10	0.886	0.287	0.521

CON, control; FN, fan; DC, drip cooling; FN+DC, fan + drip cooling. [a,b] Means within a variable with no common superscript differ significantly ($p < 0.05$).

Figures captions

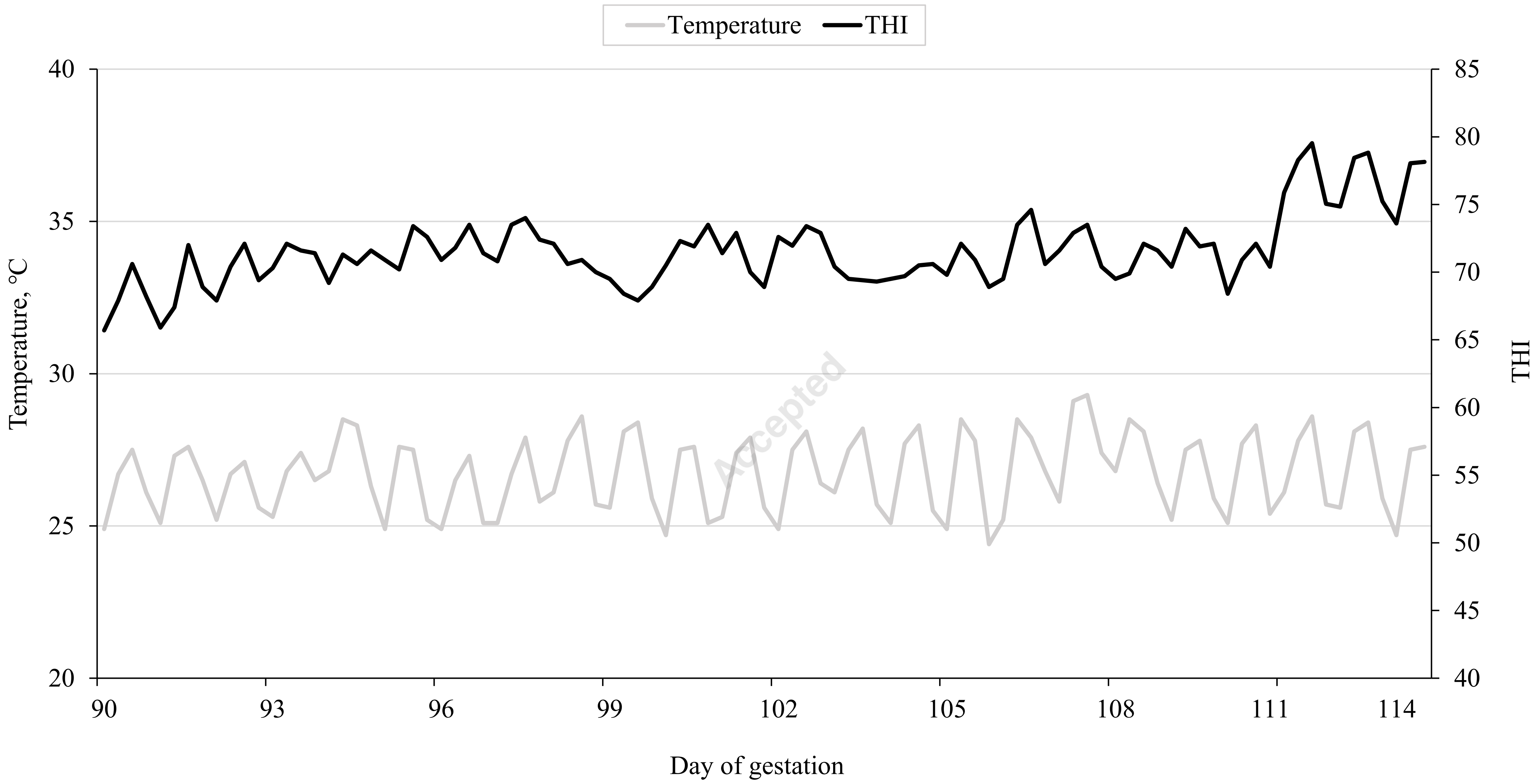
Fig. 1. Daily means of ambient temperature (black line) and THI (gray line) representing the variation of outcomes for both parameters during the experimental period. THI, temperature-humidity index.

Fig. 2. Effects of different cooling systems on respiratory rate of sows during late gestation period under high ambient temperature. CON, control; FN, fan; DC, drip cooling; FN+DC, fan + drip cooling. Asterisks (*) indicate statistical significance ($p < 0.05$).

Fig. 3. Effects of different cooling systems on rectal temperature of sows during late gestation period under high ambient temperature. CON, control; FN, fan; DC, drip cooling; FN+DC, fan + drip cooling. Asterisks (*) indicate statistical significance ($p < 0.05$).

Fig. 4. Effects of different cooling system on hair cortisol of sows during late gestation period under high ambient temperature. CON, control; FN, fan; DC, drip cooling; FN+DC, fan + drip cooling. ^{a,b} Means within a variable with no common superscript differ significantly ($p < 0.05$).

Fig. 5. Effects of different cooling systems on TNF- α, IL-1β, IL-6 of sows during late gestation period under high ambient temperature. CON, control; FN, fan; DC, drip cooling; FN+DC, fan + drip cooling. ^{a,b} Means within a variable with no common superscript differ significantly ($p < 0.05$). a) TNF- α; b) IL-1β; c) IL-6.



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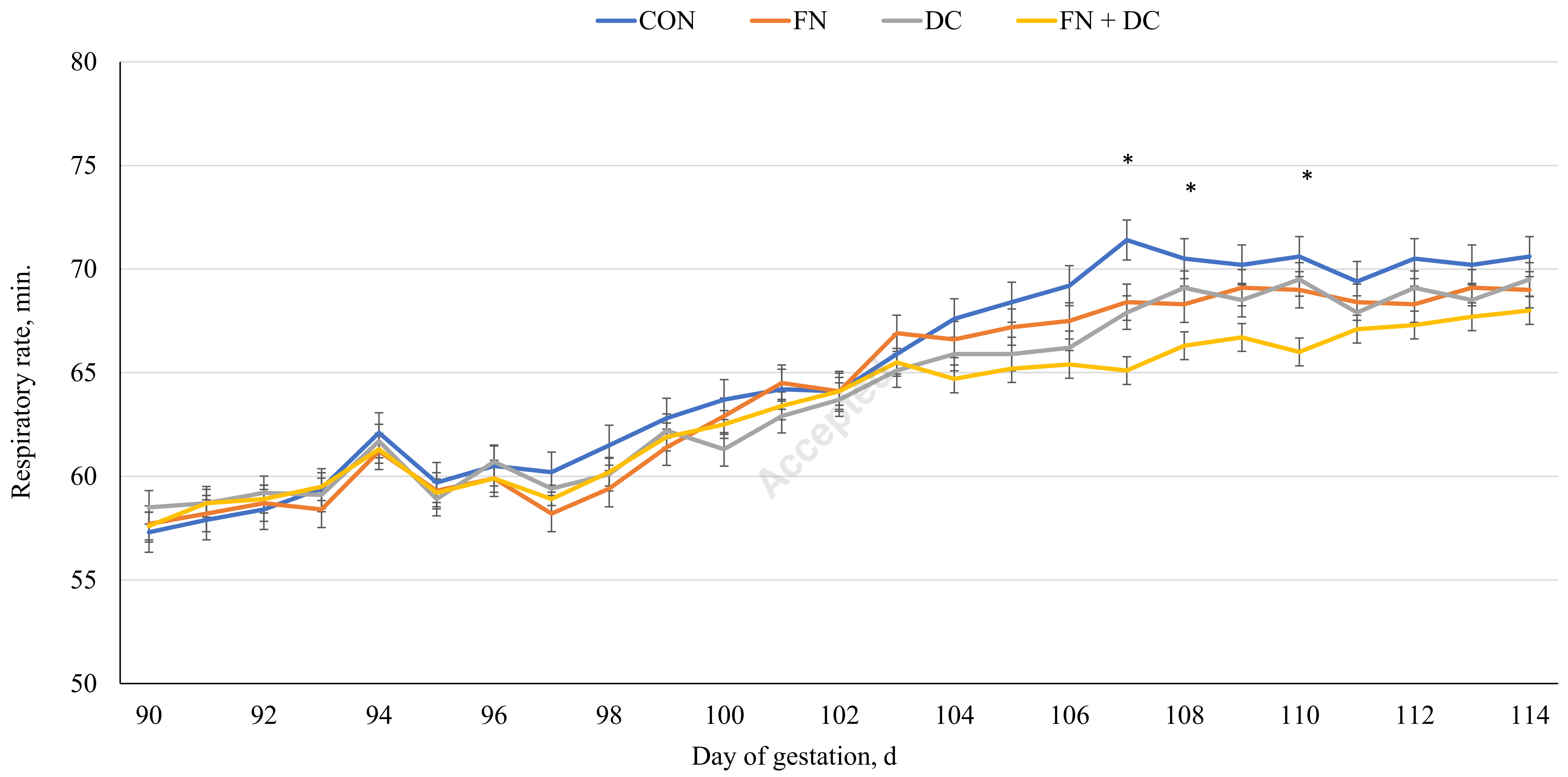

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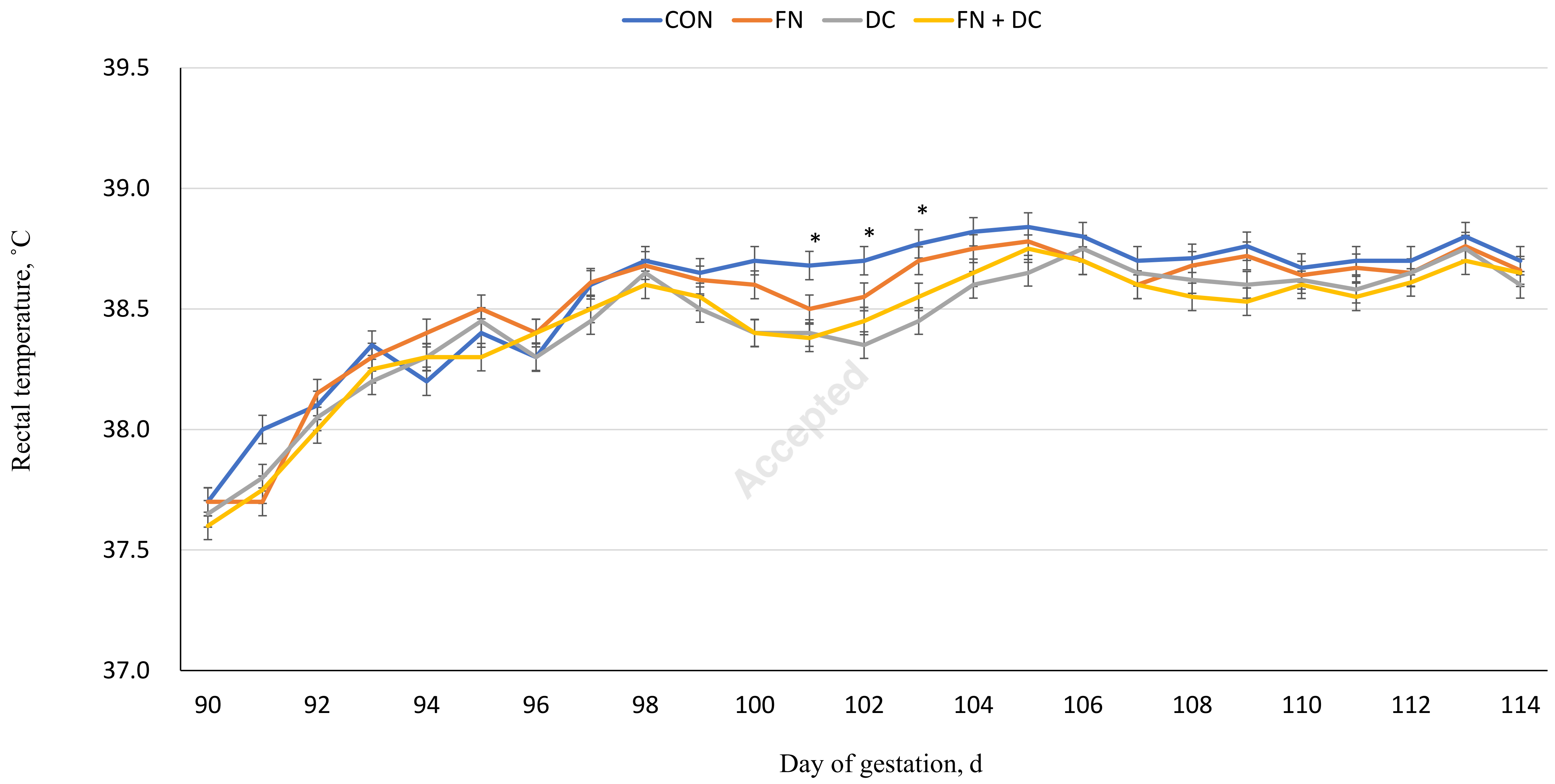

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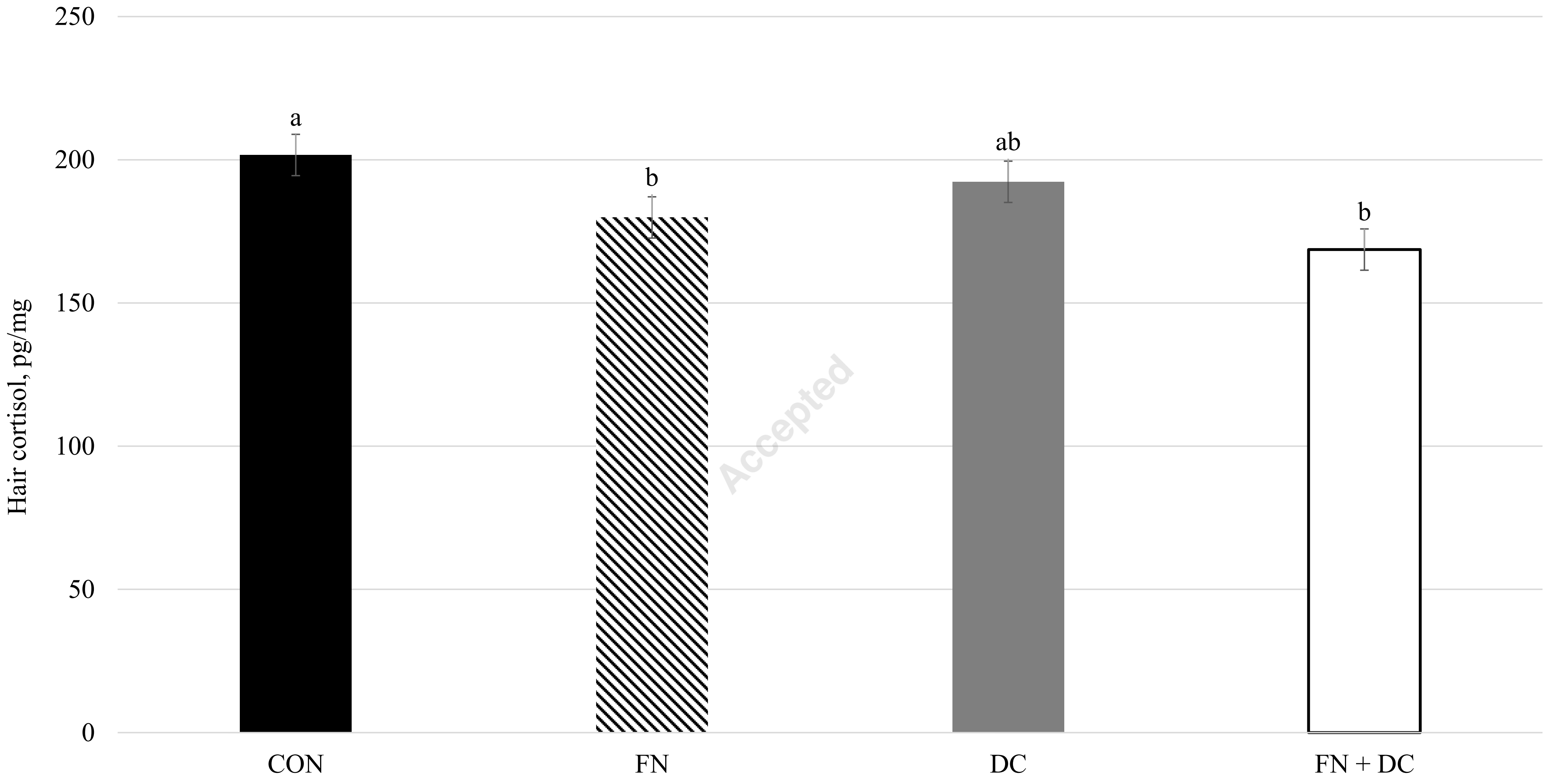

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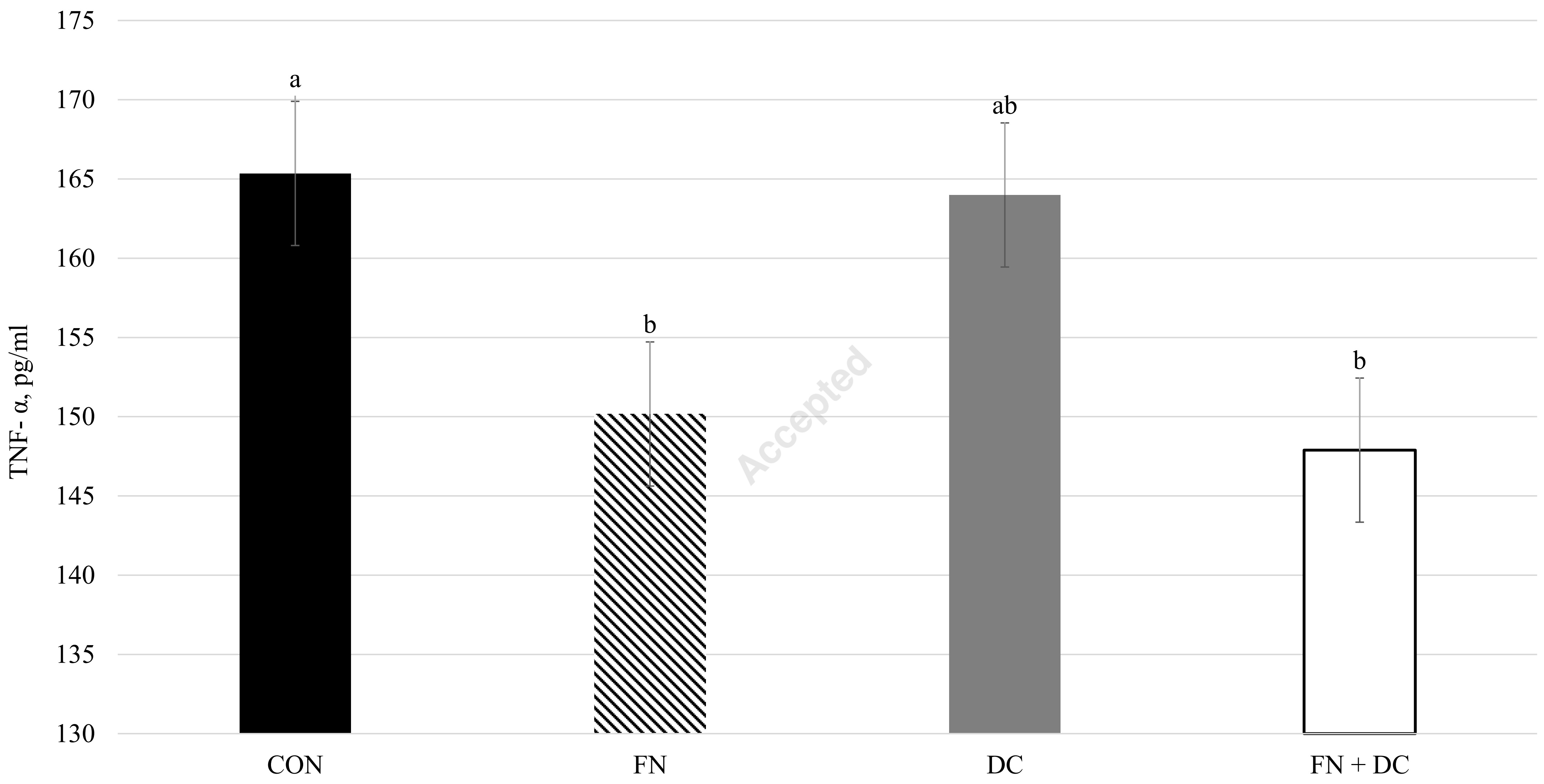
a)



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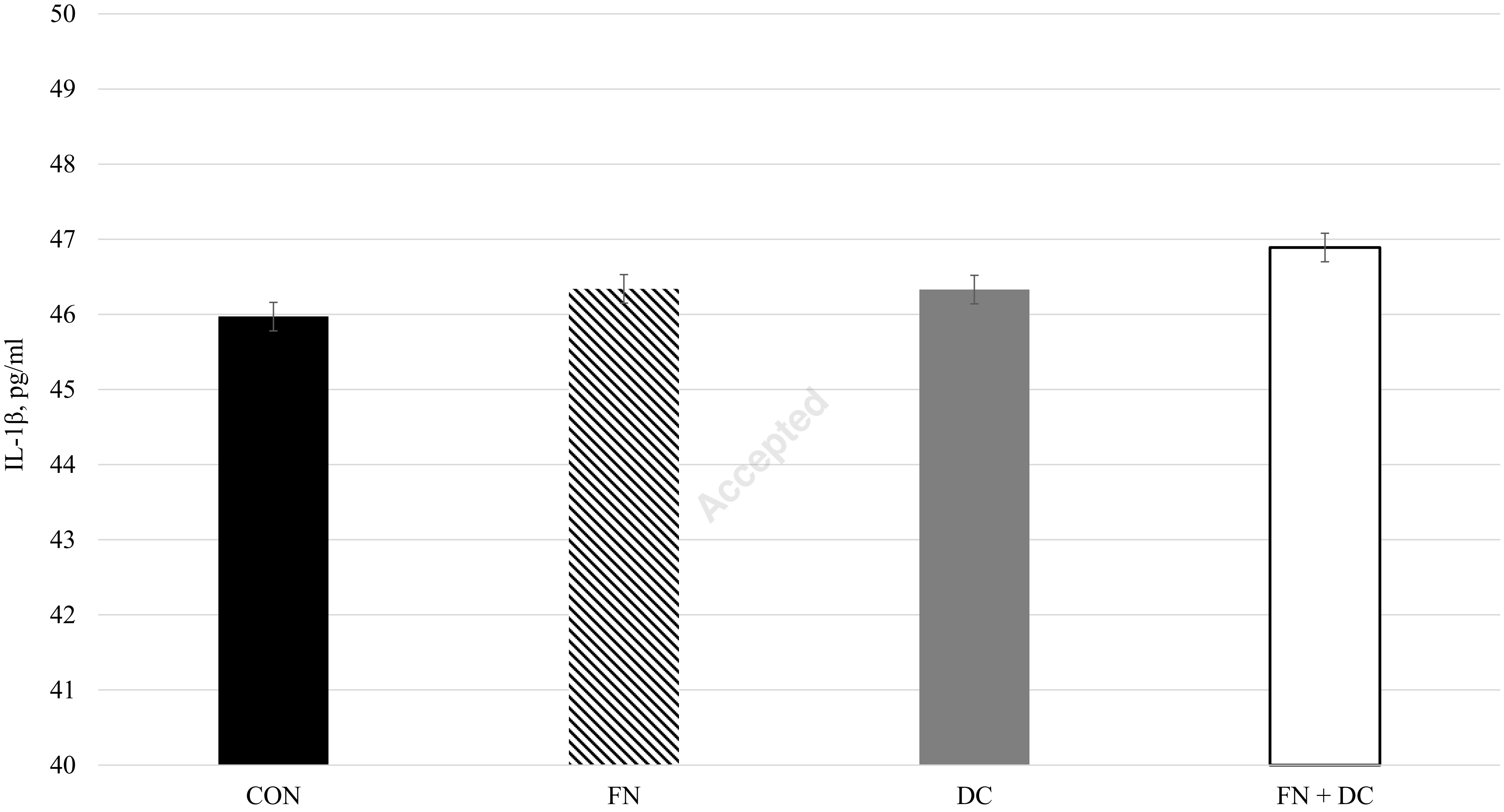
b)



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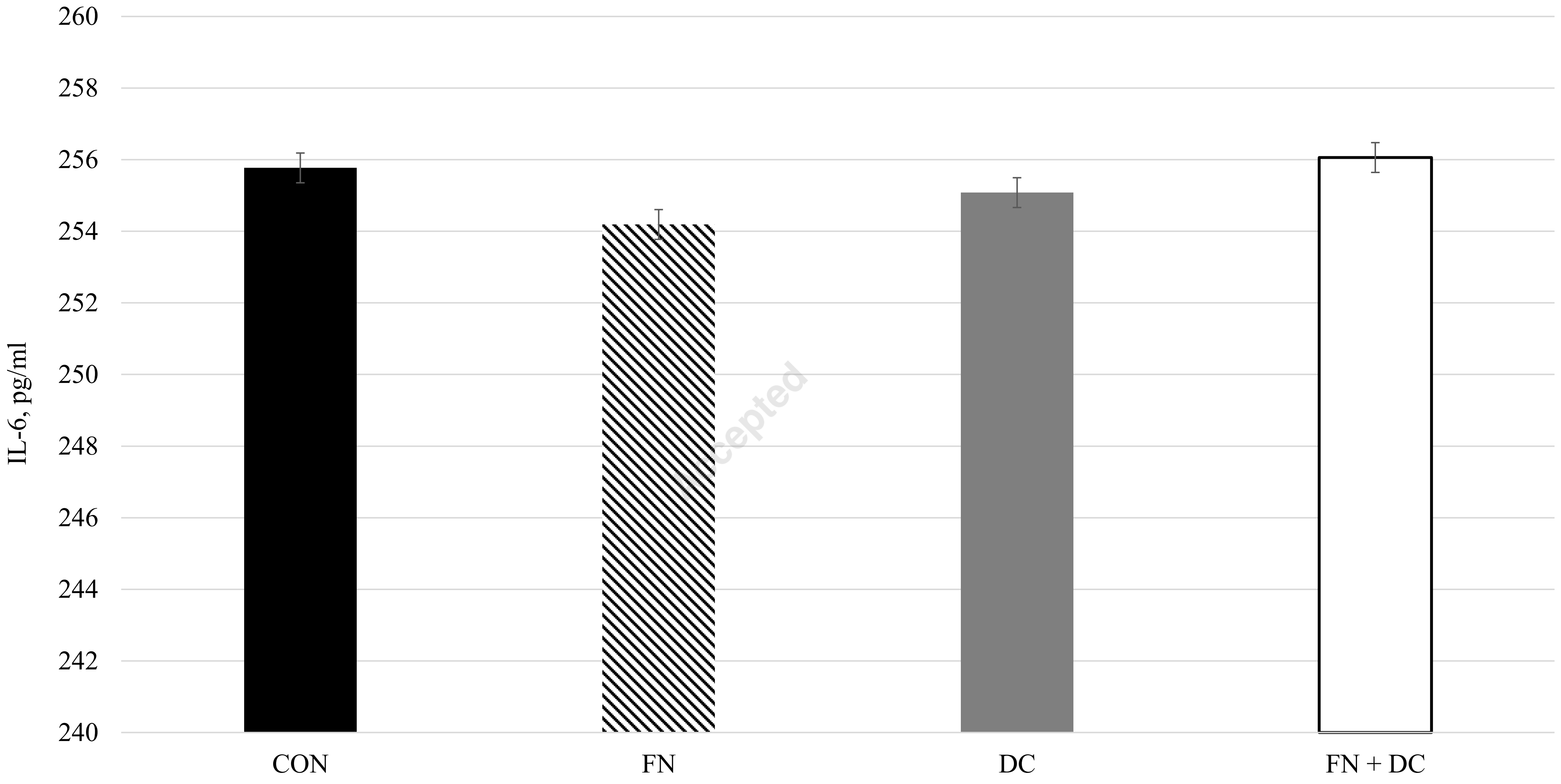
c)



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