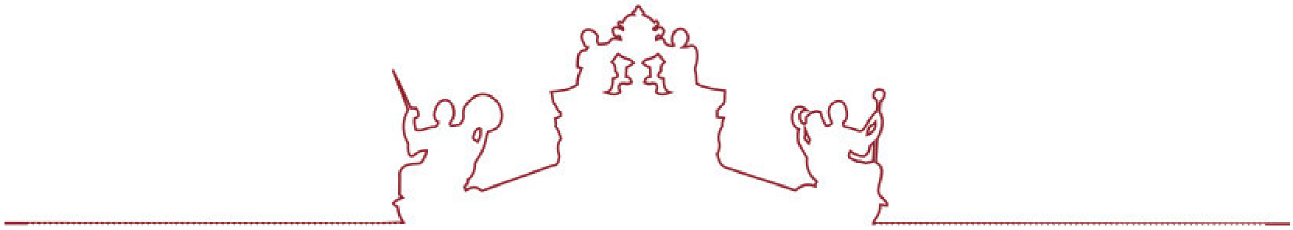

Universidade de Évora - Instituto de Investigação e Formação Avançada
Universidade do Algarve - Faculdade de Ciências e Tecnologia

Programa de Doutoramento em Ciências Agrárias e Ambientais

Tese de Doutoramento

Effect of housing environmental conditions on productive performances and welfare of growing-finishing pigs. Precision livestock farming contribution.

José Carlos Silva Rico

Orientador(es) | Rui Miguel Charneca
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Évora 2024

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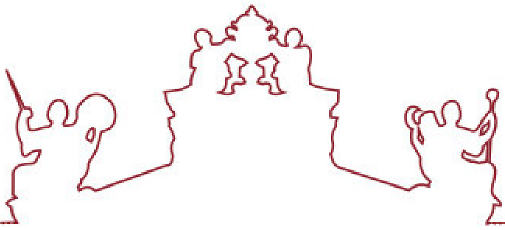

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Évora 2024

Aos meus pais.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS GLOSSARY

ADG – Average Daily Gain

ANN – Artificial Neural Networks

BW – Body Weight

CCD – Charge-Coupled Device

CH_4 – Methane

CIGR – Comission Internationale du Génie Rural

CO – Carbon Monoxide

CO_2 – Carbon Dioxide

CRH – Corticotropin-Releasing Hormone

EFS – Electronic Feed Station

FAWC – Farm Animal Welfare Council

FCR – Feed Conversion Rate

FIPM – Feed Intake Per Meal

FI – Feed Intake

GE – Gross Energy

GHG – Greenhouse Gas

HRF – Heart Rate Frequency

HPA – Hypothalamic-Pituitary-Adrenal

ICT – Information and Communication Technology

IoAT – Internt of Animal Things

IoE – Internet of Everything

IoT – Internet of Things

IT – Information Technology

LCT – Lower Critical Temperature

LF-RFID – Low Frequency RFID

LWSI – Livestock Weather Safety Index

ME – Metabolizable Energy

NH_3 – Ammonia

NE – Net Energy

NM – Number of Meals

PI – Proximity Index

PLF – Precision Livestock Farming

RFID – Radio-Frequency Identification

RH – Relative Humidity

RMSE – Root Mean Square Error

RR – Respiration Rate

R^2 – Determination Coefficient

RH_i – Indoor RH

RMSE – Root Mean Square Error

TCI – Thermal Comfort Indices

THI – Temperature-Humidity Index

T – Temperature

T_i – Indoor Temperature

TN – Thermoneutral

TNZ – Thermoneutrality Zone

TM – Time Per Meal

UCT – Upper Critical Temperature

UHF-RFID – Ultra-High-Frequency RFID

WCT – Wind Chill Temperature

WQP – Welfare Quality Project

$\bar{X}$ – Mean

Y_i – Observed Value

Y'_i – Predicted Value

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ABSTRACT

This thesis aimed to study the effect of housing environmental conditions on the productive performances and welfare of growing-finishing pigs through the support of precision livestock farming (PLF) tools. Three experiments were conducted, each involving eight Piétrain x TN60 females. Three distinct environmental conditions were simulated in an environmental controlled room – winter (W), thermoneutrality (TNZ) and summer (S). The studied performance parameters were feed intake (FI), average daily gain (ADG) and feed conversion rate (FCR), while the behavioural parameters were the number of meals (NM), time per meal (TM), feed intake per meal (FIPM) and lying and resting behaviour (Proximity Index, PI). In W condition, the growing-finishing pigs presented the lowest ADG and the highest FCR, NM and PI. During the TNZ condition, the animals demonstrated the highest performance across several metrics, achieving the highest FI, ADG and FIPM. In the S condition, the pigs experienced the lowest FI, FCR, TM, FIPM and PI, but the highest NM. The use of PLF tools allowed a better understanding the interactions between environment and animal's performance/behaviour prospecting its usefulness to pig production management and optimisation.

Key-words: Precision livestock Farming; Pigs; Environmental control; Animal welfare; Monitoring.

Título: Efeito das condições ambientais de alojamento sobre as performances produtivas e bem-estar de suínos em fase de crescimento e engorda. O contributo da zootecnia de precisão.

RESUMO

Esta tese teve como objetivo estudar o efeito das condições ambientais de alojamento no desempenho produtivo e bem-estar dos suínos em fase de crescimento e engorda com recurso a ferramentas de zootecnia de precisão (PLF). Foram realizados três ensaios, utilizando em cada um oito fêmeas Piétrain x TN60. Foram simuladas três condições ambientais distintas numa sala de ambiente controlado – inverno (W), termoneutralidade (TNZ) e verão (S) – com o objetivo de analisar os parâmetros de desempenho produtivo e comportamentais dos suínos. Os parâmetros de desempenho produtivo estudados incluíram a ingestão alimentar (FI), o ganho médio diário (ADG) e o índice de conversão alimentar (FCR), enquanto os parâmetros comportamentais compreenderam o número de refeições (NM), o tempo por refeição (TM), o consumo de alimento por refeição (FIPM) e o comportamento de repouso e descanso (Índice de Proximidade, PI). Na condição de inverno, os animais apresentaram o menor ADG e o maior FCR, NM e PI. Durante a condição TNZ, os animais demonstraram o melhor desempenho em várias métricas, alcançando o maior FI, ADG e FIPM. Na condição de verão, os animais exibiram o menor FI, FCR, TM, FIPM e PI, mas o maior NM. O uso de ferramentas de PLF permitiu uma melhor compreensão das interações entre o ambiente e o desempenho/comportamento dos animais, prospetando a sua utilidade para a gestão e otimização da produção de suínos.

Palavras-chave: Zootecnia de precisão; Suínos; Condicionamento ambiental; Bem-estar animal; Monitorização.

Título: Efeito das condições ambientais de alojamento sobre as performances produtivas e bem-estar de suínos em fase de crescimento e engorda. O contributo da zootecnia de precisão.

RESUMO ALARGADO

Introdução:

A maior parte da produção mundial de suínos ocorre em sistemas intensivos que, apesar da sua eficiência, têm suscitado preocupações significativas ao nível dos seus impactes ambientais, bem como no desempenho, saúde e bem-estar dos animais. Deste modo, para ser competitiva e responder às exigências dos consumidores atuais, na produção intensiva de suínos torna-se fundamental otimizar a produtividade/desempenho, saúde e bem-estar animal.

Em resposta a estes desafios, as ferramentas de zootecnia de precisão (PLF) tornaram-se indispensáveis nas práticas de produção animal atuais. Estas ferramentas facilitam a monitorização e controlo de forma detalhada não só dos parâmetros ambientais, mas também de aspetos chave como a produtividade, crescimento, saúde, padrões comportamentais individuais ou a nível de grupo, etc.

Materiais e Métodos:

De modo a avaliar o impacto das condições ambientais no desempenho e bem-estar dos suínos em fase de crescimento e engorda, foram realizados três trabalhos experimentais, cada um com 8 fêmeas Piétrain x TN60 com peso vivo compreendido entre 52.8 ± 3.1kg, numa sala de ambiente controlado onde a temperatura do ar (T) e a humidade relativa (RH) foram monitorizadas e controladas permanentemente. Em cada ensaio, foi simulada uma condição ambiental diferente: inverno (W: T=10 ± 2°C; RH: 80%), termoneutralidade (TNZ: T=18 ± 2°C; RH: 70%) e verão (S: T=30 ± 2°C; RH: 60%).

Os parâmetros de desempenho produtivo estudados incluíram a ingestão alimentar (FI), o ganho médio diário (ADG) e o índice de conversão alimentar (FCR), enquanto os parâmetros comportamentais compreenderam o número de refeições (NM), o tempo por refeição (TM), o consumo de alimento por refeição (FIPM) e o comportamento de repouso e descanso.

Para este último, foi desenvolvido um Índice de Proximidade (PI) com o intuito de procurar avaliar o nível de dispersão dos animais no parque, baseado num algoritmo de visão artificial. O comportamento alimentar foi avaliado através de uma máquina de alimentação automática que, através de um sistema RFID, permitiu a monitorização e controlo individual do alimento fornecido e ingerido, bem como o número e duração das visitas à máquina de alimentação. Este equipamento permitiu também monitorizar a cada visita ao comedouro, o peso vivo dos animais, o que possibilitou, através de cálculos auxiliares, avaliar os parâmetros de desempenho produtivo.

De modo a avaliar a influência do peso corporal (BW) dos suínos nos parâmetros estudados, foram considerados dois períodos: período de crescimento, de 55kg a 76kg de peso vivo e período de engorda, de 76kg a 97kg.

Resultados:

O estudo dos parâmetros produtivos revelou diferenças significativas entre todas as condições ($P < 0.001$) na ingestão alimentar (FI), com o valor médio mais elevado na condição TNZ (2.78 ± 0.07 kg) e o mais baixo na condição S (1.95 ± 0.06 kg). A FI também foi influenciada pelo período, observando-se valores mais elevados no período de engorda. O ganho médio diário (ADG) foi significativamente diferente entre as condições ($P < 0.001$), verificando-se o valor mais alto na TNZ (947 ± 32 g) e mais baixo na condição W (807 ± 31 g). Este parâmetro foi influenciado pelo período, apresentando também valores mais elevados no período de engorda do que no de crescimento, no entanto, não foram observadas diferenças significativas. O índice de conversão alimentar (FCR) foi mais baixo na condição S (2.39 ± 0.08), indicando uma melhor eficiência de conversão alimentar ($P < 0.001$) nesta condição, quando comparada com as outras. A FCR foi significativamente influenciada pelo período na condição TNZ.

O número de refeições (NM) não foi influenciado nem pela condição, nem pelo período, apresentando valores médios que variaram entre 13 ± 1 a 15 ± 1 visitas. No entanto, o tempo por refeição (TM) foi significativamente mais longo na condição W (8.1 ± 0.5 min/refeição), quando comparado com a condição S (5.8 ± 0.5 min/refeição), enquanto que na TNZ foi observado um valor intermediário (7.3 ± 0.5 min/refeição). Este parâmetro não foi significativamente influenciado pelo período. O consumo de alimento por refeição (FIPM) foi significativamente diferente ($P < 0.001$) entre a condição TNZ (224 ± 10 g/refeição) e a condição S (151 ± 9 g/refeição). Este parâmetro também foi influenciado pelo período, registando-se um aumento significativo do período de crescimento para o de engorda apenas na condição TNZ.

Da análise a uma possível interação entre o NM e a FIPM ao longo do período de crescimento e engorda, verificou-se que, durante o período de crescimento na condição S, os animais aumentaram o NM e reduziram significativamente a FIPM (15 x 139), enquanto na condição W se observou uma redução do NM e da FIPM (14 x 174), embora não significativa em comparação com a condição TNZ (15 x 190). Por outro lado, durante o período de engorda na condição S, verificou-se um aumento do NM e uma diminuição significativa da FIPM (18 x 156), enquanto que na condição W ocorreu uma diminuição do NM e da FIPM (não significativa) em comparação com a condição TNZ.

Os comportamentos de repouso e descanso foram analisados com recurso ao Índice de Proximidade (PI) e os resultados mostraram um PI significativamente mais elevado na condição W (0.95 ± 0.02), quando comparado com a condição TNZ e S, onde foi observado nesta última o PI mais baixo (0.45 ± 0.02).

Considerações finais:

De um modo geral, as condições ambientais influenciaram o desempenho e bem-estar de suínos em fase de crescimento e engorda. Estes resultados podem ser explicados pelas respostas metabólicas e comportamentais dos suínos às condições ambientais expostas durante o período de crescimento e engorda em cada condição ambiental simulada.

As condições de TNZ favorecem a FI, a FIPM e o ADG, mas não o FCR, enquanto condições mais extremas levam a uma menor FI, TM e PI em ambientes mais quentes (condição S) e a um maior TM e PI em ambientes mais frios (condição W). Os resultados são discutidos e as razões explicativas são expostas nesta tese, juntamente com a potencial contribuição das ferramentas de PLF não só para o apoio à investigação, como também nas decisões técnicas ao nível da exploração.

1. INTRODUCTION

It is estimated that the world population will increase around 30% by 2050, reaching over 9 billion of habitants and consequently, the demand for agri-food products will increase by 70%, with the human consumption of animal-origin foods expected to double from 258 to 455 million tons (Rojas-Downing et al., 2017). Thus, in order to meet the demand for animal protein, agricultural systems are faced with the need to increase their production through intensification systems (Berckmans, 2014).

Intensive production systems, characterized by high animal density, are those where the majority (90%) of pigs worldwide are produced, using improved genotypes and highly developed and industrialized housing systems (Rodríguez et al., 2013). Simultaneously, there is a trend toward decreasing the number of farms, leading to an increase in the number of animals produced on the intensive farms that remain operational (Berckmans, 2014). In this sense, the main challenge foreseen in the near future for intensive animal production is the difficulty in monitoring and controlling the performance, health and welfare of animals in larger numbers (Berckmans, 2017).

Precision livestock farming emerges as a potential solution to these challenges, as it is defined as the application of engineering process technology principles in livestock management (Cruz and Baptista, 2006). Its applicability allows for monitoring not only the physical environment of facilities (microclimate/emissions), but also the animals' behavioural and physiological status, providing valuable insights that can enhance animal health, welfare and productivity (Fournel et al., 2017; Vranken and Berckmans, 2017).

Understanding the interaction between environmental conditions and animals' performance and welfare is critical. In this sense, it is necessary to know, on the one hand, the indoor environmental parameters and on the other hand, their effect on the animal. Factors such as air temperature, relative humidity, air quality (concentration of gases and dust), air velocity, noise and luminosity level have significant influence on animals, with a strong impact on their behavioural, physiological and immunological status (Cruz, 1997).

Air temperature is one of the most important environmental factors that influences pig performance. Thermal stress is one of the main sources of production losses in pig production systems, as it has a strong impact on performance parameters (feed intake, average daily weight gain and feed conversion ratio) (Pearce et al., 2013).

Due to their low heat dissipation capacity, to maintain a constant body temperature in hot conditions, pigs seek to reduce metabolic heat production more than other domesticated species (Renaudeau et al., 2014). For that, pigs use to present a decrease in their activity, an increase in water intake and a reduction in feed intake (Cruz, 1997; Godyń et al., 2020; Huynh et al., 2005b; Kim et al., 2021; Mayorga et al., 2019; Quiniou et al., 2000; Renaudeau et al., 2012). While heat stress is one of the main concerns in pig production, cold stress also significantly influences pig performance. Under low temperature conditions, pigs use to increase their activity and feed intake to increase heat production (Bus et al., 2021; Cruz, 1997; Govindasamy et al., 2022; Quiniou et al., 2000).

Despite the complexity of the interaction between animals and their surrounding environment (Banhazi et al., 2009), significant advancements have been made in technological tools over the past few decades. These tools enable more precise monitoring and management of environmental, physiological and behavioural parameters, contributing to a more efficient livestock production process (Fournel et al., 2017).

In the subsequent literature review, the environmental parameters within livestock facilities will first be identified and analysed. Following this, methods for effective monitoring and control of these parameters will be explained. The concept of animal welfare and its assessment methods will then be examined. Finally, the role of PLF in enhancing intensive production systems will be analysed, highlighting how this technology can monitor and control not only environmental parameters but also behavioural and physiological indicators, ultimately improving animal welfare.

2. LITERATURE REVIEW

2.1. Environmental Conditions on Growing-Finishing Pig facilities

Most pig production in the world is done in intensive systems, characterized by high animal density, using genetically improved breeds and developed and industrialized livestock facilities with closed structures (Rodríguez et al., 2013). In these systems animals are often subject to environmental conditions that can have a high impact on their behavioural, physiological and immunological status (Cruz, 1997; Gebreyes et al., 2014).

Knowing the environmental parameters that exist within a livestock facility is important for a correct livestock management, as this know-how allows to create conditions for animal welfare and also a more efficient and sustainable production system.

2.1.1. Environmental Parameters

Within the environmental parameters, those that are most relevant in pig production are the temperature, relative humidity, air velocity, luminosity, noise level and air quality (gases and dust concentrations).

2.1.1.1. Air Temperature

Air temperature is the most important environmental parameter within a livestock facility. Exposure to wide temperature fluctuations or extremes can result in health problems and/or behavioural, physiologic and morphologic changes which might negatively affect animal welfare and influence the overall performance in pigs (Chantziaras et al., 2020; NRC, 2011).

However, air temperature effects are dependent of other environment parameter that is relative air humidity (Zhou et al., 2022). To understand the impact of temperature on animals, specifically pigs, it is necessary to know their interactions and adaptive mechanisms. These issues will be addressed more prominently in Chapter 2.4.

According to Cruz and Baptista (2006), animals are a constant source of sensible and latent heat and contribute to change the value of temperature inside an animal facility. At the same time, pigs are homeothermic animals that maintain their body temperature within a certain range of temperatures. Therefore, animals should be housed within temperature ranges appropriate for each species, to which they can adapt with minimal stress and physiologic alterations (NRC, 2011).

Since the main goal inside an animal housing is to reach a situation of thermal balance, there are different studies that recommend temperatures between 15 and 25°C as the range of air temperatures where the pig, in the growing-finishing phase, can generally maximize its performances and welfare (Babot and Revuelta, 2009; Huynh et al., 2004; Morrow-Tesch et al., 1994).

2.1.1.2. Relative Humidity

Relative humidity is defined as the ratio between the amount of water vapor present in the air at a given temperature and the maximum amount it can hold at that temperature and pressure, expressed as a percentage (Albright, 1990; Cruz, 1997).

This is an important environmental parameter since the concentration of humidity at high levels is harmful to the health and comfort of animals. Previous investigations have indicated that the occurrence and prevalence of some infectious diseases are associated with ambient humidity (Xiong et al., 2017).

High humidity levels enhance the development of microorganisms on the surfaces of the facilities and equipment, which can increase the frequency and severity of certain pathogen infections and diseases as rheumatism or respiratory diseases (Baêta and Souza, 2010; Xiong et al., 2017)

In addition to the incidence of infectious diseases, relative humidity affects also animal bedding, which results in increased litter moisture and ammonia concentrations (Weaver and Meijerhof, 1991).

Therefore, the relative humidity must be kept below critical limits. However, the first difficulty is to define these values, since it depends on factors such as the animal species, its production stage and the ambient temperature (Cruz and Baptista, 2006). According to Babot and Revuelta (2009), 80% is accepted as the maximum value of moisture content that should exist inside an animal facility and 40% as the minimum value. In the case of growing and finishing pigs, different optimal values of relative humidity have been suggested by several authors. The recommended range of RH for growing-finishing pigs, as mentioned in the literature, varies between 50% and 70% (Cruz and Baptista, 2006; Salvador and Vidal, 2004).

2.1.1.3. Air Velocity

Air velocity is an important parameter that needs to be considered inside an animal facility because it affects the animals' status and is strictly related to ventilation.

Air velocity can affect pigs by regulating their body temperature and maintaining thermal comfort, which directly influences their behaviour and welfare. In low-temperature environments, increased air velocity may lead to thermal discomfort due to excessive body heat loss. Conversely, in hot conditions, appropriate air velocity aids in dissipating body heat, thereby reducing thermal stress and improving the productivity and welfare of pigs (Olczak et al., 2015).

Cooling the pigs during hot summer periods with increased air velocity is a well-known method used in growing-finishing facilities (Jeppsson et al., 2021). In this case, the air should be directed to the animals, increasing convection heat exchange, which translates into a feeling of freshness (Cruz and Baptista, 2006). On the other hand, in the winter situation, the cold air coming from outside must be prevented from reaching directly on the animals, which increases heat loss and also the risks of some diseases such as pneumonia (Stärk, 2000).

The acceptable values for the air velocity depend mainly on the outside and inside temperature. According to Cruz and Baptista (2006), the maximum values during winter should be 0.2 m/s in growing-finishing pigs. However, a 60 to 70 kg body weight pig could maintain a heat loss balance in a 10ºC and 20ºC environment even if the air velocity was raised from 0.2 m/s to 0.8 m/s (Song et al., 2013).

On the other hand, during the summer this value can exceed 0.4 m/s (Cruz and Baptista, 2006). According to Sällvik and Walberg (1984), the optimum convective heat loss for a 70 kg body weight pig in a confined housing system was induced by an air velocity of between 0.74-1.31 m/s when the indoor temperature was 28°C.

2.1.1.4. Air Quality

The main factors that influence the accumulation of gases inside livestock facilities are reduced or incorrect air ventilation rates (Baêta and Souza, 2010), high animal densities, lack of hygiene (agglomeration of faeces and urine on the floors) and poor waste removal systems (Barcellos et al., 2008).

Air quality in intensive production systems is directly related to the metabolism of pigs, which release heat, humidity and carbon dioxide (CO_2) from respiration (Sampaio, 2004). Diet composition is a factor that influences the amounts and types of emitted gases (Aarnink and Verstegen, 2007), since the waste deposited, resulting from the digestive process, also releases gases capable of causing human and animal discomfort, namely ammonia (NH_3), hydrogen sulfide (H_2S), carbon dioxide (CO_2) and methane (CH_4) (Cecchin et al., 2017). There are still other gases that are present in residual quantities they are not normally considered limiting for production (Baêta and Souza, 2010).

Gas concentration has been increasingly important in the analysis of animal welfare inside animal facilities since high concentrations of some of these gases, namely ammonia, can irritate the respiratory system and produce behavioural and physiological changes, reduce food consumption and weight gain, and possibly affect the health of animals and stockperson (Cecchin et al., 2017; Conti et al., 2021).

Based on European Directive laying down minimum standards for the protection of pigs (CD 2008/120/EC), in Portugal concentrations of some gases must be kept within limits that are not harmful to animals. These limits were established by the CIGR (*Commission Internationale du Génie Rural*), which recommends that the concentrations of the most common gases in the swine environment should not exceed 3000 ppm for CO_2, 20 ppm for NH_3, 10 ppm for CO and 0,5 ppm for H_2S (CIGR, 1994; Sampaio et al., 2006).

On the other hand, in addition to gases, there are other environmental contaminants in the air inside a livestock facility, such as dust (small particles suspended in the air with a diameter of less than 1 µm). According to several authors, dusts are the main responsible for health and welfare deterioration in animals and humans (Kwon et al., 2016) and can cause serious respiratory problems (Escobet et al., 2009).

2.1.1.5. Other parameters

There are other environmental parameters, such as luminosity, noise level or atmospheric pressure, that are not yet directly related to the thermal environment but are still part of the physical environment in a growing-finishing pigs' facility. Luminosity and noise level are the most important examples of these parameters.

The lighting in pig housing alters the display of active behaviours and physiological processes. According to Scaillierez et al. (2022), the available literature mainly reports about the effect of light period on production aspects like growth, reproduction, health or production related behaviours such as feeding and resting. The relevance of light intensity and light spectrum for welfare is often neglected, as also important welfare indicators such as social and exploratory behaviour and affective states.

Adequate lighting must allow all tasks to be carried out within the facility. According to the European Directive CD 2008/120/EC, pigs must be exposed to light with an intensity of at least 40 lux (below 20 lux, the pig has difficulties in finding feed and water) for a minimum of eight hours a day. The importance of these values, whose compliance is mandatory, demonstrates the dependence that pigs have on light levels to satisfy their behavioural and physiological needs (Martelli et al., 2015).

Excessive noise can be considered a stressor that affects animal welfare, having a negative impact on animal's growth and health (Sistkovaa et al., 2014).

As a rule, the parameters used to measure noise in installations are the sound pressure level and the frequency at which it is emitted (Düpjan et al., 2008). Regarding these parameters, it should be noted that they are influenced by the equipment present on the facility, especially ventilation (Manteuffel et al., 2004). In Portugal, according to the legislation (Decreto-Lei 135, 2003), constant or sudden noise levels equal to or greater than 85 dB must be avoided in pig housing.

2.1.2. Thermal Comfort Indices

Thermal comfort indices (TCI) have been used with the aim to provide data for the management of the thermal environment and to assess the risk of losses, through the link between the environment and physiological or productive responses of the animals. This link is based on careful observations of physiological and performance parameters (body temperature, respiration rate, growth, milk production) along with environmental data (temperature, relative humidity, radiation and air velocity). These data are used as inputs for TCI, making an empirical relationship of biological response, which is developed to predict the response of animals to thermal conditions (Hahn et al., 2009).

TCI typically combine the effects of two or more thermal measures that represent the influence of sensible and latent heat transferred between the animal and its environment. As such, an index value represents the effect produced by the heat exchange process, which can alter the biological response (Fournel et al., 2017).

According to Fournel et al. (2017) review, several researchers have been developing different TCI over the years. The temperature-humidity index (THI) is one of the oldest and most widely used TCIs. This index was applied for the first time in 1962 to determine the effects of temperature and humidity on milk yield and comfort in Holstein cows and was initially obtained by combining dry and wet bulb temperatures. Later it was concluded that the THI could be calculated using the dew point temperature instead of the wet bulb temperature and that this index could be adjusted to different animal species. The first THI developed for pigs is presented in equation 1:

$$\boldsymbol{THI = Tdb + 0,36\,Tdp + 41,2} \text{ (Yousef, 1985)} \qquad \textbf{(eq. 1)}$$

Note: Tdb is the dry bulb temperature and Tdp is the dew point temperature.

This discovery facilitated the calculation of the THI value, since obtaining the dew point temperature value, although not an immediate process, is simpler in relation to the wet bulb temperature.

However, in subsequent studies, the THI for pigs was adjusted to the relative humidity values (eq. 2 and 3) at the expense of the dew point temperature (Mader et al., 2006):

$$\boldsymbol{THI = \big((1,8Tdb) + 32\big) - \big((0,55 - (0,0055RH)\big) * \big((1,8Tdb) - 26,8\big)} \qquad \textbf{(eq. 2)}$$

(NRC, 1971)

Note: Tdb is the dry bulb temperature and RH is the relative humidity in %.

$$\boldsymbol{THI = (0,8Tdb) + \left(\left(\frac{RH}{100}\right) * (Tbs - 14,4)\right) + 46,4} \text{ (Mader et al., 2006)} \qquad \textbf{(eq. 3)}$$

Note: Tdb is the dry bulb temperature and RH is the relative humidity in %.

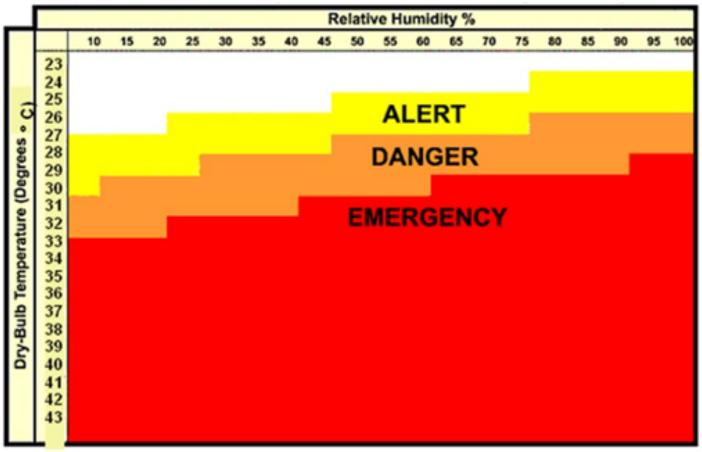


Figure 1 - Temperature and Humidity Stress Index (THI) for Growing-Finishing Pigs (Source: The Pig Site, 2002)

By integrating the effects of relative humidity, THI has now covered part of the impact of warm environmental conditions on animals, however more research should be developed to improve these tools (Fu et al., 2022; Shao and Xin, 2008).

Beyond the THI equations, Iowa State University developed in 1998 a THI chart for growing-finishing pigs (Figure 1). This is a support decision tool that can be used to determine the stress factor (Mutua et al., 2020; Xin and Harmon, 1998).

The THI has been also used as the basis for the livestock weather safety index (LWSI) to describe categories of **heat stress**. According to this index, the thermal comfort limits used are presented in the following table:

Table 1 - Thermal Comfort Limits for Growing-Finishing Pigs (Source: Oliveira Júnior et al., 2018)

THI	**≤ 74**	**75 – 78**	**79 – 83**	**≥ 84**
Condition	Normal	Alert	Danger	Emergency

In fact, the THI is the most widely used thermal environment index. Although this index is widely used to assess heat stress, it can also be used to assess cold stress (Foroushani and Amon, 2022). However, the studies that do exist in these conditions were carried out mainly on dairy cattle and there are no adaptations and, consequently, reference values for pigs. In this sense, future modifications to the THI are inevitable, considering that there are limitations not only associated with cold conditions, but also with thermal radiation, wind speed, intensity and duration of heat and the specific characteristics of different species (Hahn et al., 2009; Fu et al., 2022).

The US and Canadian Meteorological Centers have jointly proposed a different index: Wind Chill Temperature (WCT). This index is a scale or graph that correlates the clinical manifestations of cold in humans and animals with some environmental parameters (wind speed and temperature) (Lankford and Fox, 2021). With regard to animal production, according to Fu et al. 2022, some studies have provided WCT tables corresponding to different temperatures and wind speeds, but only for cows.

This approach allows to understand that, although the main cause of heat stress in pigs occurs in hot conditions, it is necessary to develop thermal comfort indices for pigs in cold stress conditions.

Finally, in open-front pig facilities, radiation is also a parameter that must be considered. In this context, the Black Globe-Humidity Index (BGHI), developed by Buffington et al. (1981) becomes relevant. Although initially created for cows, it can also be applied to pigs. This index is based on the THI but uses black globe temperature instead of dry bulb temperature to provide a more accurate assessment of thermal comfort (Baêta and Souza, 2010).

2.2. Climatization Systems

Some animal production systems require appropriate environmental control in order to maximize animal welfare and productivity and prolong the lifespan of infrastructure.

With the environmental control, it is intended to adapt the values of the interior climatic parameters to the needs of the animals. This is carried out through air climatization systems: ventilation (natural or mechanical), heaters for cold conditions and cooling equipment for high temperature conditions (Baêta and Souza, 2010; Fournel et al., 2017).

The equipment used in environmental control is designed to adjust environmental parameters such as temperature, humidity and air quality. To effectively control the environmental conditions within the facility, ventilation rates and heating or cooling needs are determined based on the thermal balance and mass balance (Baêta and Souza, 2010; Fournel et al., 2017).

The climatization systems must be correctly designed according to the location of the facility, the animal's species and production stage, as in this way it is possible to reduce the energy consumption required for the climatization of the facilities (Navas et al., 2010).

2.2.1. Ventilation

Ventilation is one of the most important environmental control techniques to determine the environmental conditions inside livestock facilities. To design a ventilation system, it is essential to consider all the factors that contribute to the definition of the environmental conditions inside a livestock facility, namely the external climatic conditions; the characteristics of the animals; the characteristics of the construction; and the characteristics of the environmental control equipment (Cruz and Baptista, 2006).

A ventilation system has as main objective to renew the air inside a livestock facility, providing an appropriate air quality and a stable environment. According to NRC (2011), ventilation provides an adequate oxygen supply; removes thermal loads caused by the animals, personnel, lights, and equipment; dilutes gaseous and particulate contaminants including allergens and airborne pathogens; adjusts the moisture content and temperature of room air; and, where appropriate, creates air pressure differentials (directional air flow) between adjoining spaces.

In this sense, to create the best conditions for the animals through environmental control is essential to have an effective and balanced control of the ventilation flow and an adequate distribution of air inside the installation (Puigdomènech et al., 2009). For a ventilation system to be effective, the amount of air entering the interior of a building must be adequate, as well as its distribution, uniform (Cruz and Baptista, 2006).

According to Puigdomènech et al. (2009), a well-dimensioned ventilation system allows to satisfy the three main objectives of ventilation:

(i) temperature control;
(ii) relative humidity control;
(iii) gas and dust concentration's control.

In animal housings, the ventilation rate is fundamentally determined in situations of hot conditions (summer) and cold conditions (winter). Thus, it is possible to consider two completely different situations and three common objectives (Baêta and Souza, 2010; Esmay, 1969).

Ventilation can be natural (static) or mechanical (dynamic). According to Cruz and Baptista (2006), there may be no difference in air quality by natural or mechanical ventilation, the only difference is in the forces that originate the two types of ventilation.

Natural ventilation is based on the formation of air currents and pressure and temperature differences between outdoor air (cold and dry) and indoor air (warm and humid). That is, in natural ventilation, there are used natural forces such as wind and thermal impulse (Puigdomènech et al., 2009).

In order to provide ventilation in a building, the natural ventilation relies on two main factors. One is the thermal buoyancy created by the warm air around the animals, which rises and exits through an open ridge, called a "chimney" or "stack" effect. Warmer air has a lower density and tends to rise, while cooler air sinks. This creates a natural flow pattern that is primarily driven by temperature. During cold outdoor temperatures, the stack effect is the main driver of ventilation (Mondaca, 2019).

The other factor is the force of the wind, which entering by the openings in the building creates gusts of wind and the air passing over the open ridge creates a lift force within the building. The stack effect still occurs during the summer, but the large openings are the main driver of ventilation (Mondaca, 2019). For this reason, according to Cruz and Baptista (2006), the design and location of ventilation areas must consider the physical principles of natural ventilation in order to take advantage of the occurrence of pressure differences through the openings.

In mechanical ventilation, the entry and exit speed air in the facility can be much higher than that achieved by natural ventilation (Puigdomènech et al., 2009).

This type of ventilation uses positive pressure, negative pressure, or a combination of both. According to Mondaca (2019), negative pressure ventilation uses exhaust fans to draw air out of the barn, creating a negative pressure inside compared with the outside. A positive pressure system pushes air into the barn, creating a positive pressure inside when compared with the outside. Some ventilation systems use to combine a positive pressure system with a matching negative pressure system, creating a so-called “neutral-pressure” barn.

2.2.2. Heating

In many animal housings, such as pig facilities, when the heat produced by the animals is not sufficient to maintain the desired air temperature, it is necessary to use, either continuously or at certain hours of the day, to some equipment intended for heating the air (Baêta and Souza, 2010). Furthermore, the energy losses by ventilation are relatively high, making up 70 to 90% of the building’s total heat losses. Heat recovery systems are also used to reduce these energy losses (Licharz et al., 2020).

The need to install heating systems in pig facilities is related to the physiological characteristics of the animals, which determine their thermal requirements. Therefore, it is important to bear in mind that not all animals housed in a livestock facility have the same thermal needs. One of the factors that can make the use of heating systems essential is the presence of piglets, whose thermal needs are higher and have a lower adaptive capacity (Blanes-Vidal and Torres, 2009).

Heating can be spatial or localized. To create the optimum temperature microclimate is necessary to provide not only quality heating but also adequate ventilation conditions in order to homogenize the temperature throughout the facility. The use of certain heating systems is largely dependent on the natural conditions of the region, flooring, location of rooms and the age of the pigs (Boltyanska, 2018).

The most used heating systems in recent decades in growing-finishing pig facilities, are conventional systems such as convection heating (Blanes-Vidal and Torres, 2009). These systems usually use direct combustion of gas or liquid fuel as a source of power. Since the costs inherent to these traditional heating systems are high and looking for a higher energy efficiency, there has been an evolution in heating systems in recent years and other alternative systems have begun to be applied in pig facilities.

An alternative system is the heating floor (Cruz, 1997). This system is almost never used alone, as its heat is not enough to effectively heat the entire facility. However, as an additional source of heat, especially to the piglets, floor heating is very important (Boltyanska, 2018). According to Fossen and Overhults (1981), floor heat for growing-finishing pigs is used only in open-front or modified open-front facilities and should not be installed in environmentally controlled buildings.

In addition, against the background of limited fossil energy resources, according to Licharz et al. 2020, systems that use renewable energy for heating are and have been investigated and evaluated under practical conditions. Different technologies for heating pig housings using renewable energy are available, such as a modular housing system with an integrated geothermal heat exchanger (Krommweh et al., 2014) or heat pump (Licharz et al., 2020)

Other strategies to reduce energy costs and increase energy efficiency can include improving the facility's thermal insulation, in order to reduce heat losses (Blanes-Vidal and Torres, 2009).

2.2.3. Cooling

Pigs are animals very sensitive to heat. In this sense, to prevent animal's thermal stress, several environmental modifications may be implemented to improve heat loss from pigs in confined housing systems under high ambient temperatures (Jeppsson et al., 2021).

The cooling systems may cause a decrease of air temperature in a building or cause direct cooling of an animal's skin. Moreover, to enhance animal comfort during hot weather conditions, a combination of different cooling methods is often used. It concerns especially technologies combining the cooling effect of forced-air velocity together with water evaporation (Godyń et al., 2020).

Evaporative cooling systems like fogging, misting/showers, drip/snout cooling or evaporative pads are cooling methods based on water evaporation that can have a direct effect on the environment and/or on the animal. These systems are an alternative, efficient and lower cost systems comparing with the conventional cooling methods (heat pumps) (Baêta and Souza, 2010; Cruz, 1997) and may significantly improve heat loss (Justino et al., 2014), especially for animals such as pig, which do not have functional sweat glands (Bracke, 2011; Gómez-Prado et al., 2022; Ingram, 1965).

According to Godyń et al. (2020), water droplets sprayed (depending on their size) either fall on a small pen area (showers) or cause wetting of a larger surface (misting). In both these cases the animal skin is wetted. This has an effect not only on the environment but also on the animals. These systems work with any type of ventilation system.

Drip cooling and snout cooling are other method to directly cool the animal surface. The drip method allows, through a slow and constant release of water in the neck zone, to refresh the sows (Barbari et al., 2007). Snout cooling, generally used in farrowing rooms, is a system that consists in sending airflows directly on the snout of the sow through centrifugal fans and well-designed distribution pipes (Barbari and Conti, 2009; Perin et al., 2015).

Evaporative pads are systems that are designed to cool the air before it gets into the building. These cooling systems were developed to be installed in closed buildings with forced ventilation because, due to the operation of the extractor fans, the outside air (warm) is forced to flow through the pads (water-soaked material) to enter the facility, which allows decrease the temperature (Samer et al., 2015).

The main drawback in these systems is that, due to the addition of water to the air moisture, the relative humidity can increase too much, reaching levels that are harmful to the health of the animals. Thus, these systems are more commonly used in hot and dry climates (Blanes-Vidal and Torres, 2009).

Other important cooling systems are based on high velocity airstreams to remove heat from the bodies of animals. In pig housing, technologies based on increasing air velocity during hot summer periods is a well-known method used in growing-finishing houses (Godyń et al., 2020). However, this method does not reduce the indoor temperature of the facility but rather lowers the effective temperature, resulting in a sensation of coolness for the animals (Wang et al., 2019).

One of the most effective ways of improving an animal's heat loss is the forced convection (Godyń et al., 2020). In pig facilities, high air speed over the animals may be achieved throughout the living area using dynamic ventilation systems (Stender et al., 2003).

Floor cooling is another system used especially for individual kept sows at the phase of pregnancy or lactation, considering a large amount of time these animals spend lying. The contact with a cool surface enhances conductive heat exchanges which may contribute to improving animal comfort conditions during hot periods (Parois et al., 2018). This system, using underground water, can be used both in open-type and closed pig facilities (Shi et al., 2006).

2.3. Animal Welfare

In the current global socioeconomic situation, there is strong evidence of public concern about the moral implications of current animal production systems in relation to animal welfare, along with environmental and food safety issues (Alonso et al., 2020; Pandorfi et al., 2006).

These issues are aspects that currently exert enormous pressure on animal production (Fournel et al., 2017; Koenders et al., 2015) and that have been promoting changes in these production systems in recent decades (Baptista et al., 2011), leading to farmers to make investments especially aimed at training workers and adapting facilities and equipment (Cruz et al., 2021).

2.3.1. Concepts of Animal Welfare

Animal welfare is an expression that tends to resist a globally accepted definition. This very complex concept is used with varied meanings and within scientific community and stakeholders there are different definitions and perceptions of animal welfare (Alonso et al., 2020; Madzingira, 2018).

According to Fraser (2003), the scientific approaches to define animal welfare can be classified into three different views: the biological functioning of the animal (health, growth and productivity); the "affective states" of animals (pain, suffering and other feelings/emotions); and the environment where animals live (animals should be allowed to live in as natural circumstances as possible, where they can express their normal behaviour).

In general, the definition of animal welfare provided by the World Organizations for Animal Health (WOAH) includes some of the different points mentioned above and means **"the physical and mental state of an animal in relation to the conditions in which it lives and dies"**.

In order to describe fundamental principles of animal welfare under human control, the **Five Freedoms**, established by the Brambell Committee in 1965 and refined in 1979 by the UK's Farm Animal Welfare Council (FAWC), have been used internationally as the conceptual framework (Fernandes et al., 2021; Vapnek and Chapman, 2010).

These principles encompass freedom from: (i) hunger, malnutrition and thirst; (ii) heat stress or physical discomfort; (iii) pain, injury and disease; (iv) the ability to express normal patterns and behaviors; and (v) fear and distress (FAWC, 1979). While these guidelines are practical for assessing welfare in livestock farms (Manteca et al., 2012) and serve as the basis for many animals' protection laws in the European Union (Madzingira, 2018), they are sometimes criticized for being too generic and overlapping in scope.

To address these limitations, the Welfare Quality® Project (WQP), funded by the European Commission, introduced a more detailed approach focusing on four key principles: proper feeding, housing, health and behavior (Welfare Quality®, 2009). This approach preferably focuses more on **animal-based measures** and although it also uses, when necessary, facilities and management-base indicators (Costa, 2015).

This framework includes 12 criteria for assessing animal welfare that complement the Five Freedoms approach (Alonso et al., 2020; Fernandes et al., 2021). These criteria ensure that animal welfare assessments are thorough and align with current best practices in the field.

Welfare principles and criteria are summarized in Table 2.

Table 2 - The principles and criteria that are the basis for the Welfare Quality® assessment protocols (Adapted from: Welfare Quality®, 2009)

Welfare principles	**Welfare criteria**	
Good feeding	**1**	Absence of prolonged hunger
	2	Absence of prolonged thirst
Good housing	**3**	Comfort around resting
	4	Thermal comfort
	5	Ease of movement
Good health	**6**	Absence of injuries
	7	Absence of disease
	8	Absence of pain induced by management procedures
Appropriate behaviour	**9**	Expression of social behaviours
	10	Expression of other behaviours
	11	Good human-animal relationship
	12	Positive emotional state

The Welfare Quality® protocols integrate animal welfare throughout the food production chain and allow to inform consumers about the reality of farms to improve the welfare of livestock species and ensure transparency (Welfare Quality®, 2009).

In 1994, Professor David Mellor and Dr Cam Reid reformulated the Five Freedoms and proposed a new model: the **Five Domains**. This model focus on physical and functional welfare in the domains of **nutrition, environment, health, behaviour** and **mental state** (Mellor, 2016). This model explores an animal's mental state in more detail (Mellor et al., 2020), acknowledging that **stress** is a critical component of animal welfare (Martins, 2020).

2.3.2. Stress

Stress is a complex concept and there are many different hypotheses of definitions within the scientific community. However, it is generally agreed that “a stress condition occurs when adverse conditions produce physiological responses into an individual” (Broom, 2008; Broom and Johnson, 2019; Jamilah et al., 2019; Mormède et al., 2007). This response is an attempt by the animal to maintain its homeostasis, that is, the normal physiological balance of the body (Esmay, 1969). Also, some definitions include certain behavioural patterns that can help restore homeostasis and thus facilitate physiological adaptations to stress (Manteca et al., 2013a; Rivera, 2006). In addition, as a rule, stress is mostly associated with negative events and/or consequences that the animal has been subjected to (Korte et al., 2005).

When discussing stress, it is essential to recognize that it is a **state** caused by a **stressor** and there are two very important terms to consider: "control and prediction" (Broom and Johnson, 2019; Rivera, 2006). That is, a stress condition is dependent on the difficulty an animal has in dealing with a given situation that it cannot control or predict (Broom, 2008). This means that depending on the degree to which the stressor can be controlled or predicted, there is greater or lesser severity of stress symptoms, which allows understanding that severity does not depend only on the stressor (Jamilah et al., 2019).

Stressors can be divided into **physical** – due to fatigue, injury, pain, disease, etc.; **physiological** – due to hunger, thirst, body temperature control, etc.; and **behavioural** – due to interaction with humans, novelty, isolation, overcrowded population, etc. Stressors have additive effects. This means that the more stressors affecting the animal at the same time, the greater its stress response (Etim et al., 2014; Manteca et al., 2013a).

Stress is naturally part of animals' lives and regardless of the type of stressor, it causes an organic response in a cumulative and sequential way denominated the General Adaptation Syndrome (Selye, 1952). This is consisted of three phases: (i) the **alarm phase** in which fight or flight is the immediate response of the body to 'perceived' stress with a large energy expenditure; (ii) the **phase of adaptation** in which, if the pressure persists, the body prepares itself for long-term protection, trying to reach an optimal adaptation in the resistance to the stressor; and (iii) the **phase of exhaustion**, associated with a chronic and continued response to stress that may be a risk factor for many multifactorial disorders (Brown and Waslien, 2003; McCarty, 2016; Selye, 1952).

According to Broom and Kirkden (2004), a sufficiently intense or prolonged condition of stress (distress) can affect animal welfare. This means that the absence of stress revels to be a potential indicator of animal welfare, although there is no standard definition of stress and no accepted methodology for measuring it (Jamilah et al., 2019).

2.3.3. Animal Welfare Assessment

Welfare refers to the "state" of an animal and therefore measurements of that state are used to assess animal welfare. The wide range of ways in which animals try to cope with their environment results in many indicators of good or poor welfare (Broom and Johnson, 2019; Broom and Kirkden, 2004) that allows to characterize the animal's status (Broom and Molento, 2004).

Thus, animal welfare can be measured through some behavioural, physiological, productive and health indicators (Candiani et al., 2008). As animal welfare is a multidimensional concept, a single measure of stress may not be a reliable indicator and it is often more informative to consider a set of indicators simultaneously to assess animal welfare (Etim et al., 2014; Manteca et al., 2013b).

According to different authors, the collection of information from these indicators should not take much time and priority should be given to collecting data obtained directly from the animals (Dias et al., 2015; Galvão et al., 2019; Manteca et al., 2013b; Temple et al., 2011; Velarde and Dalmau, 2012). However, to improve the assessment of animal welfare, the use of new technologies and respective methodologies is recommended, in order to enable real-time monitoring, based on objective indicators (Buller et al., 2020; Dawkins, 2016).

The choice and parameterization of indicators used to measure welfare will then allow the improvement of the monitoring system, as well as the recognition of practices and situations that can cause stress to the animal (Candiani et al., 2008).

2.3.3.1. Performance Indicators

There is evidence that factors that are detrimental to animal welfare have a negative effect on health, reproduction and growth performance, which can, in extreme cases, lead to the death of the animals (Broom and Molento, 2004; Baptista et al., 2011 Madzingira, 2018).

Any stress condition can harm the development of the animal. **Weight gain**, **feed intake**, **feed conversion** and **carcass quality** are some of the production indicators that can be used to assess the animal welfare of growing-finishing pigs (Manteca et al., 2013b; Martínez-Miró et al. 2016; Pierozan et al., 2020).

Thermal environment has a significant negative impact on animal production and performance (weight gain, feed intake, feed conversion). This topic will be covered in more detail in sub-chapter 2.4.3.

Carcass quality can also be used as an indicator in the evaluation of animal welfare, especially in the period prior to slaughter, since reduced levels of animal welfare can compromise profitability and the quality of the final product (Brennecke et al., 2021). Pre-slaughter stress can have negative consequences on meat quality, increasing the risk of PSE (pale, soft, exudative) and DFD (dark, firm, dry) incidence in carcasses (Gregory and Grandin, 1998).

The carcass composition of animals is strongly influenced by the environment in which they are raised. Environmental conditions and food availability play a crucial role in the distribution of tissues, such as muscle and fat, throughout the animals' growth (Gómez-Prado et al., 2022; Irshad et al., 2013). For instance, animals housed in colder environments tend to exhibit fattier carcasses due to increased adiposity resulting from an increase in food intake as a response to the cold. Moreover, ambient temperature influences energy retention, with a preference for protein fixation over fat fixation even in adverse environmental conditions (Cruz, 1997). In contrast, high temperatures have been linked to reductions in both live and carcass weights, underscoring the importance of implementing effective heat stress management strategies throughout the production cycle (Gonzalez-Rivas et al., 2020).

These variations in carcass composition, morphology and tissue distribution can serve as important medium-term indicators of animal welfare and their ability to adapt to the environment, providing crucial insights for management and promoting healthy development of animals over time. In this sense, monitoring parameters such as muscle pH, fat deposition patterns and lean muscle mass provides insights into animal health and development, facilitating the implementation of appropriate management practices to support their overall welfare and growth (Gonzalez-Rivas et al., 2020; Irshad et al., 2013; Lonergan et al., 2019).

2.3.3.2. Behavioural Indicators

Behaviour and behavioural changes are mechanisms that animals use in order to deal with the environment (Mench, 1998), being fundamental in the adaptations of biological functions (Snowdon, 1999). Consequently, behavioural measures are a quick and practical method of assessing animal welfare (Broom, 2010; Matthews et al., 2016).

Behavioural indicators are based on variations in pig behaviour and these variations can manifest themselves due to the difficulty in expressing certain movements or in adapting to environmental stimuli (Costa et al., 2009). Thus, if any animal strongly avoids an object or event, this provides information about its feelings and, consequently, its well-being (Broom, 2010; Lesimple, 2020).

Pig behaviour results from the interaction of hereditary and acquired factors, which produce a pattern that may influence the animal's performance (O'Connell et al., 2004). The observation of changes in behaviour patterns (e.g., self-harm, stereotyped behaviours, aggressive behaviours) usually represents the first level of an animal's response to negative or stressful stimuli. These behaviours are associated with a low level of welfare (Broom and Molento, 2004; Temple et al., 2011).

The behavioural indicators can be divided in:

- **Feeding and drinking behaviour:**

According to Chen et al. (2020), feeding and drinking behaviours are two behaviours with a strong relationship and there is a positive correlation between feed and water intake.

By monitoring **feeding behaviour**, it is possible to assess some of the theories that were at the origin of the principles of animal welfare (absence of thirst and hunger) and even indicate the presence of some diseases, in case these patterns undergo changes (Rushen et al., 2012; Zhuang et al., 2022). Feeding behaviour is controlled by hunger and satiety mechanisms, however, it can be influenced by external factors such as **treatments and diets**; **feeding and housing systems**; **health and breed**; and **thermal environment** (Maselyne et al., 2015a).

Regarding **drinking behaviour**, this often occurs around feeding behaviour and under normal conditions and thermal comfort, usually appear after 10 minutes of food intake (Linden, 2014). Changes in this pattern may reflect metabolic diseases emerging, for example, in response to dehydration resulting from diarrhoea. Water intake patterns can then be influenced by **disease states** (Andersen et al., 2014;

Seddon, 2011), **stress** (Averos et al., 2007; Broom and Johnson, 2019) and **high environmental temperatures** (Linden, 2014; Rushen et al., 2012).

- **Social behaviour:**

In all phases of pig production, a linear social hierarchy is detected, characterized by a clear classification from dominant to subdominant (Meese and Ewbank, 1973).

Communication between these animals can occur through sound (vocalization), smell, sight and touch. However, the main form of communication is **vocalization** (Deen, 2009). Vocalizations may change depending on the situation the pigs are in. These alterations, as a rule, are associated with stress as **thermal discomfort**, **pain** and **fear**. In these cases, the sounds have higher intensities and higher pitches (Cruz et al., 2021). Because of that, vocalizations can be used to assess animal welfare in a non-evasive way, namely through the detection and measurement (frequencies, amplitude and duration) of vocal patterns (Düpjan et al., 2008; Laurijs et al., 2021).

In order to establish the hierarchy, pigs have some agonistic behaviour towards each other (Scheffler et al., 2016), mainly due to competition for physical space, food and resources (Martins, 2020).

Aggressive behaviour (contact threats) is a component of agonistic behaviour (Petherick and Blackshaw, 1987). Pigs also exhibit behaviours that cause injuries to the animals, such as: **biting** and **sucking habits** of the tail, ear, flank and vulva (Baptista et al., 2011; Honeck et al., 2019; Prunier et al., 2020). These behaviours may be related to a series of stressors, caused by problems in the facilities (space and access to food and water) and in animal management (introduction of new animals in the group) (Baptista et al., 2011; Camerlink et al., 2018; Scheffler et al., 2016).

Welfare is also compromised when animals exhibit **stereotyped behaviours**. This type of behaviour is defined by the succession of repetitive and non-functional actions (Dantzer, 1986), and the most likely causes for this type of behaviour are cases of **frustration**, **lack of control over the environment** (Deen, 2009), **famine** (Arellano et al., 1992) and/or central nervous system dysfunction (Radkowska et al., 2020).

- **Exploratory behaviour:**

Exploratory and foraging behaviour is an innate behaviour in pigs. Irrespective of the type of explorative behaviour performed, pigs develop actions based on same behavioural elements as looking, smelling, licking, rooting, sniffing and chewing. This behaviour may serve different purposes depending upon the type of motivation (Studnitz et al., 2007).

According to Keeling (2019), there are two types of exploratory behaviour: the inquisitive exploration when the animal is looking for a change and the inspective exploration when an animal responds to a change.

In intensive production systems, where the environment is practically sterile and without stimuli, pigs tend to direct this behaviour towards each other, which may be considered as an indicator of poor welfare (Foppa et al., 2014). Thus, several studies have been carried out with pigs on environmental enrichment, seeking to combat animal welfare problems, allow the expression of specific behaviours of the species and promote the physical and psychological development of the animal (Foppa et al., 2014; Godyń et al., 2019; Mkwanazi et al., 2019).

- **Behaviour associated with posture and locomotion:**

According to Linden (2014), pigs spend about 75 to 85% of their time lying down, 5 to 10% eating and the rest walking and exploring. Although most of the time is spent resting, locomotion disorders (i.e., lameness) have an impact on animal welfare (Deen, 2009). A sick animal presents a drop in its activity and consequently in its posture and locomotion (Rostagno et al., 2011).

Tail posture in pigs is as an important indicator of behaviour and emotional state and thus subsequently for animal welfare (Camerlink and Ursinus, 2020). In a general way, an animal that has a curled and upturned tail means that it is an active animal. On the other hand, if an animal is faced with situations that cause fear, discomfort or submission, it is common to observe the lowered tail (Groffen, 2012).

To assist in the thermoregulation process, pigs adopt some adaptions related to posture and locomotion behaviours. This topic will be covered in more detail in Chapter 2.4.

2.3.3.3. Physiological Indicators

There is no defined standard procedure to accurately determine an animal's degree of animal welfare and stress level (Martínez-Miró et al., 2016). Behavioural indicators have the advantage of allowing a quick and economically viable assessment, however, they do not allow an objective assessment of what is happening at the physiological level. Furthermore, they also do not allow the detection of potentially negative situations at a stage prior to the appearance of behavioural signs. For this reason, there is also a need to have indicators of the animal's physiological condition (Cruz et al., 2021).

Physiological stress is one of the main indicators used in the evaluation of animal welfare (Bozzo et al., 2018) and can be measured through evaluations such as: **internal and surface temperature**, **heart and respiratory rate**, **immune system responses**, **level of certain anabolites** such as cortisol or α-amylase, among others (Dawkins, 2021; Hellhammer et al., 2009). It should be noted that the result of physiological measurements must be interpreted with care, as they may be an indication of pre-pathologies (Broom and Molento, 2004; Serra et al., 2018).

- **Internal and Surface temperature:**

The internal temperature is an important physiological signal that characterizes the state of health of the pig because it’s an objective reflection of the activity in the animal body. This means that, variations in internal temperature may be related to some diseases or in the case of adult sows, to the stage of the oestrus cycle (Zhang et al., 2019).

Although there are methods for non-invasive internal temperature measurement, traditional methods commonly use rectal temperature. In pigs, rectal temperature ranges between 38 – 40°C and is influenced by physical activity, food intake, solar radiation, age, sex and size (Sacristán et al., 1998). The manual collection of rectal temperature can affect results due to handling stress, which may increase the temperature (Godyń and Herbut, 2017).

Surface temperature varies according to breed, environmental factors, contact between animals, radiation exposure, among others (Cecchin et al., 2016; Rodrigues et al., 2010; Soerensen and Pedersen, 2015). Since the skin is the main organ for sensible heat exchanges, surface temperature reflects thermoregulation mechanisms, allowing the identification of thermal discomfort and, consequently, the assessment of animal welfare (Martins, 2020). This topic will be further explored in Chapter 2.4.

When comparing rectal and surface temperatures, the latter is more reliable for detecting thermal discomfort and assessing animal welfare, as it changes with ambient temperature, unlike rectal temperature.

- **Other physiological indicators**

The assessment of heart rate frequency (HRF) is a non-invasive technique employed to examine the autonomic nervous system's operation, particularly the balance between sympathetic and vagal functions. Widely utilized in human studies, HRV has demonstrated utility in research on cardiovascular ailments, diabetic autonomic dysfunction, hypertension, as well as psychiatric and psychological conditions. In recent years, HRV has been used increasingly in animal research, enabling the analysis of shifts in sympathovagal balance linked to ailments, psychological stressors, environmental factors and individual traits like temperament and coping mechanisms (Von Borell et al., 2007).

Respiration rate (RR) serves as an essential physiological marker in assessing animals' responses to environmental conditions, particularly heat stress. Studies have demonstrated its correlation with factors like solar radiation, relative humidity and overall thermal stress levels, indicating its broader applicability across various animal species. Additionally, RR indirectly reflects respiratory volume, making it a valuable metric for evaluating animals' welfare and environmental adaptation in diverse settings (Milan et al., 2016).

The animals’ immune response also plays a crucial role in assessing animal welfare, providing valuable insights into the interaction between the immune system and stress response. In this context, the analysis of immunoglobulin emerges as a promising and non-invasive biomarker for evaluating the balance between stress and the immune system. The effective sampling capability, using minimally invasive methods such as saliva or fecal collection, makes immunoglobulin analysis an accessible and reliable tool for monitoring the health and welfare of animals (Staley et al., 2018).

The cortisol, a hormone from the glucocorticoid group, plays a crucial role in regulating the physiological mechanisms that help animals adapt to their environment (Cunningham, 1993). Its production is triggered by the hypothalamic-pituitary-adrenal (HPA) axis in response to Corticotropin-Releasing Hormone (CRH). Cortisol regulates the catabolism of carbohydrates and proteins, directly influenced by physical and psychological stress (Cunha, 2012). Blood cortisol concentration follows a circadian pattern, peaking in the morning. Physical or psychological stress situations induce a rapid increase in cortisol concentration, returning to baseline levels after the stimulus resolves (Ruis et al., 1997). Chronic elevation of cortisol can have negative effects on physical and reproductive health. Although a valuable indicator of stress and animal welfare, blood sampling for cortisol measurement can be invasive and stressful, so non-invasive methods like saliva or urine are preferable (Casal et al., 2017; Escribano et al., 2019).

Similarly, salivary alpha-amylase, a marker of Sympathetic Nervous System (SNS) activation, has been studied as a stress indicator in animals (Fuentes et al., 2011;

Contreras-Aguilar et al., 2018). SNS activation during stress leads to increased salivary alpha-amylase production, which can be measured non-invasively and is less susceptible to momentary stress variations (Yamaguchi et al., 2004). Both cortisol and salivary alpha-amylase provide valuable insights into animals' physiological response to stress and can be useful in assessing their welfare (Martins, 2020).

2.4. Growing-Finishing Pig's adaptation to Environmental Conditions

The pig is a homeothermic animal, which means that maintains its internal temperature within limits when ambient temperature changes occur (Cossins and Bowler, 1987). According to Esmay (1969), this maintenance of body temperature **(homeostasis)** is achieved through **thermoregulation**: a mechanism responsible for ensuring the dynamic balance between the **heat produced** by the body (thermogenesis) and **released** to the environment (thermolysis).

The ambient temperature range in which animals can maintain its body temperature, regardless of the ambient temperature, is denominated as **homeothermy zone** (Figure 2) (Babot and Revuelta, 2009; Esmay, 1969).

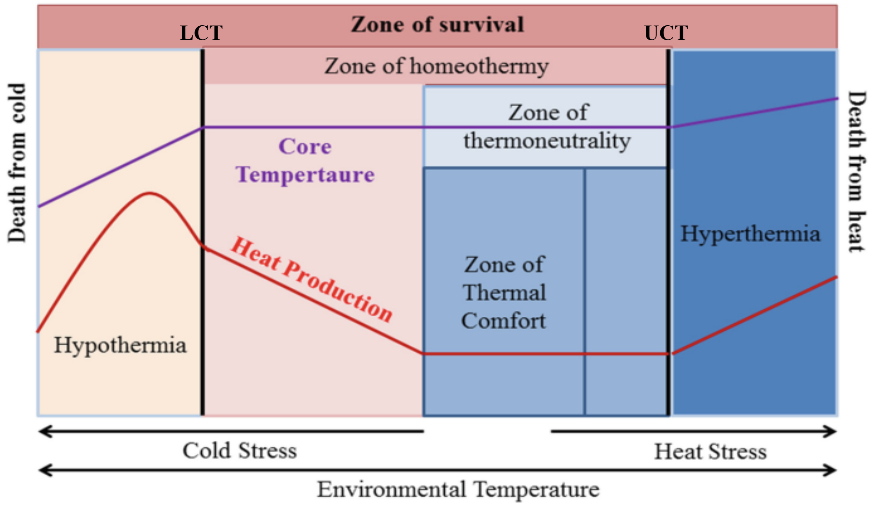


Figure 2 - Homeothermy Zone (Adapted from: Somal, 2022)

Within the homeothermic zone there is the **thermoneutrality zone** (TNZ). This zone is defined as the ambient temperature range where, for a certain level of food, the production of heat is minimal, constant and independent of the air temperature (Babot and Revuelta, 2009; Cruz, 1997). That is, it is the ambient temperature range in which thermoregulation occurs without the need to increase metabolic heat production or activate evaporative heat loss mechanisms (Hillman, 2009; NRC, 2011).

However, thermal behaviour plays a significant role in maintaining body temperature homeostasis and is driven by thermal comfort. The **thermal comfort zone** (TCZ) is defined in terms of perception and reflects the degree of satisfaction with the thermal environment. This allows for positive anticipations of the current thermal environment. Conversely, thermal discomfort leads individuals to adjust to their environment to counteract negative anticipation (Kingma et al., 2014).

Homeothermic zone is bounded by the **lower critical temperature** (LCT) and **upper critical temperature** (UCT) as limits (Cruz, 1997; NRC, 2011). This range varies mainly with the type of species (Cruz and Baptista, 2006). Within the TNZ, to maintain body temperature under a given environmental temperature, animals adjust physiologically (including their thermogenesis-thermolysis balance) and behaviourally (including their activity level and resource use) (NRC, 2011; Rojas-Downing et al., 2017).

When these limits are exceeded, the animal enters a situation of **thermal stress**. This means that when the LCT is exceeded, the mechanisms that regulate heat losses are also exceeded which causes a decrease in the body temperature. In this case, the homeothermic process is maintained through an increase of heat production. If the mechanisms linked to thermogenesis are overcome due to the continuous decrease in temperature, it is not possible to maintain a situation of homeothermy, which causes a hypothermia in the animal (Close et al., 1981; Hutu and Onan, 2019).

On the other hand, when the ambient temperature is above the UCT, the animals enter a condition of heat stress, which causes the homeothermic mechanisms linked to thermolysis and thermogenesis to become deregulated, which can lead the animal to enter into a situation of hyperthermia (Esmay, 1969; Fonseca et al., 2016; Hutu and Onan, 2019).

Pigs have different strategies to influence heat production and heat losses. According to Cruz (1997), the **production of heat** results, in addition to biochemical reactions (cellular metabolism and cell work), from the voluntary activity of animals (locomotion, feeding, etc.) that originates energy used in the muscular work. On the other hand, environmental conditions also have a high influence on the production of heat by the animal, which is a result of the metabolic processes associated with the maintenance and use of food (Henken et al., 1993).

Heat losses can occur in two ways: **sensible** and **latent**. In this sense, the total heat losses result from their sum (Cossins and Bowler, 1987).

The **sensible heat** transfer mechanisms use three different processes: **conduction, convection** and **radiation**. According to Stone and Heap (1982), these follow the normal laws of physics, that is, there is a flow of heat from the zone of higher kinetic energy to the zone of lower kinetic energy. Heat lost by conduction can be influenced by the pig's choice between standing or lying, their lying posture and the choice of their lying location. Convective heat loss is mainly influenced by the temperature difference between the skin and the air, the air velocity, and the area of the skin exposed to the air. Radiation heat loss mainly depends on the temperature difference between the pig's skin and the surrounding construction and on the area of skin exposed to this construction (Aarnink et al., 2016; Cruz, 1997).

According to different authors, with increasing temperature, sensible heat loss decreases and latent heat loss increases (Aarnink et al., 2016; Brown-Brandl et al., 2014; Esmay, 1969).

The **latent heat** exchanges are classified as **cutaneous** (occurring at the level of the skin) and **respiratory** (occurring at the level of the respiratory tract) (Meneses, 1985). However, as the pig does not have functional sweat glands (Bracke, 2011; Gómez-Prado et al., 2022; Ingram, 1965), it uses two basic processes to release heat through the skin: perspiration (process by which the body releases moisture through the skin's pores) and evaporation of water (from liquid waste or other water on the floors on which they lie) (Cruz, 1997; Huynh et al., 2005b; Olczak et al., 2015). Due to the thick layer of subcutaneous fat, the pig in situations of high temperatures is one of the animal species with the lowest water loss through the skin, so the second process mentioned (evaporation) becomes dominant in these temperature conditions (Godyń et al., 2020; Ingram, 1965; Meneses, 1985).

Respiratory heat losses occur because the air, when inhaled, heats up and absorbs water vapor, which is released through the mucous membranes, which, when exhaled, leaves with a greater amount of water vapor and at a higher temperature than the air inspired. This type of heat loss depends on several factors, such as respiratory rate, volume of inspired air and air humidity (Stone and Heap, 1982).

In short, an animal's homeostasis is achieved through the thermoregulation process, which is a mechanism that seeks to establish a dynamic balance between heat production and heat loss. This mechanism translates into physiological and behavioural responses or adaptations that animals adopt to deal with the thermal environment. However, the response mechanisms that ensure survival are detrimental to animal performance, productivity and reproduction. In this sense, knowledge of these adaptations allows us to assist in the decision-making process (i.e.: modification of management, nutritional diet, facilities and equipment, etc.), aiming to maximize the animal’s performance and welfare.

2.4.1. Heat Adaptation

Heat stress is a main concern in pig production since, as mentioned earlier, pigs cannot sweat. If in a cold situation the animal tries to use the metabolic heat associated with production (extra-heat) for thermoregulation, in a hot situation the objective is to eliminate this heat (Cruz, 1997).

When the temperature exceeds the point above which the equilibrium between heat production and heat loss can be maintained, the maximum heat loss by evaporation is reached and respiratory evaporation (panting) proves inadequate to lose enough heat to maintain the body temperature constant (Huynh et al., 2005a; Huynh et al., 2007). Thus, as a response to the high temperature, several behavioural patterns are observed in pigs.

In order to eliminate heat, the animal increases its surface area of exposure to heat exchanges, adopting a more relaxed posture and moving away from the other animals, thus also allowing the air to circulate around it. This means that, under high temperatures conditions, pigs altered their **behaviour connected with resting and lying** (Cruz, 1997; Huynh et al., 2005b; Kim et al., 2021; Olczak et al., 2015; Shi et al., 2006).

As mentioned in Chapter 2.4, in an intensive housing system, pigs spend about 75 to 85% of their time lying down. This behaviour is interrupted when the temperature is very high and, with that, the animals start looking for a suitable place to lie down without contact with other individuals (Aarnink et al., 2016; Godyń et al., 2020; Kim et al., 2021).

In these environmental temperature conditions, it is also common to see pigs increasing wallowing behaviour and lying down in their own fecal area, with dirty resting areas occurring, as the pig needs to evaporate the water contained in the feces, as this process represents an important form of heat loss in hot environments (Cruz, 1997; Huynh et al., 2007; Olczak et al., 2015; Shi et al., 2006; Spoolder et al., 2012).

On the other hand, to reduce heat production in a situation of thermal stress, pigs present a **decrease in their activity** (Godyń et al., 2020; Huynh et al., 2005b; Johnson et al., 2008), an **increase in water intake** (Olczak et al., 2015; Kim et al., 2021; Silva et al., 2009) and a **reduction in feed intake** (Cruz, 1997; Godyń et al., 2020; Mayorga et al., 2019; Quiniou et al., 2000; Renaudeau et al., 2012; Santos et al., 2018).

Adjustment of voluntary feed intake is one of the most important adaptation processes to modify metabolic heat production in response to ambient temperature (Cruz, 1997; Mayorga et al., 2019; Renaudeau et al., 2012). The severity of reduction in feed intake behaviour depends on genotype, sex, breed, age, body weight, physiological state, diet composition, feeding regime, group size and environmental factors (Godyń et al., 2020; Renaudeau et al., 2012; Santos et al., 2018).

According to the literature, high ambient temperature compared with thermoneutral environmental conditions (≈30ºC vs ≈20ºC) may cause a decrease in voluntary feed intake in growing-finishing pigs at the level of 50% (Godyń et al., 2020; Huynh et al., 2005a; Ma et al., 2019; Pearce et al., 2015).

In addition to reducing feed intake, pigs can change their feeding behaviour, changing their mealtimes to early morning and late evening (Bus et al., 2021; Cross et al., 2020; Santos et al., 2018; Quiniou et al., 2000). This alteration does not occur if the high temperature persists during the night (Collin et al., 2001).

It is not entirely clear how these changes in feed intake are mediated by underlying feeding behaviours. However, there is general agreement that the daily duration of feeding decreases with increasing temperature (Collin et al., 2001; Fraga et al., 2019; Gertheiss et al., 2015).

In the studies conducted by Salgado et al. (2021) with growing-finishing pigs (BW > 80 kg) under thermoneutral conditions (18–22°C), findings regarding meal frequency identified an average of 7 meals per day. Meal duration varied between 7.4 and 11.9 minutes, while food intake per meal ranged from 373.7 to 500.4 g per meal.

Despite the changes identified in feeding behaviour in response to increased ambient temperature, several studies have reported no impact of heat stress on the set of parameters that characterize this behaviour (Bus et al., 2021).

Quiniou et al. (2000) observed no effect on the frequency of daily meals when temperatures exceeded the thermoneutrality zones, attributing this to the fact that pigs adjust their mealtimes. Based on the investigation conducted by Cross et al. (2020), were also not identified variations in the total time spent at feeders across most THI categories, except in the most extreme (> 28.9ºC) case, where a decrease of about 4 min/meal was noted.

The study conducted by Renaudeau et al. (2006) also noted a decrease in meal size (from 393 to 316 g/meal) and an increase in the number of daily meals from 7 to 8 meals/day with rising temperatures (28ºC). This effect was also observed in the meal duration, where the animals reduced the time spent on meals by 2.3 minutes (from 13.2 to 10.9 min/meal). On the other hand, according to Santos et al. (2018), pigs raised under heat stress conditions exhibited a 15% decrease in the amount of time spent feeding, number of visits to the feeder and feed intake per meal compared to those raised under TNZ conditions.

2.4.2. Cold Adaptation

In addition to the biological mechanisms of thermoregulation adopted by pigs (whether in cold or hot situations) mentioned previously, behavioural adjustments are an important contribution to the adaptation of the pig, in the short and medium term, to heat stress.

Thus, in cold conditions the pig tries to reduce the surface area exposed to heat exchanges, firstly **changing its posture** by adopting a huddled position, building "nests" and reducing the area of contact with the floor (Govindasamy et al., 2022; Hayne et al., 2000; Olczak et al., 2015). With its tendency to cluster under these ambient temperature conditions the pig is able to reduce the body surface area exposed to heat exchanges, resulting in a substantial drop in the lower critical temperature (Close et al., 1981; Cruz, 1997).

Vasoconstriction, decreased respiratory rate and piloerection are also behavioural adjustments that pigs use to deal with a cold environment (Azevêdo and Alves, 2009; Herpin et al., 2002). Effectively, in the case of piloerection, the hairs form veritable webs of closed air, which hinder heat exchange by convection (Cruz, 1997).

Another type of adaptation performed in low temperature conditions is the increase in heat production. This is carried out in a first phase at the expense of **increasing activity** and **food intake** (Bus et al., 2021; Cruz, 1997; Govindasamy et al., 2022; Quiniou et al., 2000).

Indeed, as mentioned previously, adjustment in feed intake is also a very important mechanism to deal with thermal stress at lower ambient temperatures, since the food consumed is required to maintain body temperature and not for growth (Bus et al., 2021; Gertheiss et al., 2015; Quiniou et al., 2000). This effect is mainly observed in young pigs that are extremely sensitive to these environmental conditions (Martins, 2020; Prunier et al., 2014).

There are not many studies that have looked at the impact of cold on feed intake since the main problem with the pigs is the heat stress. In general, these conditions lead to an increase in food intake, which is associated with a longer daily feeding duration (Gertheiss et al., 2015; Quiniou et al., 2000). Furthermore, Quiniou et al. 2000 did not identify an effect of cold temperatures on feed intake and feeding duration per visit.

When pigs are subject a long cold stress period, feed intake will reduce back to baseline levels after about two weeks (Lopez et al., 1991). The extent to which feed intake is increased depends on several factors, including pig body size (small pigs are more susceptible to cold stress than large pigs) and feed composition (Bus et al., 2021; Quiniou et al., 2000).

2.4.3. Effects of Temperature on Growth Performances

In order to understand the effects of temperature on the growth performances of growing-finishing pigs, it’s important to be aware that the efficiency of pig production depends on how the animal manages to optimize the use of nutrients contained in the feed for its maintenance and growth (Whittemore et al., 2001). According to Cruz (1997), the thermal environment has a direct effect on the heat exchange between the animal and the environment, with consequences on the energy retained for growth and other productive processes. These effects almost always result in changes in production efficiency.

The source of energy for metabolism is food. However, as can be seen in Figure 3, the pig does not use all the total energy contained in them – gross energy (GE) – because some of this energy is lost in faeces, urine, methane and hydrogen (Jo et al., 2010).

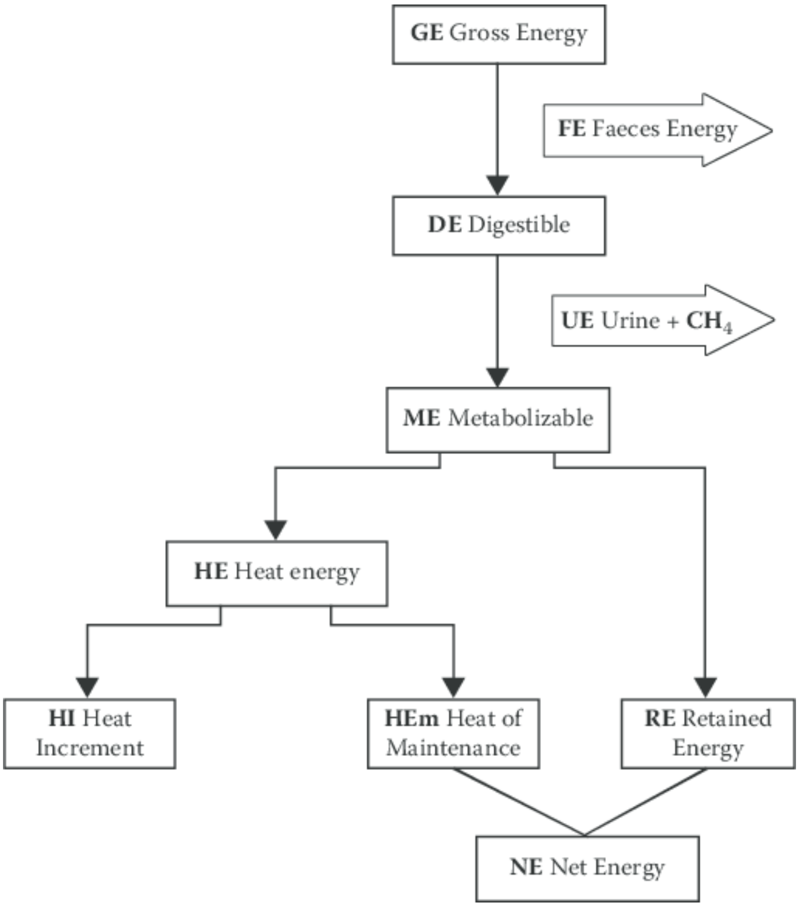


Figure 3 - The partition and losses of food energy in the body (Source: Jo et al., 2010)

The remaining energy - metabolizable energy (ME) - is the energy available for maintenance and protein/fat retention (growth, reproduction, lactation and work) (Jo et al., 2010; van Milgen and Noblet, 2003; Whittemore et al., 2001). According to Lizardo et al. (2002), ME is prioritized first for maintenance and additional excess energy is retained as protein or lipids in the body. Furthermore, the energy requirement for maintenance accounts for approximately one-third of the total ME utilization and the remainder is stored as proteins or lipids in growing pigs (NRC, 2012; Patience et al., 2015). However, this proportion varies with the growth stage of the pig and with the genetic and thermal environment and the nutritional composition of the diet (Kil et al., 2013).

It is observed that part of ME is lost due to energy expenditure during the digestive processes and metabolism of nutrients and all energy loss in the form of heat inherent to the metabolization of food is called caloric increment (Oliveira and Formigoni, 2018).

Deducting the heat increment of a food from its ME gives the net energy (NE) value of the food. This is the remaining part of the food energy used for different life processes (Jo et al., 2010).

Growth performance is related to the amount and efficiency of feed consumption. In this sense, the thermal environment exerts a strong influence on the pig's growth performance, since these animals change their **feed intake (FI)** as a function of the ambient temperature.

As mentioned previously, increasing temperature causes a drop in FI. This behaviour leads to performance and, consequently, economic losses, because when environmental conditions exceed the pig's TNZ, the energy from the feed is diverted from growth to maintaining body temperature, thus compromising efficiency (Ross et al., 2015).

In the study of Rauw et al. (2017), feed intake dropped by 25% in finishing pigs when ambient temperatures increased to approximately 32°C. The meta-analysis by Oliveira et al. (2019) reported that at ambient temperatures between 29 and 35ºC feed consumption decreased by 12%.

Le Dividich et al. (1998) reported a drop in feed consumption from 40–80 g/d per °C increase in ambient temperature between 20 and 30°C. Huynh et al. (2005a) found a slightly higher reduction in feed consumption of 81–106 g/d per °C above 23°C, depending on humidity. According to Mun et al. (2022) and Renaudeau et al. (2011), the effect of temperature is greater or lesser, depending on the pig's body weight (BW). These authors reported that between 20 and 30°C, a 50kg pig declines its FI by an average of 32 g/d per °C and at 100kg it decreases by 78 g/d per °C.

Pigs fed ad libitum and kept in TNZ or cold conditions will eat until their maintenance and growth needs are met. The same does not happen in a hot environment. In other words, when temperatures drop, FI increases at the same rate as maintenance energy needs increase (Cruz, 1997). Faure et al. (2013) found that under cold conditions (T=12°C), feed intake increased by 17%. However, according to Hines (2019), when temperatures are too cold and persistent, pigs often find themselves in a negative energy balance that cannot be corrected with feed alone. Similarly, in consistently hot conditions, pigs also enter a negative energy balance, despite adjustments in their feed intake.

The relationships between FI, **average daily gain (ADG)** and ambient temperature are very important, since the growth rate of pigs receiving a balanced diet is mainly related to the amount of feed consumption.

With ad libitum feeding, average ambient temperature recommendations for maximum ADG are between 15 and 20°C for growing-finishing pigs (Hansen and Bjerg, 2018; Massabie et al., 1996; Mun et al., 2022; Nichols et al., 1980; Nienaber et al., 1987; Renaudeau et al., 2008). When the ambient temperature deviates from these values, the bibliography indicates that there are decreases in the ADG, as can be seen in Figure 4.

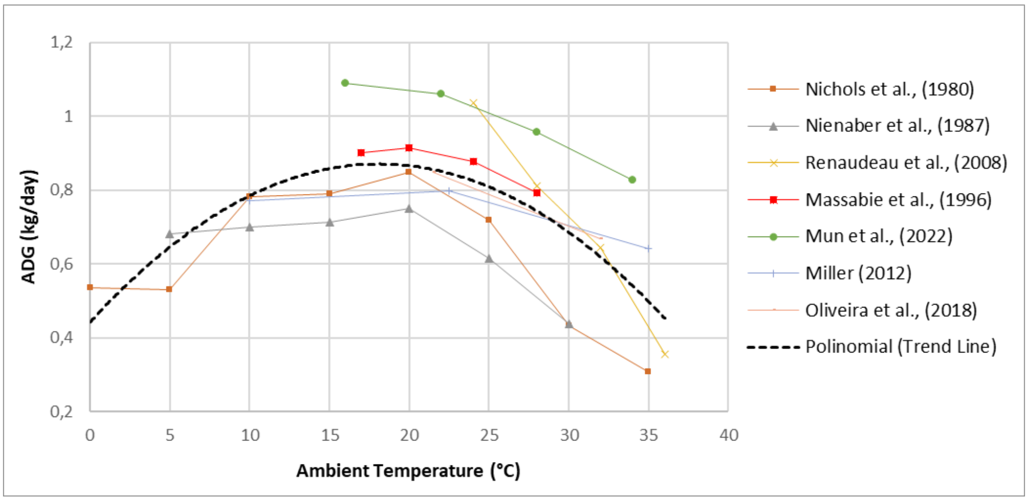


Figure 4 - Average Daily Gain vs Ambient Temperature (Source: author production)

According to Boltyanska et al. (2018), numerous practical observations have confirmed that a significant deviation from the optimum ambient temperature, whether above or below, can result in a marked decrease in the performance of pigs (15–30%). When the temperature drops considerably in relation to the recommendations, the pig cannot maintain its growth rate under these conditions by increasing FI. In these situations, the growth rate decreases with the decrease in ambient temperature since there is a high increase in maintenance needs (Cruz, 1997).

On the other hand, when temperatures rise above the recommended levels, growth rate reduction has been observed. According to Hyun et al. (1998), the growth rate decreased by 11.9% when ambient temperature increased from 24°C to 28–34°C. In the studies conducted by Collin et al. (2001), Huynh et al. (2005a), and Rauw et al. (2017), a reduction in ADG of 30%, 46%, and 60%, respectively, was observed for pigs raised at 32–33°C. In the study by Faure et al. (2013), growth performance under cold conditions (12°C) was very similar to that in TNZ conditions (23°C).

The **feed conversion rate (FCR)** is directly related to ambient temperature and feed efficiency. According to Gaillard et al. (2020), FCR is affected by the efficiency of energy utilization, which depends on the energy content of BW gain and the effect of maintenance requirements.

Figure 5 shows that the FCR for finishing pigs is minimum (maximum feed efficiency) with ambient temperatures around 20 and 25°C, not corresponding to the same temperatures range in which the ADG is maximum (15-20°C).

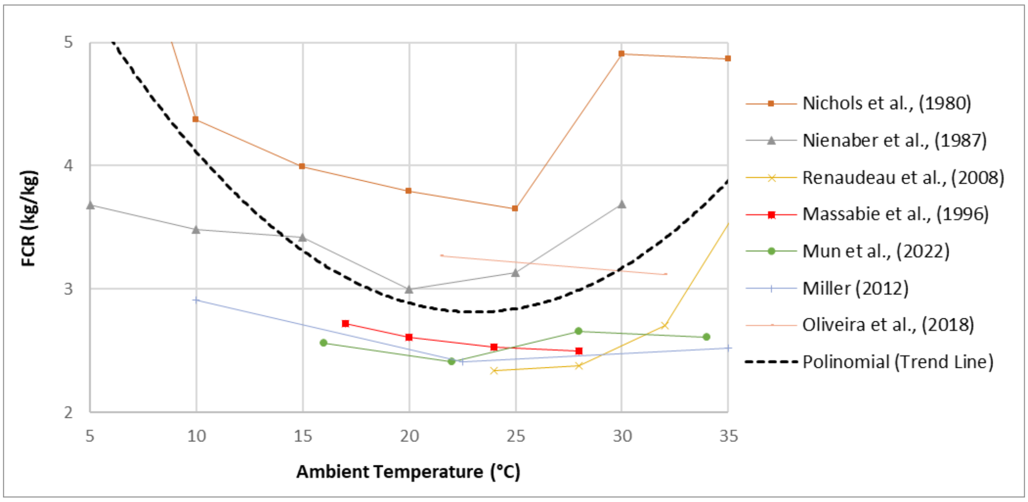


Figure 5 - Feed Conversion Rate vs Ambient Temperature (Source: author production)

The studies conducted by Nichols et al. (1980) and Oliveira et al. (2019), at thermoneutrality conditions (T ≈ 20°C), recorded an FCR of 3.79 and 3.27 kg/kg, respectively. In contrast, for the same temperatures, Massabie et al. (1996) obtained values of 2.61 kg/kg. Miller (2012) and Mun et al. (2022), at temperatures of 22°C, recorded an FCR of 2.41 kg/kg. Renaudeau et al. (2008) achieved an FCR of 2.34 kg/kg for temperatures around 24°C.

As mentioned before, in cold conditions to maintain a constant growth rate, pigs need additional amounts of feed to compensate heat losses (Bus et al., 2021; Close, 1981; Gertheiss et al., 2015; Hutu and Onan, 2019; Quiniou et al., 2000), which leads to an increase in FCR. Despite there being limited studies on the impact of cold thermal stress on the performance of growing-finishing pigs, Miller (2012) and Nienaber et al. (1987) recorded FCR values of 2.91 and 3.48 kg/kg, respectively, at an ambient temperature around 10°C. Additionally, Faure et al. (2013) identified a 21% increase in FCR when animals were subjected to cold conditions (12°C) compared to TNZ conditions (23°C).

In hot conditions, feed intake decreases, with less energy available for growth. However, according to the literature, FCR is less affected under these environmental conditions (Liu et al., 2022). The meta-analysis by Oliveira et al. (2019) demonstrated that hot conditions (29–35°C) did not affect FCR. For the same temperature range, the studies conducted by Massabie et al. (1996) and Miller (2012) reported FCR values around 2.50 kg/kg, while Mun et al. (2022) and Renaudeau et al. (2008) calculated FCR values around 2.70 kg/kg. According to Renaudeau et al. (2008), the FCR was only slightly reduced during extremely hot conditions (30–36°C) and the FCR recorded for 36°C was 3.81 kg/kg.

Understanding the effects of environmental conditions on pig **carcass composition** is crucial for ensuring meat quality and production performance. Heat stress significantly influences energy partitioning, metabolism and animal growth, ultimately affecting growth rate, reproductive performance, and carcass quality (Baumgard and Rhoads, 2012; Gonzales-Rivas et al., 2019). High ambient temperatures have been associated with reduced live and carcass weights, as well as an increased incidence of PSE meat, emphasizing the need for effective management strategies (Čobanović et al., 2016; Cruzen et al., 2015). Prolonged heat stress affects muscle structure, function and growth, leading to changes in post-mortem meat characteristics such as pH and drip loss (Cruzen et al., 2017; Yang et al., 2014). Heat stress also compromises pork fat quality, impacting ease of processing and handling, especially pork bellies, due to changes in adipose tissue consistency (Seibert et al., 2018).

Conversely, cold environments tend to result in fattier carcasses due to decreased adiposity resulting from reduced food intake. According to Cruz (1997), studies indicate that the partitioning of retained energy as protein and fat remains relatively unchanged within certain temperature ranges, but as temperatures rise, there is a reduction in energy retention as fat. Further research supports these findings, emphasizing the inverse relationship between fat tissue unsaturation and temperature. Additionally, pigs grown in cold environments may exhibit a shift in fat deposition from internal to external depots (Dunshea and D'Souza, 2003).

Moreover, the impact of heat stress on pig carcasses extends to oxidative stress and product deterioration, characterized by disrupted pro-oxidant:antioxidant balance and increased malondialdehyde content in muscle tissue (Yang et al., 2014). Carcass quality in pigs is also influenced by factors such as carcass weight, primal cuts weight and fat deposition, with heat-stressed pigs exhibiting increased lipid storage (Qu and Ajuwon, 2018).

The relationship between temperature and carcass composition underscores the importance of appropriate management practices to mitigate the adverse effects of heat stress on pig production and meat quality.

2.5. Precision Livestock Farming

With the expected world population increment, demand for agri-food products is projected to increase by 70%, doubling the consumption of animal-derived foods (Morrone et al., 2022; Rojas-Downing et al., 2017). To meet this demand, agricultural systems must intensify production (Berckmans, 2014; Ramankutty et al., 2018), which may affect animal health and welfare and raises the risk of diseases and zoonoses (Gebreyes et al., 2014; Berckmans, 2017).

Another issue associated with intensive production systems is environmental impact (Tullo et al., 2019). The livestock sector is a contributor to greenhouse gas emissions (GHG), accounting for about 10-12% of global emissions. The pig, cattle and poultry species represent the top three sources of GHG emissions generated by animal production, being the pig industry the second contributor (Gerber et al., 2013; Yang et al., 2023). Simultaneously, the number of farms is decreasing, leading to larger-scale operations and associated challenges in managing animal health and welfare (Berckmans, 2014).

The primary future challenge for intensive animal production is the ability to monitor and control the health, welfare and performance of animals in large groups. For this, it is crucial for producers to have access to tools that enable individual animal monitoring, regardless of group size (Berckmans, 2017). Precision Livestock Farming (PLF) was developed to address these challenges, providing farmers with the means to make timely, data-driven decisions regarding animal needs (Norton and Berckmans, 2018).

2.5.1. Concepts of Precision Livestock Farming

PLF is a complex concept with several different definitions within the scientific community. PLF was first suggested in 2003 by Professor Christopher Wathes and according to this author, this concept can be described as the management of livestock production using the principles and technology of process engineering (Wathes et al., 2008).

The main goal of PLF is to increase the economic, social and environmental sustainability of livestock farming (Vranken and Berckmans, 2017). This is possible because the PLF's fundamental concept is to support farmers by developing a management system based on integrated automated control and real-time monitoring of production/reproduction, animal health, welfare and the physical environment of livestock buildings, including the microenvironment and gaseous pollutant emissions (Banhazi and Black, 2009; Berckmans, 2014; Fournel et al., 2017).

The great potential of PLF is focused on early warnings, which provide farmers with the opportunity to take actions as soon as the first signs of impaired welfare or health emerge (Dominiak and Kristensen, 2017).

These monitoring and management systems demonstrates that the PLF is based on the observation of animals using sensor technologies; the application of current control theory to increase the autonomy of the production process; and the use of advanced data processing methods to synthesise and combine diverse data sources (Norton et al., 2019).

However, to obtain a functional control and monitoring system (Figure 6) three conditions must be fulfilled (Berckmans, 2006; Fournel et al., 2017; Whates et al., 2008):

(i) **Animal responses** (behavioural, physiological or productive) need to be measured continuously with accurate and cost-effective sensor technology at an appropriate frequency and scale with information feedback sent to the process controller.

(ii) A compact **mathematical model** is required to reliable predict (expect) at every moment on how animal variables will vary or how the animal will respond (outputs) to process input changes (environment, nutrition, etc.). The continuous comparison between this prediction and the actual measured values allows to identify the animal activities and determine when something abnormal is occurring.

(iii) Predictive models together with the online measurements are integrated in an analysing algorithm (**online controlling system**) for automatic monitoring and/or management when critical thresholds are breached according to predetermined criteria such as target values and trajectory for each process output.

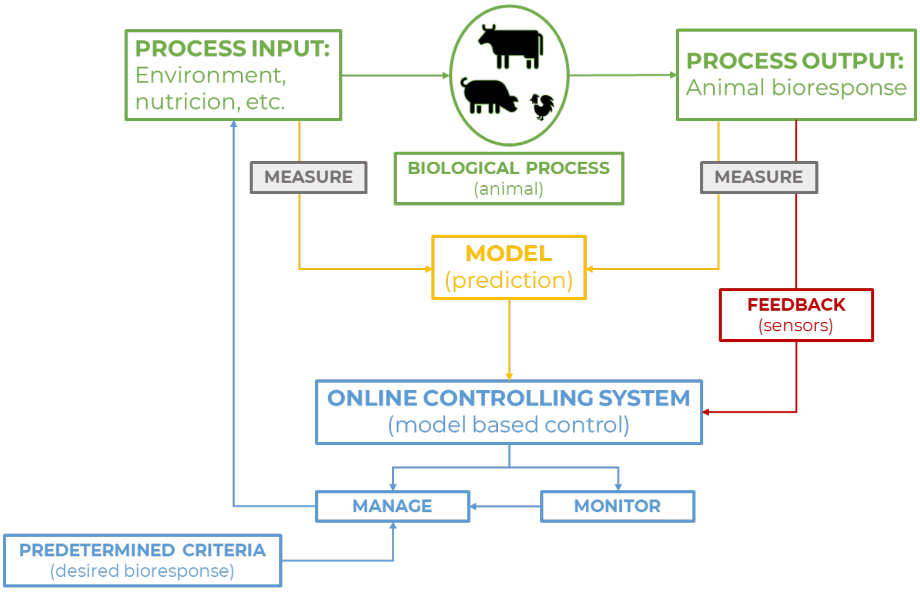


Figure 6 - General scheme of model-based monitoring and management system (Adapted from: Berckmans, 2006; Fournel et al., 2017; Whates et al., 2008)

Although the general premise of using technology and automation to enhance precision in industrial manufacturing is easily transferable to PLF, the transition from inert items to live animals poses new challenges that must be addressed when developing PLF operations (Føre et al., 2018).

According to Berckmans (2017), it was stated during the first European PLF Conference in 2003 (Berlin) that a living organism is considered a **CITD system** (complex, individually different, time-varying and dynamic) due to its complexity compared to any mechanical, electronic or Information and Communication Technology (ICT) system.

In fact, this is a key point when we are talking about PLF systems, because most of the early advances in research based on ICT-supported livestock management systems were based on the simulation of different scenarios that had an impact on economic indicators or production sustainability. These optimised functions represented the farm's processes and did not seek to interface with the animals themselves (Norton et al., 2019). However, the **animal is the central component of the process** and each individual have a different bio-response to some specific stimuli.

Due to animals' time-varying behaviour, monitoring according the PLF approach requires continuous measurements of the animals’ responses directly on the animal rather than in the environment that surrounds it. The word “continuous”, depending on the monitored variable, can mean every second (i.e., for behaviour monitoring) or once a day (i.e., for weight monitoring) (Berckmans, 2017).

Nowadays, due to technological advancement over the previous decade, accurate, powerful and low-cost devices are accessible to manage individual animals by continuous real time monitoring. The purpose of these technological instruments is not to replace, but rather to assist a farmer, who still the most essential part of good animal management (Berckmans, 2017; Morrone et al., 2022).

2.5.2. Internet of Things (IoT) and Big Data

First conceptualized by Kevin Ashton, the **Internet of Things (IoT)** refers to the global network of digitally connected devices and machines (“things”) that communicate, sense and interact through embedded technology (Lee and Lee, 2015; Misra et al., 2020; Morrone et al., 2022; Whitmore et al., 2015). This concept is often referred to as the “Internet of Everything” (IoE) or the “Industrial Internet of Things” (IIoT) due to its potential applications. In this approach, a system is created not only of objects but also for everything that can be treated as a variable (processes, data, people, animals, climate, etc.) (Witkowski, 2017).

According to Misra et al. (2020), IoT platforms serve as the bridge between the devices' sensors and the data networks, where the connected IoT devices exchange information using internet transfer protocols.

At the core of the Internet of Things is an integrated computer system that must perform critical decision-making functions in real time (Tien, 2017). This means that within an IoT network, a large amount of data is continuously transmitted to a “data lake” (local physical server or cloud-based storage) where this data is processed through appropriate algorithms or machine learning techniques (artificial intelligence technologies) to generate actionable insights (Misra et al., 2020). However, with the rapid development and the large number of devices deployed in IoT environments, an unprecedented amount of data (Big Data) is continuously generated (Morrone et al., 2022).

Big data, similar to IoT, is an abstract concept with different opinions on its definition. Apart from masses of data, it also has some other characteristics that distinguish it from “massive data” or “very big data". In general, big data refers to datasets that cannot be perceived, acquired, managed, and processed in a tolerable time using conventional IT (Information Technology) and software/hardware tools (Chen et al., 2014, Saleem and Chishti, 2019). Because of this, Big Data technologies have emerged as a critical data analysis tool (reveal trends, hidden patterns, hidden correlations, inferences and actionable insights) in order to better serve the purpose of IoT systems and support critical decision making (Ge et al., 2018).

Due to the industry's interest in the potential of these tools, Big Data and its technologies have opened opportunities for the development of new IoT solutions and applications. The fusion of Big Data and IoT, as well as the constant and dynamic evolution of the two domains, created conditions for the development of solutions for many complex systems (Ge et al., 2018).

In this context, related to livestock production, a new concept is emerging: the Internet of Animal Things (IoAT). However, as previously mentioned, the animal is the centre of the process in a PLF system and therefore its CITD nature has a relevant impact on the type of algorithms that need to be developed to monitor these time-varying individuals. As a consequence, only a few approaches are appropriate for creating real-time monitoring tools for humans and animals (Berckmans, 2017).

The success of PLF depends on interdisciplinary collaboration between complementary research fields, such as animal scientists (physiologists, ethologists, nutritionists, geneticists, etc.), laboratory technicians, data scientists, computer science, engineers and others (Norton and Berckmans, 2018; Norton et al., 2019).

The most significant challenge facing PLF field applications is the data science task of converting diverse types of data (from different sensors and sources) into actionable information (Morrone et al., 2022). In this sense, the introduction of Information and Communication Technology in the livestock industry, as well as the increasing use of IoT and Big Data technologies, opened a new era of connectivity between things, people and animals, capable of providing the key to sustainable livestock farming in the future (Halachmi et al., 2019).

2.5.3. PLF Technologies in Pig Production

PLF technologies have been developed in a general way for a range of applications, including improving traceability (Banhazi et al., 2012; Vranken and Berckmans, 2017); improving control of diseases and health and, consequently, animal welfare (Buller et al., 2020; Neethirajan et al., 2017; Racewicz et al., 2021); reducing environmental impact (Correia, 2019; Tullo et al., 2019); and creating added value for farmers (Berckmans, 2017; Norton et al., 2019) through early warning systems for livestock production variables, and developing descriptive and predictive models.

As mentioned in the previous sub-chapters, the purpose of developing PLF technologies is to monitor continuously, dynamically and in real time, the health and welfare of each animal and, when this is not possible, a group of animals to assist the farmer in caring for his animals (Norton et al., 2019). For this, there are several technologies that can be used to automatically monitor and control environmental, physiological, behavioural and productive variables, without any disturbance or manipulation. Cameras, microphones, sensors, IoT, Big Data technologies and cloud storage are examples (Berkmans, 2014).

The connection between these PLF technologies and animal welfare indicators is a key process to “measure”, evaluate and manage animal status. Ensuring this, is the necessary condition to obtain an optimal productive and reproductive performance while improving sustainability and minimising environmental impact (Tullo et al., 2019; Vaintrub, 2021).

The European pig industry has been familiar with the concept of PLF for some time now, and its implementation is currently expanding rapidly (Morrone et al., 2022). The following topics will provide a summary of the different technologies that are used to monitor the key animal parameters in growing-finishing pig production.

2.5.3.1. Environmental parameters

The environmental parameters generally measured in relation to animal thermal comfort include ambient temperature, humidity, radiation and air velocity. These roughly characterize the environment where the animals are (Fournel et al., 2017) and are measured in the area where the animals are confined (Eigenberg et al., 2009). This allows the information obtained by production system managers to be more accurate and up to date, which facilitates the decision-making process (Eigenberg et al., 2009).

- **Ambient Temperature**

Ambient temperatures in livestock facilities can be successfully measured using **thermocouples** or **thermistors** (Fournel et al., 2017). Thermocouples measure the ambient temperature through the thermal voltage associated with dissimilar metals and offer some advantages such as their durability, relatively low costs and versatility. On the other hand, thermistors are based on the electrical resistance of metals to measure the ambient temperature and have the advantage of being much more sensitive and tolerant of large temperature differences than thermocouples, although their construction makes them more fragile (Eigenberg et al., 2009; Frost et al., 1997).

- **Humidity**

Research has shown that in harsh environments, such as livestock facilities, thermal conductivity methods can be used successfully to determine the water vapor content present in the facility (Fournel et al., 2017). The accuracy of the method decreases with lower temperatures. However, the sensors can work with high temperatures, corrosive gases and dust. A **thermistor combined with a relative humidity sensor**, protected by a sintered stainless-steel filter, are usually installed in livestock facilities (Banhazi, 2009; Fournel et al., 2012).

Furthermore, to measure humidity, other sensors also can be employed: **capacitive sensors** measure changes in capacitance caused by humidity; **resistive sensors** detect changes in electrical resistance as humidity is absorbed; and **semiconductor sensors** alter their electrical properties in response to humidity. Additionally, **optical sensors** detect changes in light absorption or refraction, while **surface acoustic wave sensors** detect changes in acoustic properties due to humidity (Sajid et al., 2022).

- **Radiation**

Radiant energy is usually measured by detecting changes in the temperature of a surface exposed to radiation or by the response of a photoelectric cell. **Pyranometers**, which measure total, direct and diffuse radiation, are the most common type of instrument used to quantify solar radiation in studies involving animals (Fournel et al., 2017).

On the other hand, the **Vernon globe thermometer** is the standard instrument for measuring the temperature of the black globe. It consists of an empty 150mm copper sphere with black painted walls on the outside, containing an unshielded dry bulb thermometer in the center of the sphere. It integrates radiant heat exchange and heating by convection or cooling into a single value that can be used to calculate the average radiant temperature (Eigenberg et al., 2009).

The amount of light or luminous flux projected per second onto a unit area of a surface (luminance) is measured by an instrument called a **luxmeter**. The unit of measurement is the lux. One lux is equal to one lumen per square meter (lm/m^2) (Pedroso et al., 2016).

- **Gas concentration**

Most of the sensors available on the market for measuring gas concentrations have three different operating principles: resistive, optical and electrochemical sensors (Gomes, 2015).

According to Aleixandre and Gerboles (2012), the measuring principle of **resistive sensors** is based on the variation in resistance or conductivity of a metal oxide when exposed to different concentrations of a given gaseous compound. Within **optical sensors**, the main type of sensor used to measure gaseous compounds is the infrared absorption sensor, however there are also photoionization sensors, based on the ionization potential as a working principle (Castell et al., 2013).

Electrochemical sensors can be divided according to their operating principle into three classes: amperimetric, potentiometric and conductimetric. In the amperimetric electrochemical sensor, when the electrochemical cell for measuring gases is exposed to a gaseous atmosphere containing an electroactive compound, electrochemical oxidation-reduction reactions are triggered (Jacquinot et al., 1999); in the potentiometric electrochemical sensor, the electrochemical reactions occurring in the sensor allow the open-circuit voltage between the two electrodes to be measured, this voltage normally being proportional to the logarithm of the gas concentration (Stetter and Li, 2008); and in the conductimetric sensor, according to Janata (2010), the concentration of the target gas is related to the reading of the conductance of the electrochemical cell, this being the reciprocal of the resistance.

- **Air velocity**

Air velocity is measured in the surrounding of the animal to capture the animal's heat and mass exchanges (Eigenberg et al., 2009). Air speed can be measured by **anemometers** of different types, based on mechanical methods, pressure relationships, thermal principles and the Doppler effect. These devices are very sensitive instruments and are easily affected by traces of dust (Eigenberg et al., 2009).

In animal production applications, depending on the type of airflow being measured, two types of anemometers are common: **hot wire anemometers** and **propeller anemometers**. A hot wire anemometer is the instrument of choice for low air velocity applications, such as 0,25 m/s (conditions found in many livestock facilities). The propeller anemometer is a more robust instrument that is well suited to air currents. These anemometers do not measure low air speeds (< 0.25m/s) because the mass of the blade requires a good amount of moving air to rotate (Fabian-Wheeler, 2012).

2.5.3.2. Animal Identification and Automatic Tracking

In order to improve pig farm management, the automatic identification of individual animals is crucial. **RFID (radio-frequency identification)** transponders have been used to replace ear tags for automated tracking, however, there are issues with the accuracy (Maselyne et al., 2014). There are two types of RFID chips: low frequency (LF-RFID) and ultra-high-frequency (UHF-RFID). LF-RFID tags are mainly used to register behaviour and health, especially feeding or drinking patterns of individual pigs and have a range of less than 1m. UHF-RFID tags can identify multiple animals at a greater range of 3-10m, but are sensitive to interface, leading to false registrations (Benjamin and Yik, 2019; Matthews et al., 2016). Although there are some disadvantages of using RFID ear tags for pigs, such as loss of tags, pain, and stress during tagging, RFID technology can improve traceability (Benjamin and Yik, 2019).

Computer vision and **artificial intelligence-based methods** are being explored to automatically evaluate many parameters, including the identification of pigs by camera images (Brünger et al., 2018).

Optical character recognition is a low-cost method for remote identification of animals that can be used to detect the characters or symbols (license plates or QR codes) on an ear tag and read them automatically using a digital camera and machine learning algorithms (Jacobs and van Erp-van der Kooij, 2021; Schmidt et al., 2022). The system can also be used to identify animals written or painted characters on the animal, however, visual patterns may not be as effective as ear tags because they can quickly disappear or blur, making them difficult to read accurately (Benjamin and Yik, 2019).

Facial recognition technology (Figure 7), originally developed for human identification, can now be employed to recognize individual pigs at high speeds (images/second), achieving in some recent works up to 95% accuracy. The typical facial features used for recognition include the snout, top of the head, and eye regions (Benjamin and Yik, 2019; Hansen et al., 2018).

Figure 7 - Set of images used for facial recognition training (Source: Benjamin and Yik, 2019)

2.5.3.3. Animal Behaviour

As previously mentioned, animal behaviour is an important indicator of animal welfare, health and performance. In the PLF approach, there are different technologies being used and tested to monitor animal behaviour. In the following text will be discuss some of these technologies:

- **Aggressive Behaviour**

Aggressive behaviour in livestock animals can cause harm and negatively impact their growth, health, welfare, and economic performance. Traditionally, such behaviour has been monitored through direct observation or video recording, but recently **image processing methods** have been developed to automatically detect and classify aggressive interactions (Nasirahmadi et al., 2017; Oczak et al., 2012). Studies have used different methods to classify aggressive behaviours based on features extracted from image data (Lee et al., 2016; Viazzi et al., 2014). Although these methods have shown high levels of accuracy in some studies, more research is needed to develop in commercial conditions to develop reliable and practical alarm systems to assist farmers (Nasirahmadi et al., 2017).

- **Social Behaviour**

Real-time monitoring of animal health and welfare can be achieved not only using cameras and image analysis, but also by utilizing **microphones and sound analysis** (Berkmans, 2017). By analysing social behaviours as the vocalizations of animals (characteristics and acoustic signs), machine learning algorithms can detect conditions of illness or suffering such as heat stress, respiratory diseases and discomfort related to poor air quality (Neethirajan, 2020; Wang et al., 2020). Coughing sounds, in particular, can be easily distinguished from other sounds and used to identify respiratory disease outbreaks between individual pens. Despite several studies having been conducted in recent years to develop cough recognition systems and there are currently some commercially available options, detecting and analysing sound can be difficult in noisy pig farm environments (Chung and Pavord, 2008; Racewicz et al., 2021).

- **Feeding and Drinking Behaviour**

Feeding behaviour in animals has traditionally been monitored through direct human observation or time-lapse video recording techniques. However, these methods are time-consuming and may cause stress (Brown-Brandl et al., 2013). Because of that, RFID systems have been used to monitor feeding and drinking behaviour (Maselyne et al., 2014; Maselyne et al., 2015b). In addition, **electronic feeding stations (EFS)** integrated with an RFID system and combined with weighing scales, may be used to separate pigs into weight groups with different diets (Jacobs and van Erp-van der Kooij, 2021; Murphy and De Lange, 2004).

This technique is called precision feeding and ensures that the proper amount of feed with the suitable composition is supplied on time to a group or individual animal (Pomar and Remus, 2019). These pieces of equipment require a significant investment (Zhuang et al., 2022), but they are the most technical feeding option for pigs and are mainly used for group-housed sows typically (40 to 60 sows per station) (Verdon, 2019). However, they can also cause stress due to ear tags and the animal's need to share limited and instrumented feeding places (Nasirahmadi et al., 2017).

Machine vision has been used as an alternative method to recognize pig's feeding and drinking behaviour (Alameer et al., 2020). Both 2D and 3D cameras have been utilized and classification models have been applied to enhance the process (Viazzi et al., 2015; Shelley, 2013). However, identifying multiple animals during feeding and drinking times presents a challenge that has not been completely solved yet (Nasirahmadi et al., 2017).

- **Behaviour associated with posture and locomotion:**

Different technologies can be used for monitoring pigs' locomotion for various purposes, such as detecting playing and lying behaviours, lameness and assessing welfare.

Pigs spend most of their time lying down and their lying behaviour can provide information about their health, welfare and production efficiency. Temperature, pen design, location of feeders and drinkers, air velocity and humidity are some factors that affect pig **lying behaviour** (Spoolder et al., 2012; Nasirahmadi et al., 2015).

Studies have used **machine vision** and **artificial neural networks** (ANN) to identify and classify pig lying behaviours based on features such as perimeter, area, length and width of animal.

Nasirahmadi et al. (2017) developed an ANN classifier using image processing and Delaunay triangulation (DT) features obtained from binary images of lying pigs (using top view cameras) to define and classify lying patterns of grouped pigs based on room set temperature. The overall accuracy of the classifier was reported as 95,6%.

Preventing pigs from lying in the dunging area is important to maintain hygiene (Spoolder et al., 2012) and to monitor this behaviour, the machine vision approach was also tested on grouped pigs by Nasirahmadi et al. (2016).

Several studies have developed software tools based on image processing techniques, such as image subtraction and automatic threshold detection methods (Lind et al., 2005), top-down view images (Kongsro, 2013) and optical flow pattern analysis (Gronskyte et al. 2016) to monitor locomotion behaviour.

Lameness detection of cows has been adopted in several studies based on back posture/arch and gait asymmetry analysis. However, monitoring individual pig locomotion within groups using **machine vision techniques** is still challenging due to their similarity in shape and size. Using some mark or paint on a pig's body or using radio frequency tags could be an alternative for short-term locomotion tracking (Nasirahmadi et al., 2017).

Accelerometers are devices used to measure linear or angular acceleration in livestock, providing accurate information about animal behaviour such as posture, walking patterns and the time spent standing (Benjamin and Yik, 2019; Racewicz et al., 2021). Research has shown that accelerometers can detect early lameness in pigs and even infections when combined with body temperature sensors (Martínez-Avilés et al., 2017). However, due to the exploratory and curious behaviour of pigs, the use of these devices is not always easy and often results in their destruction.

2.5.3.4. Animal Physiology

Early detection of symptoms of illness or abnormal behaviour in pigs is crucial for effectively addressing animal welfare and disease challenges, contributing to minimize lost production and prevent death of livestock (Morrone et al., 2022). However, measuring physiological parameters in pigs can be challenging as it may produce a stress response in the animal. There are some technologies available and ongoing research to measure these indicators, particularly internal and surface temperature.

- **Internal and Surface temperature:**

The use of **temperature sensors** to measure **internal temperature** in pigs is moderately reliable but is characterized by a high degree of variability, due to the fact that these devices are usually embedded in a data logger or a sensor installed in an ear tag or subcutaneous transponder, which decreases their precision compared to rectal measures (Lohse et al., 2010; Racewicz et al., 2021).

An alternative method to measure surface temperature is **thermal imaging** (Figure 8), which allows for non-invasive and remote assessment of body **surface temperature** distribution (Ludwing et al., 2014; Zhang et al., 2019). Thermography, also known as thermovision, is a technique that can detect various physiological and pathological processes in pigs, such as inflammation and infectious diseases and can monitor welfare and stress levels (Racewicz et al., 2018).

Figure 8 - Thermographic analysis using a thermal camera (Source: Cruz et al., 2021)

However, temperature readings obtained through thermal imaging depends on many factors, including the temperature of the facility and equipment (such as floor, walls, ceiling, feeders, drinkers, etc.), the variable distance from object to lens and the animal's age and thermoregulation (Nasirahmadi et al., 2017; Sellier et al., 2014). Furthermore, the interpretation of animal surface temperature can be difficult, making the real-time monitoring of health and disease using thermography more challenging (Nasirahmadi et al., 2017).

2.5.3.5. Animal Performances

The key in growing-finishing pigs is to optimize the growth performance of the animals. Knowledge of the **body weight** of pigs is essential in managing performance-related parameters that have an impact on the herd's output, such as animal growth, uniformity, feed conversion efficiency, space allowance, health and market readiness (Kongsro, 2014). The body weight of a pig is typically measured through manual or automatic weighing scales, which involves driving the pigs to the scale. This process is labour-intensive and stressful for both the animals and the workers involved (Wang et al., 2008; Kongsro, 2014).

Therefore, an accurate and non-invasive method for regularly weighing pigs without stressful and labour-intensive procedures is a valuable tool for pig farmers. Several research teams have attempted to develop different **image processing** methods for monitoring pig's body weight (Vranken and Berckmans, 2017). According to these authors, the principle of the automated weight detection by video image analyses is, in theory, quite simple but, in practice, more challenging.

Some researchers have utilized top-down view CCD (charge-coupled device) cameras to obtain individual pig live weight estimates based on length and width dimensions (i.e., length from scapula to snout, length from tail to scapula, shoulder width, breadth at middle and back) and boundary area (Schofield et al., 1999; Doeschl-Wilson et al., 2004).

Other several techniques have been developed for live weight estimation in pigs using top view image analysis using extracted features such as area, convex area, perimeter, eccentricity, major and minor axis length and boundary detection with artificial neural network methods (Wang et al. 2008; Wongsriworaphon et al. 2015) and infrared depth map images from a Kinect camera (Kongsro, 2014).

Cameras have the potential to estimate weight in pigs, but a commercially available solution for individual animals does not yet exist. However, the addition of an RFID reader to a weight estimation camera could solve this issue (Jacobs and van Erp-van der Kooij, 2021).

Alternatively, automatic weighing in pigs is feasible by installing a weighing device in the pen, which can record the weights of the animals automatically. **Electronic feeders** combined with **weighing scales** and an **RFID system** can automatically identify and weigh pigs every time they are fed, allowing for efficient monitoring and control of their growth (Maselyne, 2015a; Rico, 2019).

2.5.4. Precision Environmental Control

Given the predicted demand for animal products, farm intensification and the desire to improve animal welfare, PLF might be the solution for livestock companies to maintain or even increase production and animal comfort. Environmental control is one of the primary areas in which PLF technology might be used (Fournel et al., 2017).

Environmental control systems in animal housing are a very important tool to provide environmental conditions that allow for adequate levels of productivity and animal welfare (Cruz, 1997; Babot and Revuelta, 2009). However, environmental control of livestock facilities is typically based on rates/balance of heat and moisture production at predetermined ambient temperature levels. This traditional control method cannot reflect the true thermal animal’s needs because it does not account some environmental, physiological and behavioural factors, such as air quality, animal surface temperature or animal feed intake (Pandorfi, 2012; Rico, 2019).

According to a review conducted by Fournel et al. (2017), it is evident that over the past two decades, a range of new technologies have become available for ventilation, heating, and cooling of livestock buildings. However, there has been limited progress in the development of adequate control algorithms in this field. This lack of advancement was already highlighted by Banhazi et al. (2009), who emphasized the need to integrate more knowledge about the interaction between animal responses and control actions into the applied algorithms.

Based on this and the general overview provided throughout the literature review, an effective precision environmental control system requires (Banhazi et al., 2012; Fournel et al., 2017; Wathes et al., 2008):

(i) **Continuous sensing of environmental parameters** and, depending on the system complexity, **physiological and behavioural responses** should also be considered.

(ii) **Data storage**: A reliable system for storing the collected data is required to ensure easy access and further analysis.

(iii) Interpretation of measurements using **bioresponse simulation models**: The collected data should be analysed using bioresponse simulation models like animal comfort indices or bioenergetic models. These models predict the real-time impact of each variable on the animals' response to changing ambient conditions.

(iv) **Online controlling system**: An automated controlling system should be in place to modify the animal microenvironment when critical thresholds are exceeded. This system should adjust environmental parameters based on predetermined criteria, such as target values and desired trajectories for each process output.

3. AIMS AND OBJECTIVES

This literature review highlights a clear interest in the use of PLF technologies in pig production. However, it also underscores the complexity and variability of different key components for the successful implementation of PLF, particularly concerning animals, facilities, technologies and data management. As a contribution to the advancement and validation of PLF use in intensive pig production, studies were conducted within the scope of the AWARTECH project (Animal Welfare Adjusted Real Time Environmental Conditions of Housing) whose goal was to develop a new tool (AWARTECH Smart Sensing platform) that would respond in real time to the environmental needs of animals through physiological, behavioural and productive indicators using smart-sensing technologies.

Based on that and in the contents addressed in the literature review, the objectives of present thesis were:

1. To develop and update study about the impact of environmental conditions on the performance and welfare of growing-finishing pigs.
2. To test and validate PLF technologies developed within the framework of the project.
3. To realise the potential contribution of precision livestock farming tools for measurement of the impacts of environmental conditions on the performance and welfare of growing-finishing pigs.
4. To evaluate how the precision livestock farming tools can help improving the growing-finishing pig’s performances and welfare.

4. MATERIAL AND METHODS

In order to achieve the goals of the present thesis, three experimental trials were made. The trials were conducted during periods where the desired experimental conditions of the facility could be more easily achieved with minimal energy use for heating or cooling. Therefore, Trial 1 aiming to have internal winter conditions (W) took place between December - February 2018/2019; trial 2, aiming internal thermoneutrality (TNZ) occurred between March and June 2019 and, finally, trial 3, having in view internal summer conditions took place between June and - September 2019.

To conduct these trials, it was necessary to set up and prepare the experimental facility. This process spanned approximately one year and involved installing all the required equipment and technologies for animal handling and data collection, as outlined in the protocol developed at the project's beginning. Data collection took place during the trial periods, with preliminary tests conducted before the animals' arrival.

4.1. Infrastructures and Equipment

All trials took place in the University of Évora. Évora is located in the South of Portugal (38°34'0"N; 7°54'0"W) in a region denominated Alentejo. This region is characterized by its Mediterranean climate, with dry and hot summers and rainy (with substantial inter-annual variations) and cold winters (Sousa Macedo et al., 2019). The experimental site was at the Mitra Experimental Farm in an environmental controlled room.

A pen with an area of approximately 12.0m^2 was installed in the environmental control room (Figure 9). The pen had a manure pit and was equipped with an automatic feeding station (*Schauer Compident MLP II*) and two nipple drinking bowls. The floor was partially concrete cover with anti-slip tactile.

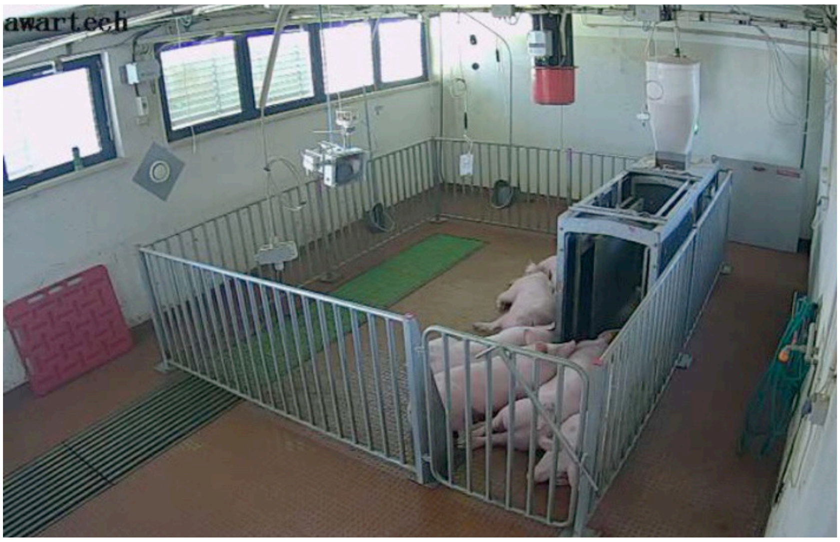


Figure 9 - Environmental controlled room (Source: author production)

Environmental control was carried out through ventilation, heating and cooling systems. Ventilation system was composed by two vertical extractors fans. The air came into the facility through a false ceiling to protect the animals and left through the extractors (negative pressure). The heating system consisted of a conventional gas heater. The cooling of the facility was made by a nebulization system.

The environmental control room was equipped with different equipment and technologies that allowed to record environmental, behavioural and physiological data. These devices are described in Table 3:

Table 3 - Characteristics of the equipment used to record environmental, behavioural and physiological data

Data	Materials	Unit.	Measurement ranges	Accuracy
Environmental	Atmospheric pressure sensor (RK300-01)	1	600 – 1100 hPa	± 0,5hPa (resolution 0,1 hPa)
	CO2 sensor (E2608-CO2-10K)	1	0 – 10 000 ppm	± 50 ppm (resolution 1ppm)
	CO sensor (CapTemp TH3-CO)	1	0 – 100 ppm	± 1 ppm (resolution 16 bits)
	Hot wire anemometer (Gill WindSonic P6022)	1	0 – 60 m/s	± 2% (resolution 0,01 m/s)
	H2S sensor (CapTemp TH3-H2S)	1	0 – 100 ppm	± 0,5 ppm (resolution 16 bits)
	Lux meter (LXT-TRM)	1	0 – 50 000 lux	± 5% (<10 000 lux); ± 10% (>10 000 lux) (resolution 1 lux)
	NH3 sensor (CapTemp TH3-NH3)	1	0 – 100 ppm	± 1 ppm (resolution 16 bits)

Data	Materials	Unit.	Measurement ranges	Accuracy
	Relative humidity probe (EE06)	1	0 – 100% RH	± 3% (10 – 90% RH); ± 5% (<10% RH e >90% RH) (resolution 0,1% HR)
	Temperature probe (COPILOT)	4	-10 – 50 °C	± 0,2 ªC (resolution 12 bits)
	Temperature probe (CapTemp TH3-Temp OW)	7	-10 – 55 °C	± 0,5 ªC (resolution 12 bits)
	Weather station (Barani Weather Station)	1	0 – 100 m/s; 0 – 360°	< 2%; 2°
Productive / Behavioural	Electronic Feed Station (Schauer Compident MLP II)	1	25 – 120 kg	± 0,1 kg
Behavioural	Microphone (Hi-fidelity Pickup DH HAP300)	1	20Hz – 20kHz	---
	Sound level meter (PCE SLT-TRM-ICA)	1	30 – 130 dB	± 1,5 dB (resolution 0,1 dB)
	Video camera (Foscam FI9961EP);	6	continuous	---
Physiological	Thermal camera (Optris PI 400/450)	1	continuous	---

4.2.Animals

In each trial, 8 female pigs of *Piétrain* x *Topigs Norsvin* (TN60) genotype were used whit an initial body weight of 52.8 ± 3.1kg (range: 47.5 – 61.3 kg). The animals were selected at the supplier farm (a multiplication unit working with Topigs Norsvin) to obtain experimental groups with the most homogeneous initial weight possible. The free space area per animal in the pen was about 1.5 m^2. After the animal's arrival, they were individually identified using an electronic ear tag (RFID system) (Figure 10).

Figure 10 - Electronic identification system (RFID ear tag) (Source: author production)

Each trail started after 15 days of habituation period to the room, feeding station, environment and human presence/handling at thermoneutral (TN) conditions (T_{mean} = 18 ± 2°C and RH_{mean} = 60%). During this period, food was provided *ad libitum* and there was free access to water.

Feed was provided to the experimental animals through an electronic feeding station describe later in this chapter. Throughout the trial, the animals were fed with a commercial balanced concentrated feed for growing-finishing pigs in the form of flour and stored in a silo located near the room, with the following nutritional information (data provided by the supplier): Metabolizable energy (3152 kcal/kg); Starch (43.4%); Crude Protein (16.8%); Crude Fat (3.5%); Crude Fiber (4.6%); Crude Ash (5.2%); Lysine (1.10%); Methionine (0.36%); and Threonine (0.78%).

The daily feed allowance per animal was set at the feeding station based on an estimated *ad libitum* consumption (INRA, 1984). Reference values for each weight are presented in table 4. The maximum amount of feed offered per visit and per day to each animal was set at 800 g and between 1.9 to 3.2 kg (depending on the animal's weight), respectively. Every 24 hours, at 6 am the machine recorded the total daily consumption of each animal, performed a check-up, and replenished the feed for all animals.

Table 4 - Estimated maximum voluntary feed intakes for growing-finishing pigs (Adapted from: INRA, 1984)

BW (kg)	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**	**105**	**110**
Kg of feed	1.7	1.9	2.0	2.2	2.3	2.4	2.6	2.7	2.8	2.9	3.0	3.2	3.3	3.4

Animals had free access to water supplied by two bowl drinkers with nipples, with an instantaneous flow rate of 130 mL/s.

4.3. Experimental procedures

In order to fulfil the objectives of the present thesis, 3 trials were made in different environmental conditions regarding air temperature and relative humidity.

The three different environmental conditions defined were: Winter (W) – cold stress (trial 1), Thermoneutrality (TNZ) – thermal neutrality (trial 2) and Summer (S) – hot stress (trial 3). The goal values for temperature and relative humidity on each trial are described in Table 5.

Table 5 - Experimental environmental setpoints

Environmental conditions	**Winter (W)**	**Thermoneutrality (TNZ)**	**Summer (S)**
T (ºC)	10 ± 2	18 ± 2	30 ± 2
RH (%)	80	70	60

Extreme environmental conditions were not simulated, as the aim was to operate within ethical animal welfare practices and in line with the realities of commercial farming, where such extreme conditions are rarely achieved.

Each trail finished when the animals reached a commercial slaughter weight of 97.4 ± 5.3 kg (range: 88.5 – 112.2 kg).

4.4. Data Collection

Environmental, productive and behavioural data were recorded automatically in this study. Each of these parameters was collected at different intervals, as outlined in the following sections.

- **Environmental measurements:**

The environmental variables measured were temperature (T) and relative humidity (RH). The collection of data was conducted through an environmental control system (Webisense) and a data collector platform (Nidus), that incorporated several specific equipment (described in *Table 3: Environmental data*), which allowed to record a high amount of data simultaneously. These measurements were taken continuously, with data recorded every minute.

The data were processed using the software of the environmental control system, which provided the hourly average values of the parameters (24 measurements per day). Based on these hourly values, the daily average was calculated for each of the parameters. The calculation of values per environmental condition resulted from the average of the daily recorded values.

- **Animal measurements:**

a) Animal productive performance

Animal's **body weight** and **feed intake** were recorded at the electronic feeding station (Figure 11), which through the RFID ear tag system, allowed to monitor and individually control, in each feeder access, the amount of feed supplied and ingested (grams) and animal's body weight (grams). At the end of each day, after the feeding machine check-up, the software provided the daily average values of live weight and feed intake. The recorded data allowed to calculate each animal **average daily gain** and **feed conversion rate** (more information in section 4.5 *i.*).

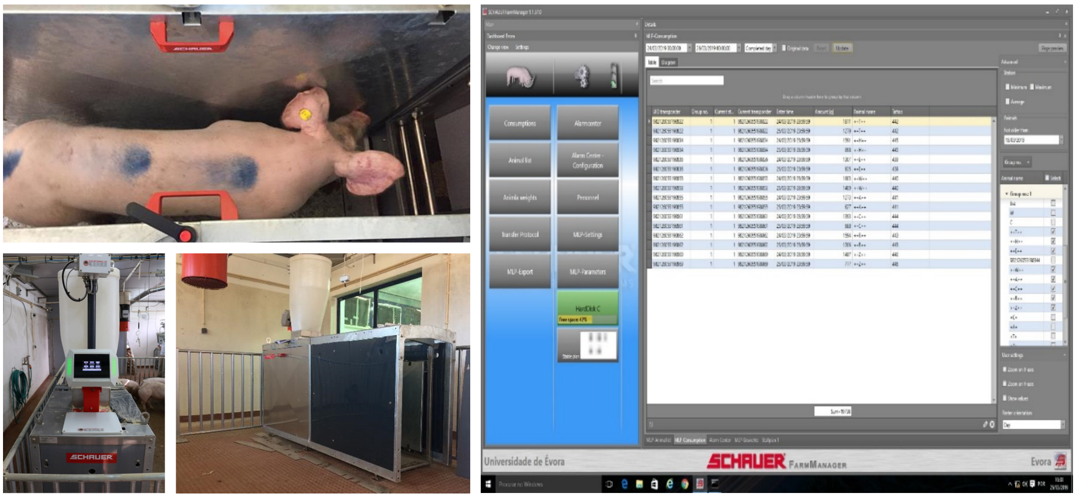


Figure 11 - Electronic feeding station Schauer Compident MLP II (Source: author production)

b) Behavioural measurements

i. Feeding behaviour

Data on feeding behaviour was recorded using the electronic feeding station. Using the RFID identification, for each animal entry at the electronic feeding station it was recorded: the **number of meals in each day**, the **duration of each meal** (h:m:s) and the **feed intake per meal** (grams). These data were obtained from the feeding machine software, which provided average values after the daily check-up.

ii. Lying and resting behaviour

The lying and resting behaviour was recorded by video cameras strategically placed in the ceiling of the environmental controlled room. Through the analysis of video camera images (Figure 12), an algorithm was developed in order to analyse the position and relative position (between them) of the animals during resting periods and, consequently, evaluate their **proximity or distance** (more information in section 4.5 *ii.*).

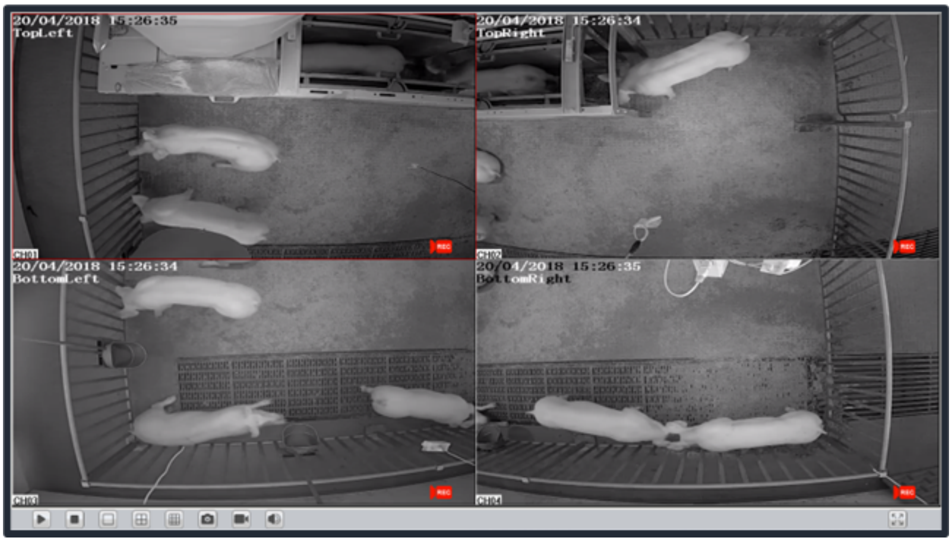


Figure 12 - Capture of pen images by video cameras (Source: author production)

4.5. Data setup and Calculations

i. Thermal-Humidity Index (THI)

The THI was calculated based on the equation developed by Mader et al., 2006:

$$\boldsymbol{THI = (0,8Tdb) + \left(\left(\frac{RH}{100}\right) * (Tbs - 14,4)\right) + 46,4} \qquad \textbf{(eq. 3)}$$

Note: Tdb is the dry bulb temperature and RH is the relative humidity in %.

ii. Performances

The ADG is a key indicator of an animal's growth rate and was determined using the following equation:

$$\boldsymbol{ADG = \frac{Weight(i) - Weight(i - l)}{Day(i) - Day(i - l)}} \qquad \textbf{(eq. 4)}$$

Note: (i) is the current weight measurement, and (i - 1) is the previous weight measurement.

The FCR is a parameter that allows us to calculate the amount of feed needed for an animal to increase its weight by 1.0 kg. This parameter was determined using the following equation:

$$\boldsymbol{FCR = \frac{FI}{BW(f) - BW(i)}} \qquad \textbf{(eq. 5)}$$

Note: FI is the total feed intake for a specific period, BW(f) is the final body weight and BW(i) is the body weight at the beginning of the considered period.

iii. Lying and resting behaviour

The lying and resting behaviour of the animals in the pen (proximity/distance) was studied through the development of a **Proximity Index (PI)**, using video images captured (24h/24h) and an artificial vision algorithm specifically developed for this purpose by a specialized company that was a partner of AWARTECH Project.

This algorithm receives video images and process them frame by frame. The analytic process occurs in two phases:

1. **<u>Recognition of animals and/or groups:</u>**

This phase was developed based on the work of Nasirahmadi et al. (2015). Using a Delaunay triangulation method (applied in the software MATLAB), the algorithm searches for shapes that match the outline of an animal (elliptical shape) (Figure 13) and records the position of each one in the pen. If several animals are in contact, forming a group of animals, the algorithm also identifies this situation.

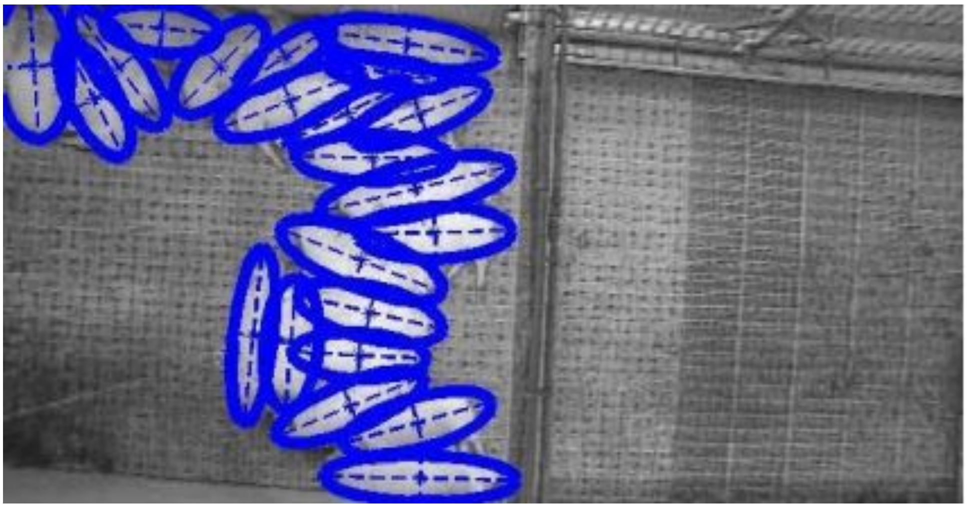


Figure 13 - Example of pig shape adjustment (Source: Nasirahmadi et al. 2015)

2. **<u>Proximity Index calculation:</u>**

Through the perimeter of each triangle, formed by the centre of the identified ellipses, the proximity of the animals was calculated.

Taking as input the pen area, the total number of animals and the position of each one, the algorithm calculates the animals' proximity index, with the result being a value between 0 and 1. A value close to 1 means that the animals are all together in a group (1 = proximity) and zero means that the animals are as dispersed as possible throughout the entire pen area (0 = distance) (Figure 14).

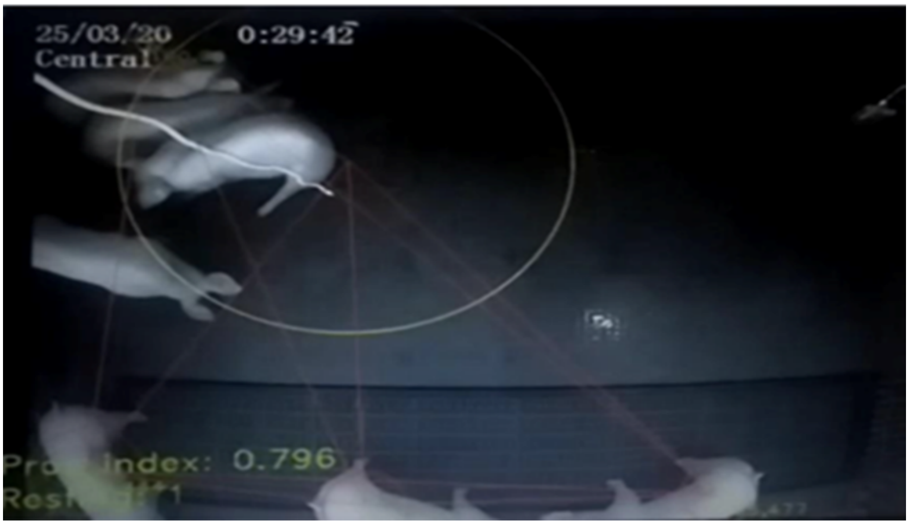


Figure 14 - Proximity Index measurement (Source: author production)

To validate the PI value associated with real lying and resting behaviour, a daily analysis of the videos was conducted, except on the days where interventions (such as room cleaning, veterinary care, sample collection, feeding, etc.) were performed on the animals, as they would lead to changes in their behavioural patterns. The videos recorded by cameras were stored in the cloud in 10-minute segments, and for each segment, there was a corresponding PI value calculated by the software.

The validation process was based on the following steps:

1. **Pattern Identification:** By analysing the videos in different environmental conditions, an attempt was made to identify the most common daily periods when the animals were resting. The identified period was between 10 a.m. and 3 p.m. in every trial.
2. **Identification of Resting Segments:** Based on the previous analysis, the goal was to find a resting situation that persisted for three consecutive segments, around 30 minutes in total.
3. **Data Collection:** After identifying the three consecutive segments, the PI value calculated by the software for the intermediate segment was collected and used for data analysis, since this segment, and consequently the PI value, ensures a true resting situation from the beginning to the end of the 10 minutes duration.

4.6. Statistical analysis

The collected data was recorded and stored in Microsoft Excel files. All Statistical analysis were performed using the IBM software SPSS Statistics, version 28.0.

Descriptive statistics were performed in order to detect wrong values (due to registration errors) or outliers and to have an overview of the observed results.

Animal's body weights at arrival and at the beginning of the experimental trial were compared by one-way analysis of variance, using environmental condition (winter, W; thermoneutral, TNZ and summer, S) as fixed effect.

The general linear model (GLM) of analysis of variance used was as follows:

$$\mathbf{X = \mu + E_i + e_{(i)}}$$

Note: **X** is the value of the parameter under analysis; **μ** is the corrected mean; $\mathbf{E_i}$ is the effect associated with environmental conditions; and $\mathbf{e_{(i)}}$ is the residual error.

Data regarding productive performances (feed intake, average daily gain, and feed conversion ratio), feeding behaviour (number of meals, time per meal, feed intake per meal) and lying and resting behaviour (proximity index) were analysed by one-way analysis of covariance (ANCOVA) using environmental condition as fixed effect. The mean initial body weight (BW_{w1}) was introduced into the model as a covariate because it was significantly different ($p = 0.01$) between conditions. Means separation were made using the Bonferroni comparison method.

The general linear model (GLM) of analysis of covariance used for all parameters was as follows:

$$\mathbf{X = \mu + E_i + I_j(cov) + E{*}I_{ij} + e_{(ijk)}}$$

Note: **X** is the value of the parameter under analysis; **μ** is the corrected mean; $\mathbf{E_i}$ is the effect associated with environmental conditions; $\mathbf{I_j(cov)}$ represents the effect associated with the animal's body weight (covariate); $\mathbf{E{*}I_{ij}}$ represents the interaction between the environmental conditions and the animal's body weight; and $\mathbf{e_{(ijk)}}$ is the residual error.

In order to assess possible differences in the parameters (performances, feeding behaviour and lying and resting behaviour) caused by the increased body weight of the pigs during the trials, each experimental period was divided in two periods, a growing and a finishing period using as division criteria the mean liveweight of the group (approximately 76 kg). In this sense, the growing period was set between 52 – 76 kg and the finishing period between 76.0 – 97 kg.

Thereafter, a two-way ANCOVA was performed using environmental condition and trial period and their interaction as fixed effects and mean initial body weight (BW_{w1}) as covariate. Differences between means were assessed using the Bonferroni comparison method.

The general linear model (GLM) used for the above-mentioned analyses was as follows:

$$\mathbf{X_{ijkl} = \mu + E_i + P_j + (E*P)_{ij} + I_k(cov) + (E*I)_{ik} + (P*I)_{jk} + (E*P*I)_{ijk} + e_{ijkl}}$$

Note: **X** is the value of the parameter under analysis; **μ** is the corrected mean; $\mathbf{E_i}$ is the effect associated with environmental conditions; $\mathbf{P_j}$ is the effect associated with the growth period; $\mathbf{(E*P)_{ij}}$ represents the interaction between the environmental conditions and the growth period; $\mathbf{I_k(cov)}$ represents the effect associated with the animal’s body weight (covariate); $\mathbf{(E*I)_{ik}}$ represents the interaction between the environmental conditions and the animal’s body weight; $\mathbf{(P*I)_{jk}}$ represents the interaction between the growth period and the animal’s body weight; $\mathbf{(E*P*I)_{ijk}}$ represents the three-way interaction among the environmental conditions, the growth period, and the animal’s body weight; and $\mathbf{e_{ijkl}}$ is the residual error.

Mean differences were considered significant when $P < 0.05$, and values between 0.05 and 0.10 were considered trends.

A regression analysis was conducted to explore the relationship between growth performance metrics (feed intake and average daily gain) and the animals' body weight. Additionally, the lying and resting behaviour (proximity index), was related with ambient temperature.

The criteria used to select the best model was based on the determination coefficient (R^2) and the root mean square error (RMSE),

$$RMSE = \sqrt{MSE} \qquad \textbf{(eq. 6)}$$

$$MSE = \frac{\sum_{i=l}^{n}(y'_i - y_i)^2}{n} \qquad \textbf{(eq. 7)}$$

Note: R^2 is a measure that indicates the proportion of variability in a dependent variable that is explained by the independent variables in a regression model; **MSE** is the mean square error or the error variance, calculated by eq. 6, in which $\boldsymbol{y'_i}$ is the predicted value, $\boldsymbol{y_i}$ the observed value and $\boldsymbol{n}$ the number of observations. The **RMSE**, also known as the standard error of the estimate, is a measure of the error in prediction. The larger its value, the less well the regression model fits the data, and the worse the prediction.

The best model was considered as the one that had the highest R^2 and the lowest RMSE.

5. RESULTS

5.1. Environmental data

The air temperature and relative humidity as well as the respective calculated THI in the three studied environmental conditions are presented on Table 6.

Table 6 - Average temperatures, relative humidity and THI in each studied environmental condition

Condition	**$T_{i\,mean}$** (ºC)	**$T_{i\,max}$** mean (ºC)	**$T_{i\,min}$** mean (ºC)	**$T_{0\,mean}$** (ºC)	**$T_{0\,max}$** mean (ºC)	**$T_{0\,min}$** mean (ºC)	**Δt** (ºC)	**$RH_{i\,mean}$** (%)	**$RH_{i\,max}$** mean (%)	**$RH_{i\,min}$** mean (%)	**THI**
W	**11.8**	12.1	11.5	**8.9**	9.3	8.1	2.9	**76**	79	75	**53.8**
TNZ	**20.3**	20.6	19.9	**16.4**	17.5	15.3	3.9	**73**	76	70	**66.9**
S	**28.6**	29.0	28.2	**25.2**	26.5	23.8	3.4	**65**	69	62	**78.5**

W: Winter condition; TNZ: Thermoneutrality condition; S: Summer condition; Ti: Indoor temperature; T0: Outdoor temperature; RHi: Indoor Relative humidity; THI: Temperature-humidity index

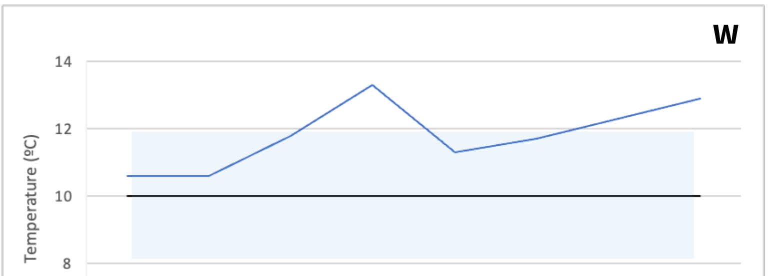
Temperature and humidity were recorded every minute, with hourly averages calculated from these values. Daily averages were then derived from the hourly data, which provided the mean values per trial.

(i) *Air temperature*

With exception of TNZ condition, in which the mean internal temperature was slightly higher than the goal interval 18 ± 2ºC, in W and S conditions, the mean internal temperatures were within the goal intervals.

As during the trials, the animals grew and the environmental impacts on animal's performance and behaviour are influenced by their body weight, the average indoor temperature variations over the 8 weeks of each trial are presented in the figure 15.

Figure 15 presents the average indoor temperature variations over the weeks in each condition.



The indoor temperature remained relatively stable over time, exhibiting a coefficient of variation (CV) of 11.1% in winter, 6.0% in TNZ, and 3.3% in S. During **W condition**, temperatures exceeded the set point slightly in weeks 4, 7 and 8. In the **TNZ condition**, maintaining indoor temperatures was particularly challenging, with temperatures consistently above the set points from week 4 until the end of the trial.

(ii) Relative Humidity

In order to better understand the indoor relative humidity variations throughout the environmental conditions simulated, Figure 16 presents the desired values for each environmental condition (set points) and the mean recorded values in each week.

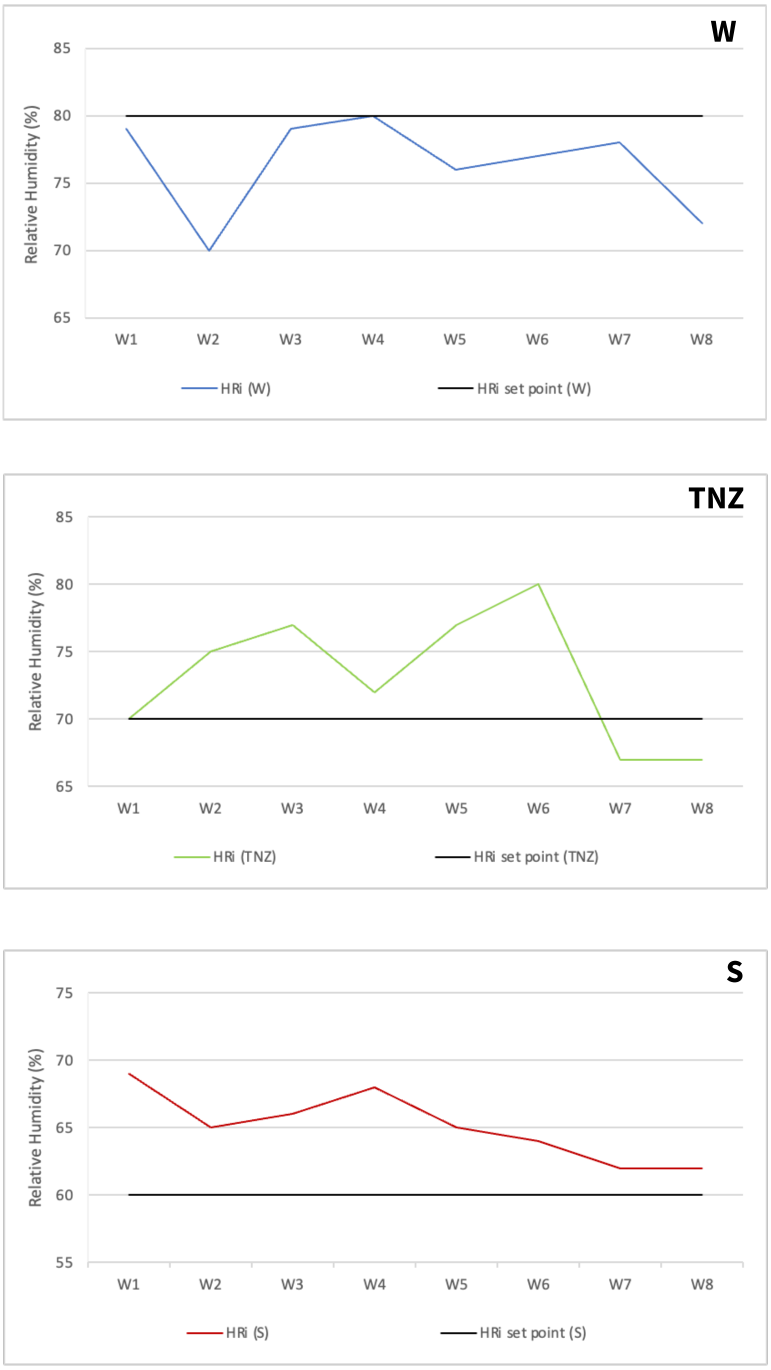


Figure 16 - Average indoor relative humidity variations over the weeks (W: Winter condition; TNZ: TNZ condition; S: Summer condition) HRi: Indoor relative humidity; W1: week 1; W2: week 2; (…); W8: week 8

By analysing this figure, it is possible to observe that during the **W condition** the average relative humidity varied between 70 and 80%; in the **TNZ condition**, relative humidity ranged from approximately 65 to 80%. During the **S condition**, this parameter varied between 60% and 70%; and in TNZ and S conditions, the values were mostly above the desired setpoint, while in the W condition, the opposite was observed.

(iii) *Temperature-Humidity Index (THI)*

Table 7 presents the THI values over the 8 weeks of each trial, calculated according to Mader et al. (2006) equation.

Table 7 - Average THI during the different weeks of the trials

Condition	**$THI_{i\,W1}$**	**$THI_{i\,W2}$**	**$THI_{i\,W3}$**	**$THI_{i\,W4}$**	**$THI_{i\,W5}$**	**$THI_{i\,W6}$**	**$THI_{i\,W7}$**	**$THI_{i\,W8}$**
W	51.9	51.6	53.8	56.2	53.1	53.7	54.6	55.6
TNZ	65.1	65.5	65.9	67.6	66.9	67.8	66.9	69.1
S	**79.5**	**78.8**	78.4	77.9	78.1	77.9	**78.8**	**78.8**

W: Winter condition; TNZ: Thermoneutrality condition; S: Summer condition; THI: Temperature-humidity index; W1: week 1; W2: week 2; (…); W8: week 8

The results of THI in this study indicate that, except for the S condition where all THI values fell within the alert or danger level, the index consistently remained within the desired (normal) range in the other environmental conditions (W and TNZ), as indicated by the range of values indicated by Oliveira Júnior et al. (2018).

The THI evolution during each experiment and its classification according to the livestock weather safety index (LWSI) can better observed in the following figure (Figure 17).

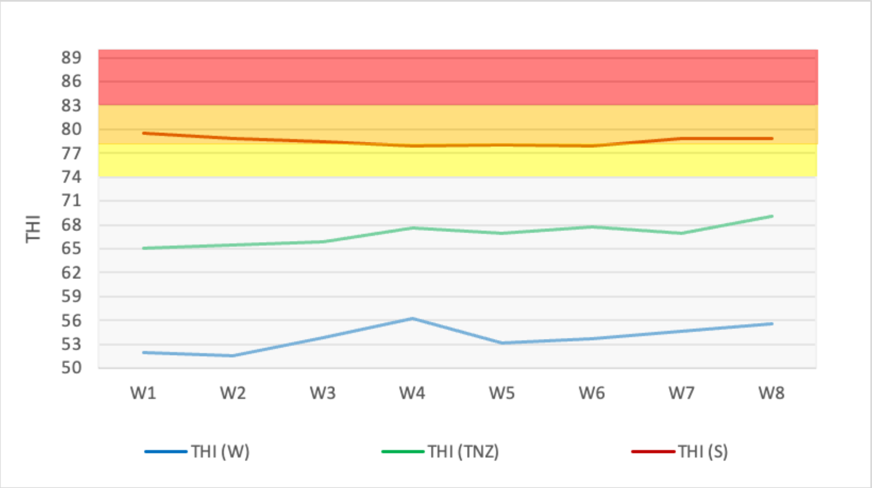


Figure 17 - THI and Thermal Comfort Limits for Growing-Finishing Pigs
W: Winter condition; TNZ: Thermoneutrality condition; S: Summer condition; W1: week 1; W2: week 2; (…); W8: week 8

5.2. Animal's body weight and productive results

(i) <u>*Body Weight*</u>

As previously mentioned in M&M Chapter, each group of experimental animals was selected from a larger group at the supplier farm, aiming body weight uniformity within group at trials start. The coefficients of variation of body weight at experimental site arrival were 5.3% in W, 5.4% in TNZ and 4.6% in S.

The body weights of the gilts at arrival and after the 15-d habituation period are presented in table 8.

Table 8 - Average body weight at arrival and after the 15-d habituation period

Condition	**BW $_{\text{initial}}$ (kg)**	**BW $_{\text{W1}}$ (kg)**
W	46.4 ± 0.8^{a} (n = 8)	57.7 ± 1.1^{a} (n = 8)
TNZ	41.4 ± 0.8^{b} (n = 8)	52.4 ± 1.1^{b} (n = 8)
S	44.4 ± 0.8^{a} (n = 8)	55.8 ± 1.1^{ab} (n = 8)
p-value	< 0.001	0.01

W: Winter condition; TNZ: Thermoneutrality condition; S: Summer condition;
BWinitial: arrival body weight; BW$_{W1}$: body weigh after the 15-d habituation period;

The initial mean live-weight at trial beginning aimed to be similar between groups but availability of animals at the supplier farm led to some statistically significant differences at this point, with lower weights in the TNZ group ($P < 0.001$).

After the habituation period TNZ group was no longer lighter than S group but it was still lighter than W group (P = 0.01).

Table 9 presents the average values of the body weight over the evaluation period of 8 weeks.

Table 9 - Average body weight during the different weeks of the trials

Condition	**BW $_{W1}$** (kg)	**BW $_{W2}$** (kg)	**BW $_{W3}$** (kg)	**BW $_{W4}$** (kg)	**BW $_{W5}$** (kg)	**BW $_{W6}$** (kg)	**BW $_{W7}$** (kg)	**BW $_{W8}$** (kg)
W	57.7 ± 1.1 ^{a} (n = 8)	62.5 ± 1.1 ^{a} (n = 8)	69.6 ± 1.3 ^{a} (n = 8)	75.3 ± 1.4 (n = 8)	78.4 ± 1.5 (n = 8)	84.9 ± 1.8 (n = 8)	90.8 ± 1.6 (n = 8)	96.0 ± 1.7 (n = 8)
TNZ	52.4 ± 1.1 ^{b} (n = 8)	57.7 ± 1.1 ^{b} (n = 8)	63.4 ± 1.3 ^{b} (n = 8)	70.9 ± 1.4 (n = 8)	74.9 ± 1.5 (n = 8)	84.2 ± 1.8 (n = 8)	91.0 ± 1.6 (n = 8)	97.7 ± 1.7 (n = 8)
S	55.8 ± 1.1 ^{ab} (n = 8)	60.3 ± 1.1 ^{ab} (n = 8)	66.4 ± 1.3 ^{ab} (n = 8)	72.6 ± 1.4 (n = 8)	78.4 ± 1.5 (n = 8)	85.0 ± 1.8 (n = 8)	91.4 ± 1.6 (n = 8)	98.0 ± 1.7 (n = 8)
p-value	0.01	0.02	0.01	0.104	0.186	0.947	0.967	0.695

W: Winter condition; TNZ: Thermoneutrality condition; S: Summer condition; BW: body weight; BWinitial: initial body weight (before 15-day habituation period); W1: week 1; W2: week 2; (…); W8: week 8

As observed in table 9, despite some significant differences on mean live-weight between experimental conditions at start and during the first weeks, on the second half of the trials (since week 4) and until trials ending, no significant differences were observed on mean live-weight of the animals.

(ii) *Feed Intake*

The feed intake results, according to the environmental conditions are presented on Table 10.

Table 10 - Influence of thermal environment on pig's feed intake

Condition	**FI** (kg/day)
W	2.45 ± 0.07 ^{a} (n = 8)
TNZ	2.78 ± 0.07 ^{b} (n = 8)
S	1.95 ± 0.06 ^{c} (n = 8)
p-value	< 0.001

W: Winter condition; TNZ: Thermoneutrality condition; S: Summer condition; FI: Feed intake

Environmental conditions had a significant effect (P < 0.001) on average feed intake with significant differences between the three environmental conditions.

The lowest mean value was observed in S condition and the highest in TNZ condition. Compared to the TNZ conditions, the animals presented a 12% lower daily feed intake in the W condition and 30% lower in the S condition. In the S condition, the feed intake reduction per degree Celsius increase was 82 g/d per °C.

Table 11 presents the average values of the feed intake throughout the growing and finishing period in each condition.

Table 11 - Influence of thermal environment on pig's feed intake over the growing-finishing period

Period	**Environmental Condition**					
	W	TNZ	S	Condition	Period	C * P
Growing (55-76 kg)	2.33 ± 0.07^{a} (n = 8)	2.45 ± 0.07^{aA} (n = 8)	1.74 ± 0.07^{bA} (n = 8)	< 0.001	< 0.001	0.003
Finishing (76-97 kg)	2.51 ± 0.07^{a} (n = 8)	3.13 ± 0.07^{bB} (n = 8)	2.20 ± 0.07^{cB} (n = 8)			

W: Winter condition; TNZ: Thermoneutrality condition; S: Summer condition;
Note: *different lowercase letters (a) denote significant differences between conditions; different uppercase letters (A) indicate significant differences between periods and within condition.*

The condition, the period and their interaction significantly influenced the FI. In all conditions there was an increase in the feed intake between the growing and the finishing period, being significant in TNZ and S conditions (P < 0.001).

During the **growing period**, a significant effect of environmental conditions on average daily feed intake was observed (P < 0.001). This effect was more pronounced in the summer condition (1.74 kg/day), which recorded a decrease in animal feed intake by approximately 29% compared to the TNZ condition (2.45 kg/day). During the winter condition (2.33 kg/day), the values obtained were very similar to those of the TNZ. However, a decrease (5%) in feed intake was also identified.

During the **finishing period**, the effect of environmental conditions on feed intake was also evident (P < 0.001). In this phase, differences were observed between all environmental conditions, with a 20% decrease in the winter (2.51 kg/day) and a 30% decrease in the summer (2.20 kg/day) compared to the TNZ (3.13 kg/day).

(iii) Average Daily Gain

Table 12 presents the average daily gain results.

Table 12 - Influence of thermal environment on pig's average daily gain

Condition	**ADG** **(g/day)**
W	807 ± 31 ^{a} (n = 7)
TNZ	947 ± 32 ^{b} (n = 8)
S	839 ± 28 ^{a} (n = 8)
p-value	0.015

W: Winter condition; TNZ: Thermoneutrality condition; S: Summer condition; ADG: Average daily gain

The analysis of Table 12 demonstrates that environmental conditions had a significant effect on average daily gain (P = 0.015). Compared to the TNZ conditions, the animals presented a 15% lower average daily gain in the winter condition and a 11% lower gain in the summer condition.

Table 13 presents the average weight daily gain values throughout the growing and finishing period of each condition.

Table 13 - Influence of thermal environment on pig's average daily gain over the growing-finishing period

Period	**Environmental Condition**					
	W	TNZ	S	Condition	Period	C * P
Growing (55-76 kg)	801 ± 42 ^{a} (n = 8)	946 ± 41 ^{b} (n = 8)	797 ± 39 ^{a} (n = 8)	0.016	0.362	0.491
Finishing (76-97 kg)	810 ± 41 (n = 7)	943 ± 41 (n = 8)	879 ± 39 (n = 8)			

W: Winter condition; TNZ: Thermoneutrality condition; S: Summer condition;
Note: *different lowercase letters (a) denote significant differences between conditions.*

The lowest ADG was observed during the growing period in S condition although a very similar value was found in the W condition. The highest ADG was recorded in the growing period of TNZ condition.

The ADG increased from growing to the finishing periods in both W and S conditions, but this increase was not significant. Conversely, in the TNZ condition, a very small reduction was observed, though it was also not significant.

However, during the growing and the finishing periods, a significant effect ($P < 0.05$) of environmental conditions on the animals' average daily gain was observed. The ADG decreased by 15% and 16% in W and S conditions, respectively, compared to TNZ during the **growing period**. In the **finishing period**, a similar trend was observed, with animals experiencing an average daily gain reduction of 14% in W and 17% in S conditions.

(iv) *Feed Conversion Rate*

The feed conversion rate results are presented on Table 14.

Table 14 - Influence of thermal environment on pig's growing-finishing feed efficiency

Condition	**FCR** **(kg/kg)**
W	3.24 ± 0.09 ^{a} (n = 8)
TNZ	2.96 ± 0.09 ^{a} (n = 8)
S	2.39 ± 0.08 ^{b} (n = 8)
p-value	< 0.001

W: Winter condition; TNZ: Thermoneutrality condition; S: Summer condition; FCR: Feed conversion rate
n = 24

The analysis of Table 14 demonstrates that environmental conditions had a significant effect ($P < 0.001$) on feed conversion rate.

These data allowed observing that the lowest feed conversion rate was recorded in the S condition, indicating a 19% higher feed efficiency compared to the TNZ condition. Conversely, in the W condition, the feed efficiency was 10% lower than in the TNZ condition.

Table 15 presents the average values of the feed conversion rate throughout the growing and finishing period of each condition.

Table 15 - Influence of thermal environment on pig's feed conversion rate over the growing-finishing period

Period	**Environmental Condition**					
	W	TNZ	S	Condition	Period	C * P
Growing (55-76 kg)	2.97 ± 0.17^{a} (n = 8)	2.58 ± 0.18^{bA} (n = 8)	2.38 ± 0.16^{b} (n = 8)	< 0.001	< 0.001	0.152
Finishing (76-97 kg)	3.56 ± 0.17^{a} (n = 8)	3.50 ± 0.17^{aB} (n = 8)	2.66 ± 0.16^{b} (n = 8)			

W: Winter condition; TNZ: Thermoneutrality condition; S: Summer condition;
Note: *different lowercase letters (a) denote significant differences between conditions; different uppercase letters (A) indicate significant differences between periods and within condition.*

The condition and the period significantly influenced the ADG. In all conditions there was an increase in the average daily gain between the growing and the finishing period, being significant in TNZ condition (P < 0.001).

During the **growing period**, the lowest feed conversion rate was recorded in the S condition (2.38 kg/kg) and the highest in the W condition (2.97 kg/kg). During **finishing period**, the animals achieved their most efficient feed conversion rate during the summer condition (2.66 kg/kg) and the least efficient during the W (3.56 kg/kg), although this value was very similar to that recorded in the TNZ condition.

5.3. Behavioural data

The following section will present the feeding and lying/resting behaviour results in this study.

5.3.1. Feeding behaviour

The feeding behaviour data (number of meals, time per meal and food intake per meal) recorded in the three trials are presented below.

(i) Number of meals

The average number of meals per day results are presented in Table 16.

Table 16 - Influence of thermal environment on pig's growing-finishing number of meals

Condition	**NM** **(meals/d)**
W	14 ± 2 (n = 8)
TNZ	14 ± 2 (n = 8)
S	16 ± 1 (n = 8)
p-value	0.554

W: Winter condition; TNZ: Thermoneutrality condition; S: Summer condition; NM: Number of meals per day

Environmental conditions did not have a significant effect on the number of meals observed.

When compared to the TNZ and W conditions, animals exhibited a 14% increase in the number of daily meals in the S condition.

Table 17 presents the average values of the number of meals per day throughout the growing and finishing period of each condition.

Table 17 - Influence of thermal environment on pig's number of meals over the growing-finishing period

Period	**Environmental Condition**					
	W	TNZ	S	Condition	Period	C * P
Growing (55-76 kg)	14 ± 3 (n = 8)	15 ± 3 (n = 8)	15 ± 2 (n = 8)	0.555	0.810	0.497
Finishing (76-97 kg)	15 ± 3 (n = 8)	13 ± 3 (n = 7)	18 ± 3 (n = 8)			

W: Winter condition; TNZ: Thermoneutrality condition; S: Summer condition; NM: Number of meals per day

The analysis of Table 17 reveals that the number of meals did not differ significantly between the environmental conditions across both periods.

During the **growing period**, animals realized the same number of meals in the TNZ and S conditions (15 meals/day). In the W condition, there was a slight decrease of 7% compared to the TNZ condition.

During the **finishing period**, the highest number of meals was observed in the S condition (18 meals/day) and the lowest in the TNZ condition (13 meals/day). When compared to the TNZ condition, animals presented an increase of 15% and 38% in the W and S conditions, respectively.

When comparing each environmental condition between the two periods, no significant differences were identified. However, there was a trend of an increased number of meals in the W and S conditions, with a 7% increase in W and a 20% increase in S. In contrast, a 13% decrease was observed in the TNZ condition.

(ii) *Time per meal*

Table 18 present the average time spent per meal.

Table 18 - Influence of thermal environment on pig's growing-finishing time per meal

Condition	**TM (min/meal)**
W	8.1 ± 0.6^{a} (n = 8)
TNZ	7.3 ± 0.6^{ab} (n = 7)
S	5.8 ± 0.5^{b} (n = 8)
p-value	0.003

W: Winter condition; TNZ: Thermoneutrality condition; S: Summer condition; TM: Time per meal

Environmental conditions did not influence the duration of meals.

Animals spent longer periods feeding in the W condition and shorter in the S condition. When compared to the TNZ condition, the animals presented a decrease in the duration of their daily meals by 21% in the S condition and an increase of 11% in the W condition.

Table 19 presents the average duration of meals per day over the growing and finishing period of each condition.

Table 19 - Influence of thermal environment on pig's time per meal over the growing-finishing period

Period	**Environmental Condition**					
	W	TNZ	S	Condition	Period	C * P
Growing (55-76 kg)	8.9 ± 0.7 ^{a} (n = 8)	7.2 ± 0.7 ^{ab} (n = 8)	6.2 ± 0.6 ^{b} (n = 8)	0.003	0.254	0.585
Finishing (76-97 kg)	7.5 ± 0.7 (n = 8)	7.4 ± 0.7 (n = 7)	5.3 ± 0.6 (n = 8)			

W: Winter condition; TNZ: Thermoneutrality condition; S: Summer condition; TM: Time per meal
Note: *different lowercase letters (a) denote significant differences between conditions.*

The environmental conditions significantly influenced the meal duration across both periods (P = 0.003). This difference was significant between W and S conditions during the **growing period**, representing a 21% increase in meal duration in condition W and a 14% decrease in condition S compared to the TNZ condition.

During the **finishing period**, significant differences were not observed. However, meal duration decreased by 28% in the S condition compared to the TNZ condition.

(iii) *Feed intake per meal*

The results of the average amount of feed consumed per meal are presented in Table 20.

Table 20 - Influence of thermal environment on pig's growing-finishing food intake per meal

Condition	**FIPM** **(g/meal)**
W	186^{ab} ± 8 (n = 8)
TNZ	233^{a} ± 8 (n = 7)
S	148^{b} ± 7 (n = 8)
p-value	< 0.001

W: Winter condition; TNZ: Thermoneutrality condition; S: Summer condition; FIPM: Food intake per meal

Environmental conditions had a significant impact on feed intake per meal (P < 0.001).

Animals consumed more food per meal in the TNZ condition and less in the summer condition, with this difference being statistically significant. When compared to the TNZ condition, the animals exhibited a daily decrease in feed intake per meal of 20% in the W condition and 36% in the S condition.

Table 21 presents the average food intake per meal throughout the growing and finishing period of each condition.

Table 21 - Influence of thermal environment on pig's food intake per meal over the growing-finishing period

Period	**Environmental Condition**					
	W	TNZ	S	Condition	Period	C * P
Growing (55-76 kg)	174 ± 11 ^{a} (n = 8)	190 ± 11 ^{aA} (n = 8)	139 ± 11 ^{b} (n = 8)	<0.001	< 0.001	0.003
Finishing (76-97 kg)	198 ± 11 ^{ab} (n = 8)	277 ± 11 ^{aB} (n = 7)	156 ± 10 ^{b} (n = 8)			

W: Winter condition; TNZ: Thermoneutrality condition; S: Summer condition; FIPM: Food intake per meal
Note: *different lowercase letters (a) denote significant differences between conditions; different uppercase letters (A) indicate significant differences between periods and within condition.*

The analysis of Table 21 reveals that the amount of feed consumed per meal was significantly different between the environmental conditions across both periods (P < 0.001).

During the **growing period**, animals consumed more feed per meal in the TNZ condition (190 g/meal) and less in the S condition (139 g/meal), with this difference being significant. In the **finishing period**, animals also demonstrate higher feed intake per meals in the TNZ condition (277 g/meal) and lower in the S condition (156 g/meal). This difference was also significant.

In all the environmental conditions there was an increase in the amount of food ingested per meal between the growing to the finishing period, being this difference significant in the TNZ condition (P = 0.003).

5.3.2. Lying and resting behaviour

The lying and resting behavioural results obtained through the Proximity Index in the three trials are presented in Table 22.

Table 22 - Animal Proximity Index

Condition	**PI**
W	0.95 ± 0.02^{a} (n = 36)
TNZ	0.73 ± 0.02^{b} (n = 32)
S	0.45 ± 0.02^{c} (n = 37)
p-value	< 0.001

W: Winter condition; TNZ: Thermoneutrality condition; S: Summer condition; PI: Proximity index

The analysis of these results demonstrates that environmental conditions had a significant effect on the lying and resting behaviour (P < 0.001). The Proximity Index obtained for the W condition was 30% higher and for the S condition was 38% lower when compared with TNZ.

Table 23 presents the average proximity index over the growing and finishing period of each condition.

Table 23 - Influence of thermal environment on pig's proximity index over the growing-finishing period

Period	**Environmental Condition**					
	W	TNZ	S	Condition	Period	C * P
Growing (55-76 kg)	0.91 ± 0.04^{a} (n = 8)	0.70 ± 0.04^{b} (n = 8)	0.45 ± 0.04^{c} (n = 8)	< 0.001	0.225	0.099
Finishing (76-97 kg)	0.98 ± 0.03^{a} (n = 8)	0.77 ± 0.03^{b} (n = 8)	0.40 ± 0.03^{c} (n = 8)			

W: Winter condition; TNZ: Thermoneutrality condition; S: Summer condition; PI: Proximity index
Note: *different lowercase letters (a) denote significant differences between conditions.*

The analysis of Table 23 reveals that the proximity index was significantly different between the environmental conditions in both periods (P < 0.001).

During the **growing period**, the higher PI value was recorded during the W condition and the lower in the S condition. Compared with the TNZ condition, animals presented a 30% higher PI in W condition and a 37% lower PI in S condition. In the **finishing period**, the PI exhibited a similar pattern to that of the growing period, with a 27% increase in the W condition and a 48% decrease in the S condition compared to the TNZ condition.

No significant differences were found when comparing each environmental condition across the two periods. Similarly, the interaction between the environmental condition and the period did not yield significant results.

6. DISCUSSION

6.1. Environmental data

(i) Air Temperature

Air temperature is the most important environmental parameter inside a livestock facility. Large fluctuations or extremes in temperature can have detrimental effects on the health, behaviour, physiology and morphology of animals, potentially compromising their welfare and overall performance (Chantziaras et al., 2020; NRC, 2011).

Comparing the indoor average temperature with the outdoor temperature (Table 6) recorded in this work, it is possible to verify that the **average temperatures** recorded inside the facility approached the target temperatures predefined for each trial.

When analysing the variation of indoor temperature recorded over the weeks in each condition (Figure 15), it is possible to verify that, despite some oscillations, the environmental control system successfully maintained the temperature within the established ranges. However, the minimum and maximum temperature values recorded inside were, respectively, 7.6ºC and 19.2ºC in W; 15.9ºC and 26.1ºC in TNZ; and 22.6ºC and 33.2ºC in S conditions, values outside the aimed ranges. These deviations can be explained by the fact that the climatization systems (heating and cooling) have some limitations when the external temperatures are quite different than those intended inside. This is mainly due to the facility insulation's efficiency and also to the air exchange with the surrounding environment, which sometimes results in greater heat gains within the facility than losses. However, we consider that these deviations are not relevant.

The recorded indoor temperature as a function of the outdoor temperature in this study can be observed in the following figure:

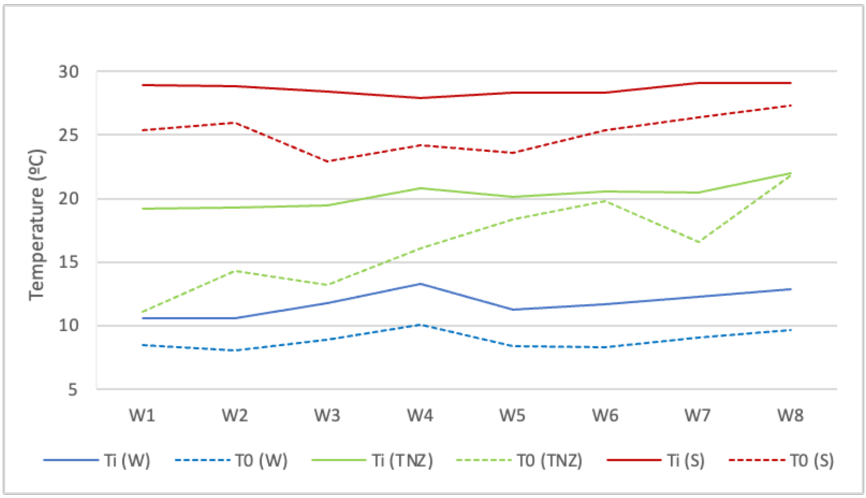


Figure 18 - Indoor and outdoor temperature conditions
Ti: Indoor temperature; T0: Outdoor temperature; W: Winter condition; TNZ: Thermoneutrality condition; S: Summer condition

The analysis of Figure 15 reveals that throughout the **winter condition**, the average indoor temperature slightly exceeded the set targets in weeks 4, 7 and 8. Based on Figure 18, this can be attributed to the higher external temperatures during these weeks compared to the rest of the trial, which had an adverse impact on the internal temperature, leading to a minimal increase.

The same effect was also observed during the **TNZ condition** from weeks 4 to 8. The influence of the external temperature was particularly evident in week 8, resulting in a 4ºC increase compared to the environmental setpoints.

During the **summer condition**, there was no influence from the external temperature since the internal temperature did not have a representative variation throughout the test. This observation reinforces the effectiveness of the cooling system, demonstrating its ability to maintain the average reference temperature inside the facility when external temperatures are not extreme.

(ii) <u>Relative Humidity</u>

Relative humidity is an important environmental parameter since the concentration of humidity at high levels is harmful to the health and comfort of animals. Previous research has highlighted the correlation between ambient humidity and the incidence of certain infectious diseases (Xiong et al., 2017), such as rheumatism (Baêta and Souza, 2010).

The relative humidity is more challenging to control when compared to air temperature. The observed mean values in each condition were, in general close to **the environmental setpoints** for each trial (Table 5 and Figure 16) with variations between 5 to 10% that, in our opinion, can be consider having no significant impact on the observed results.

During the **winter condition**, the target set (80%) only was reached in week 4 (Figure 16). This can be explained by the fact that during that week, the recorded average indoor temperature (13.3ºC) exceeded the environmental setpoints. As a result, the cooling system (mist system) was activated, contributing to an increase in relative humidity. In the other weeks, when the indoor temperature remained within the desired range, no sufficient modifications to the thermal environment of the facilities occurred to increase the indoor relative humidity.

In the **summer condition**, despite slightly exceeding the target level of 60%, better control over relative humidity was achieved due to the need for periodic heating in the environmental control room. The heating process effectively reduced humidity and maintained it with minimal oscillations.

(iii) Temperature-Humidity Index (THI)

The THI is one of the most widely used thermal comfort indexes. This index has been used to evaluate the effect of temperature and humidity on animal's performance and thermal comfort (Fournel et al., 2017; Fu et al., 2022; Johnson et al., 1962; Mader et al., 2006; Shao and Xin, 2008; Yousef, 1971).

According to the parameters proposed by Oliveira Júnior et al. 2018 (Table 1), animals experience thermal comfort when the THI is 74 or lower. An alert condition arises when the THI falls between 75 and 78. The danger situation occurs within the range of 79 to 83, while the emergency condition is signaled by a THI exceeding 84.

The analysis of THI values in this study revel that the animals **experienced thermal discomfort during the summer condition** (THI = 78.5). This result reinforce that the intended environmental conditions (temperature and humidity) were successfully simulated. Indeed, through the analysis of Figure 17, it is evident that the animals were in a condition of danger and alert throughout the summer trial (heat stress). This result also demonstrates the impact of high temperatures and humidity on the thermal comfort of growing-finishing pigs.

In the **TNZ condition**, the THI remained within the 'normal' range, indicating that the environmental conditions did not affect the animals' thermal comfort. A similar outcome was observed in the **W condition**, although there are evident differences between them (W = 51.9 vs TNZ = 65.1), evealing an effect of the environmental conditions. However, during winter, it is unclear if the animals experienced thermal discomfort, since, even with the possibility of using the THI in situations of cold stress, the studies that exist were mainly carried out on dairy cattle and there are no adaptations for pigs (Foroushani and Amon, 2022).

6.2. Animal’s body weight and productive results

(i) *Body Weight*

In commercial farms, the growing-finishing phase is the last stage in pig production and is defined as the period between the exit of nursery (when the animal weights around 25 – 30 kg) and slaughterhouse (when the animals reach the market weight: > 100 kg) (Agostini et al., 2015; Orpí, 2020).This means that the animals used in this study had an initial average live weight within the growth and finishing period typical of commercial pig farms and the final weights correspond to common market weights for animals of these genetics raised in intensive systems.

Also, the pig’s body weight plays a significant role in their response to environmental conditions. Heavier pigs tend to be more sensitive to high temperatures compared to younger, lighter pigs (Noblet et al., 2000; Van Heugten, 2010). Conversely, smaller pigs are more susceptible to heat loss, meaning that lower temperatures have a greater effect on smaller pigs compared to larger ones (Bus et al., 2021; Martins, 2020; Prunier et al., 2014; Quiniou, 2000).

In this study, the significant differences between the winter and TNZ conditions during the first three weeks of the trials can be explained by the fact that the animals' initial weight ($BW_{initial}$) was also significantly different between the trials. This effect was not verified after week 4, which demonstrates the influence of environmental conditions on the animals' growth, since under conditions of thermal discomfort (W), the animals have grown less than the animals in thermal comfort (TNZ) that were able to compensate for this difference in initial body weight after 3 weeks.

It was also found that, regardless of initial body weight, the animals reached a very similar average final body weight in all the trials. Moreover, between week 6 and 7 (85 - 90kg) the animals recorded the same body weight regardless of the environmental condition. This can be observed in the following figure:

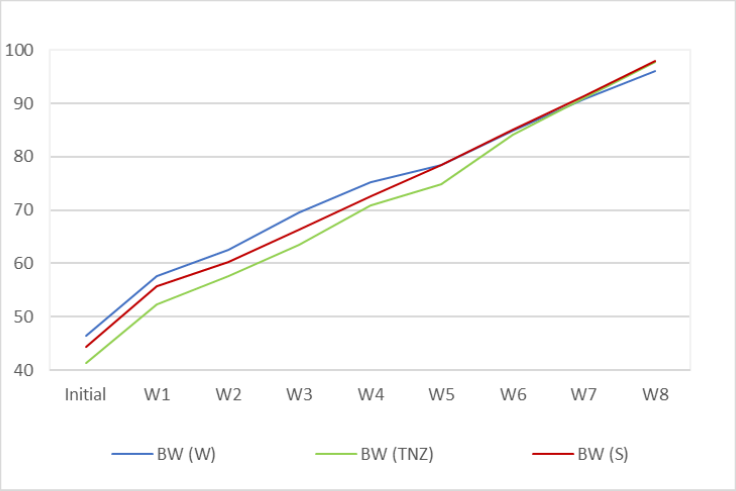


Figure 19 - Evolution of body weight during the trials
W: Winter condition; TNZ: Thermoneutrality condition; S: Summer condition; W1: week 1; W2: week 2; (…); W8: week 8

These results highlight, on one hand, the detrimental effect of low temperatures on pig growth, as observed by Collin et al. (2001), Hyun et al. (1998), Huynh et al. (2005a) and Rauw et al. (2017). Despite initially heavier than pigs in the TNZ condition, animals in W condition ultimately attained a similar final body weight to those in the TNZ. This can be attributed to the adjustment in feed intake, a crucial mechanism for coping with lower ambient temperatures (Cruz, 1997; Mayorga et al., 2019; Renaudeau et al., 2012). In such conditions, consumed food is primarily used to maintain body temperature rather than for growth (Bus et al., 2021; Gertheiss et al., 2015; Quiniou et al., 2000). This effect is particularly noticeable in young pigs, which are highly sensitive to such environmental conditions (Martins, 2020; Prunier et al., 2014).

On the other hand, these variations in body weight in the TNZ condition also underscore the growth capacity of animals under thermoneutral conditions, considering the differences in initial body weights, aligning with literature suggesting that pigs grow and function better under thermoneutral temperature conditions (Babot and Revuelta, 2009; Cecchin et al., 2019; Cruz, 1997).

(ii) *Feed Intake*

Adjustment of voluntary feed intake is one of the most important adaptation processes to modify metabolic heat production in response to ambient temperature (Cruz, 1997; Mayorga et al., 2019; Renaudeau et al., 2012). The extent of this adjustment depends on several factors such as genotype, sex, breed, age, body weight, physiological state, diet composition, feeding regime, group size and environmental factors (Godyń et al., 2020; Renaudeau et al., 2012; Santos et al., 2018).

Elevated ambient temperature may cause a decrease in voluntary feed intake in growing-finishing pigs at the level that can attain 50% (Godyń et al., 2020; Huynh et al., 2005a; Ma et al., 2019; Pearce et al., 2015). On the other hand, pigs fed *ad libitum* in thermoneutral or cold conditions consume enough to achieve maintenance and growth needs (Li and Patience, 2017). This means that FI is adjusted at the same rate as maintenance energy needs change (Cruz, 1997). Additionally, prolonged exposure to cold temperatures can result in a negative energy balance that cannot be compensated only through increased feed intake (Hines, 2019).

The overall results obtained in this study (Table 10) align with previous research regarding the impact of environmental conditions on feed intake in pigs. The observed decrease in feed intake during the **summer condition** corroborates findings from different studies (Cruz, 1997; Godyń et al., 2020; Huynh et al., 2005a; Rauw et al., 2017) and underscores the negative effect of high ambient temperatures on appetite and feed consumption. This effect is particularly pronounced in pigs, which face significant challenges in dissipating heat under such environmental conditions (Cruz, 1997; Godyń et al., 2020; Ingram, 1965; Mayorga et al., 2019; Quiniou et al., 2000; Renaudeau et al., 2012; Santos et al., 2018) mainly due to the absence of functional sweat glands (Bracke, 2011; Gómez-Prado et al., 2022; Ingram, 1965).

Compared with TNZ condition, the 30% decrease in average feed intake during the S condition in the present study is comparable to the 25% decrease reported by Rauw et al. (2017) under 32ºC. On the other hand, this FI decrease was higher to that reported by Oliveira et al. (2019) (17%), although the temperature range in the heat stress condition in that study was 29 to 35ºC. This difference can also be attributed to the fact that this meta-analysis included 22 studies covering a total wide range of body weights (30 – 117 kg), with the majority falling between 30 and 60 kg, which is lower than the weight range used in this study, which justifies the lower effect of high environmental conditions, since younger (lighter) pigs are less sensitive to high temperatures compared to heavier pigs (Noblet et al., 2000; Van Heugten, 2010).

Moreover, the analysis of feed intake reduction per degree Celsius increase (82 g/d per ºC) aligns with findings from other studies (Huyuh et al., 2005a; Le Dividich et al., 1998; Mun et al., 2022; Renaudeau et al., 2011), further supporting the observed response to high environmental temperatures.

The decrease in feed intake observed during the **winter condition** (13%) when compared with TNZ condition, contradicts conventional expectations, as cold temperatures typically stimulate increased food consumption in pigs to compensate for higher heat losses (Bus et al., 2021; Gertheiss et al., 2015; Li and Patience, 2017; Quiniou et al., 2000). This finding diverges from previous studies and warrants further investigation into the underlying factors contributing to this phenomenon.

A possible explanation for this result is that during the winter trial, the feed silo occasionally clogged due to indoor air humidity. This prevented the machine from dispensing feed when animals accessed it, requiring human intervention to resolve. Whenever this occurred, the animals were fed small amounts on the floor to avoid competition for the machine. This issue may have influenced the results and could potentially explain why the animals consumed more during thermal comfort conditions than in winter, contrary to expectations.

The observed variations in feed intake across different environmental conditions and growth stages reflect the dynamic interplay between animal physiology, environmental factors and metabolic demands.

In general, the analysis of this parameter throughout **the growing and the finishing period** demonstrates that feed intake increases with body weight gain, which is consistent with the literature (Godyń et al., 2020; Renaudeau et al., 2012; Santos et al., 2018). However, this increase only was significant in TNZ and S conditions, which was expected in the TNZ condition since the animals were in thermal comfort but not in the S condition as they were experienced heat stress conditions. This can be explained because during the summer trial, although the average temperature was 28.6ºC, the minimum and maximum ambient temperature value recorded were 22.6°C and 33.2°C, respectively. This wide temperature range may explain some significant temperature variations within the facility during the trial. In extreme cases, this could lead to situations where animals experienced heat stress and others where they were in thermal comfort. This type of variation may have occurred frequently throughout the weeks of the trial or even on specific days (i.e., day/night periods), which may also have led to changes in the animals' feeding times, so the effect of the environmental conditions may not have been as pronounced.

Conversely, in the W condition, the marginal increase in FI (8%) observed between the growing and finishing periods deviates from the expected trend. Literature suggests that the magnitude of this increase depends on several factors, such as pig body size (small pigs are more susceptible to cold stress than large pigs) and feed composition (Bus et al., 2021; Quiniou et al., 2000). Thus, it was expected that animals in the finishing period, owing to their enhanced ability to tolerate cold stress conditions, would exhibit a more substantial rise in FI. The discrepancy between these findings and existing literature may imply the influence of other factors on this behaviour, underscoring the necessity for further investigations into the impact of cold conditions on pigs during the growing-finishing phase.

However, upon analyzing the periods separately, it becomes apparent that during the growing period, animals in the W condition exhibited a feed intake level similar to that observed in the TNZ condition. This result is in line with the literature, as previously mentioned, indicating that younger pigs face greater challenges in coping with cold stress conditions, leading to an increase in feed intake to meet maintenance needs (Bus et al., 2021; Cruz, 1997; Quiniou et al., 2000).

The opposite effect was observed in the S condition during the finishing phase, as the animals significantly reduced their feed intake compared to the TNZ condition (30%), which is consistent with the literature, as pigs face greater challenges in dissipating heat under high temperatures (Cruz, 1997; Godyń et al., 2020; Ingram, 1965; Mayorga et al., 2019; Quiniou et al., 2000; Renaudeau et al., 2012; Santos et al., 2018).

In this sense, the analysis of the results from the three conditions over the growth and finishing period seem to revel the existence of an interaction between ambient temperature and the animals' growth period in feed intake (P = 0.003).

In order to better explain these results, the following relations were determined:

$$\boldsymbol{FI(W) = 1.0971 + 0.0186BW} \quad \textbf{(n=48, R}^2\textbf{ = 0.37, RSME = 0.14)} \quad \textbf{(eq. 8)}$$

$$\boldsymbol{FI(TNZ) = -2.8330 + 0.1226BW - (6.25X10^{-4})BW^2} \quad \textbf{(n=48, R}^2\textbf{ = 0.83, RSME = 0.09)} \quad \textbf{(eq. 9)}$$

$$\boldsymbol{FI(S) = 0.7172 + 0.0168BW} \quad \textbf{(n=48, R}^2\textbf{ = 0.52, RSME = 0.10)} \quad \textbf{(eq. 10)}$$

Note: FI (kg/day) is the feed intake in winter (W), thermoneutrality (TNZ) or summer (S) conditions and BW (kg) is the animal body weight.

Based on the equations presented above, the following graph (Figure 20) was generated:

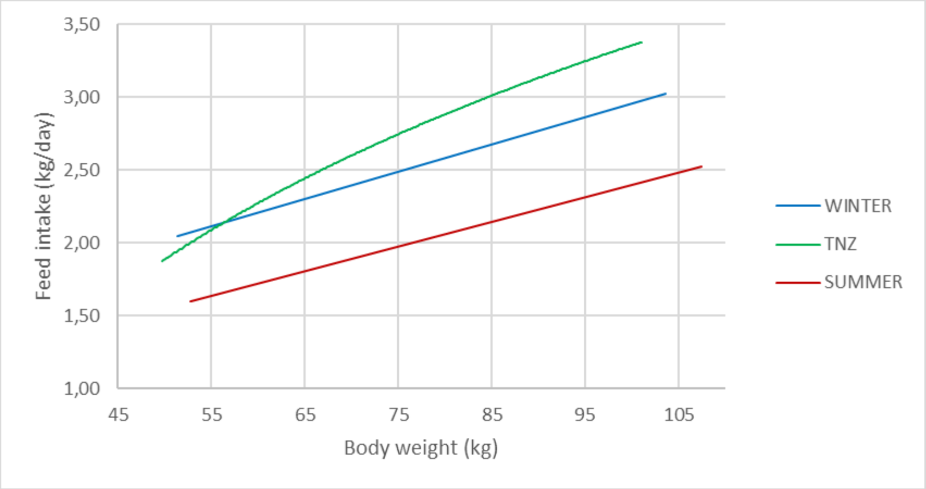


Figure 20 - Evolution of feed intake with the body weight of pigs according to the environmental trial condition

In the TNZ condition, the average feed intake increased quadratically with the increase in body weight (eq. 9), while in the winter condition (eq. 8) and summer condition (eq. 10), this relationship increased linearly. In the case of winter, a 1 kg increase in body weight was associated with a 17 g increase in average daily intake, and in the case of summer, it was 19 g. However, these equations (eq. 8 and 10) may have limited value due to their relatively low R^2. This could lead to the assumption that, in the winter and summer conditions, feed intake do not depend essentially on the body weight, but it can be influenced by environmental and/or physiological factors.

The analysis of Figure 20 reveals that in the TNZ condition, the animals were in thermal comfort enabled higher food consumption compared to other conditions, except for the initial phase of the trial (above to approx. 57 kg) because in this trial the animals had a slightly lower body weight (Table 9). Additionally, food intake tended to stabilize in the final phase of the trial and through Eq. 9, it was possible to determine that the maximum food intake would occur at 98.1 kg. The same behaviour was not observed in the other conditions and this may be related to the effect of environmental conditions on the animals, preventing them from reaching their maximum food intake capacity until the slaughter weight.

Additionally, although animals were fed *ad libitum*, a daily maximum value above their nutritional needs (3.2 kg of feed/day) was provided per animal according to Table 4. This limitation may have influenced the food intake of the animals in the final phase of the trial (especially in the winter condition), as these reference values are derived from outdated tables without recent updates that may be better adapted to modern genetics.

However, feeding behaviour will be discussed in greater detail in a subsequent section.

(iii) *Average Daily Gain*

The pig's growth performance is significantly influenced by the thermal environment, as they adjust their feed intake based on ambient temperature, diverting energy from growth to maintaining body temperature, resulting in performance and economic losses (Ross et al., 2015). In this sense, the relationship between FI, ADG and ambient temperature is very important, since the pigs' growth rate receiving a balanced diet is mainly related to the amount of feed consumption.

For growing-finishing pigs with *ad libitum* feeding, the average ambient temperature recommendations for maximum daily weight gain are between 15 and 20°C. When the ambient temperature deviates from these values, literature suggests a decrease in ADG (Hansen and Bjerg, 2018; Massabie et al., 1996; Mun et al., 2022; Nichols et al., 1980; Nienaber et al., 1987; Renaudeau et al., 2008). According to Boltyanska et al. (2018), a significant deviation from the optimum ambient temperature, whether above or below, can result in a marked decrease in the performance of pigs (15 – 30% lower ADG).

The analysis of the overall results (Table 12) highlights the significant influence of environmental conditions on ADG in growing-finishing pigs. This aligns with existing literature emphasizing the impact of ambient temperature on feed intake and subsequent growth performance (Ross et al., 2015).

The observed reduction in ADG during both summer and winter conditions underscores the sensitivity of pigs to thermal stress, resulting in altered feed intake and compromised growth rates.

The findings indicate that pigs exposed to heat stress conditions during the **summer condition** exhibited a significant decrease in ADG when compared to TNZ condition. This is consistent with the literature, which indicates that regardless of the severity of the environmental conditions, animals subjected to heat stress conditions exhibit a decrease in their average daily gain, mainly due to the reduced feed intake (Boltyanska et al., 2018; Cruz, 1997; Hyun et al., 1998; Huynh et al., 2005a; Pearce et al., 2013; Rauw et al., 2017).

This growth rate reduction (11%) was similar to the results reported by Hyun et al. (1998), who observed an 11.9% decrease when ambient temperature increased from 24°C to 28–34°C, and it was lower than the reductions reported by Collin et al. (2001), Huynh et al. (2005a) and Raw et al. (2017), who observed a 30%, 46% and 60% reduction in ADG, respectively, for pigs raised at 32–33°C.

The differences observed in these results compared with the literature can be attributed to several factors. From the perspective of the literature, firstly, in the study by Hyun et al. (1998), the animals were exposed to a slightly higher TNZ conditions compared to those examined in this study, which could have led to a lesser reduction in ADG. Secondly, studies conducted by Collin et al. (2001), Huynh et al. (2005a) and Rauw et al. (2017) reported heat stress conditions at temperatures ranging from 32 – 33°C, which are higher than those observed in this study (≈ 28ºC). Additionally, Huynh et al. (2005a) noted a RH of 80%, which is 15% higher than the RH conditions in this study, potentially contributing to the decreased ADG. Lastly, Rauw et al. (2017) studied Iberian crossed animals, which have a higher predisposition to deposit fat (Charneca, 2010), potentially increasing their susceptibility to thermal stress under high temperature conditions.

Furthermore, as mentioned previously, the average temperature recorded for this situation, although representative of a summer condition, may have been insufficient to induce extreme thermoregulatory responses in the animals. The THI obtained for this condition (THI = 78.5) can also help justify this, as this THI falls within the threshold between the alert and dangerous thermal comfort conditions.

Another factor that could be related to the animals' apparent increased resilience to these environmental conditions could be their genetics. According to the swine genetics company Topigs Norsvin, TN60 hybrid sows are suitable for productions in hot climates under challenging production conditions, which makes the animals more tolerant of hot environmental conditions (TN, s.d).

During the **winter conditions**, pigs exposed to cold stress also experienced a decrease in ADG. This outcome aligns with the literature, considering that the average temperature recorded during this period (11.8ºC) fell below the recommended range of 15 – 20°C for achieving the maximum average daily gain in growing-finishing pigs (Hansen and Bjerg, 2018; Massabie et al., 1996; Mun et al., 2022; Nichols et al., 1980; Nienaber et al., 1987; Renaudeau et al., 2008).

As previously discussed, when animals are exposed to temperatures below their LCT, they experience thermal cold stress, leading to increased heat losses to the environment. To compensate for these losses and maintain body temperature, animals typically increase their food consumption (Bus et al., 2021; Gertheiss et al., 2015; Li and Patience, 2017; Quiniou et al., 2000). Consequently, the energy that would otherwise support growth is diverted toward maintaining body temperature, resulting in a reduction in growth rate (Bus et al., 2021; Cruz, 1997; Gertheiss et al., 2015; Quiniou et al., 2000; Ross et al., 2015).

The 15% decrease in average daily gain observed during the winter condition aligns with findings in the literature. According to Boltyanska et al. (2018), numerous practical observations have confirmed that a significant deviation from the optimum ambient temperature, whether above or below, can result in a 15-30% decrease in growth performance. However, Faure et al. (2013) did not observe variations between animals subjected to cold conditions (12°C) and TNZ conditions (23°C). Given the notable lack of studies on this subject, further research is necessary to better understand this relationship.

When analyzing growth performance during the **growing and finishing periods** (Table 13), it is observed that during the **growing period**, ADG decreased by 15% and 16% in W and S conditions, respectively, compared to the TNZ condition. These results align with previously identified literature (Boltyanska et al., 2018; Faure et al., 2013; Hyun et al., 1998). In the case of the summer condition, this decrease is not as pronounced as reported by Collin et al. (2001), Huynh et al. (2005a) and Raw et al. (2017), who observed a 30%, 46% and 60% reduction in ADG, respectively, for pigs raised at 32–33°C, due to reasons identified in the analysis of overall average results, but mainly because young animals exhibit lower sensitive to, and consequently are less affected by high temperatures (Noblet et al., 2000; Van Heugten, 2010).

During the **finishing period**, a decrease in ADG was also observed in both winter (14%) and summer (17%) conditions compared to the TNZ condition. This decrease was more evident in the summer condition, which corroborates the literature indicating that heavier animals are more susceptible to high temperatures (Noblet et al., 2000; Van Heugten, 2010).

(iv) *Feed Conversion Rate*

Growth performance is related, among many factors, to the amount and efficiency of nutrient and energy utilization. Furthermore, the growing-finishing phase is considered the most expensive period in pig production, since feed represents approximately 65 to 75% of the total costs of production (Agostini et al., 2015; Camp Montoro et al., 2020; Rocadembosch et al., 2016; Van Heugten, 2010).

In this sense, improving production efficiency during this phase is crucial, as it significantly influences farm profitability by reducing feed costs and increasing growth performance (Camp Montoro et al., 2020; Van Heugten, 2010).

The FCR is a production parameter resulting from the two parameters discussed earlier and, for this reason, is directly affected by them. In general, compared to the results reported by the *Institut Du Porc* (IFIP-GTE) for 2015 in France, the values obtained in this study were consistent with the acceptable standards for modern genetics of growing-finishing pigs (x̄ = 2.74 kg/kg) in both TNZ and S conditions.

Analysis of the overall results (Table 14) revealed that, while literature would suggest optimal FCR in thermal comfort conditions (Massabie et al., 1996; Miller, 2012; Mun et al., 2022; Nichols et al., 1980; Oliveira et al., 2019; Renaudeau et al., 2008), the results indicate that pigs exhibited higher feed efficiency during the **summer condition** (2.39 kg/kg). This discrepancy can be explained because according to the literature, even though animals theoretically decrease their food consumption when subjected to high temperatures, FCR is less affected under hot environmental conditions (Liu et al., 2022; Oliveira et al., 2019; Renaudeau et al., 2008). Furthermore, the values recorded in this condition are similar to those reported by Massabie et al. (1996), Miller (2012), Mun et al. (2022) and Renaudeau et al. (2008) (2.50 – 2.70 kg/kg).

On the other hand, the results obtained in the **TNZ condition** (2.96 kg/kg) small exceeded the established in the literature (Miller, 2012; Mun et al., 2022; Oliveira et al., 2019; Renaudeau et al., 2008). However, values obtained in this condition were similar to the acceptable data for modern genetics of growing-finishing pigs (x̄ = 2.74 kg/kg).

Although not statistically significant, the FCR increased by 10% during the **winter condition** compared to the TNZ condition. This effect is consistent with the literature, as in cold conditions, pigs require additional amounts of feed to compensate heat losses (Bus et al., 2021; Close, 1981; Gertheiss et al., 2015; Hutu and Onan, 2019; Quiniou et al., 2000). This results in lower feed efficiency and, consequently, a higher FCR. However, this increase was smaller than that reported by Faure et al. (2013) when animals were exposed to cold conditions (12°C) compared to TNZ conditions (23°C).

Further examination of FCR during the **growing and finishing periods** demonstrated significant effects of environmental conditions on feed efficiency.

During the **growing period**, a significant influence of environmental conditions on feed conversion rate was observed, with statistically significant differences between W condition and both TNZ and S conditions. These results highlight the sensitivity of pigs to environmental variations during the growth period, especially in the W condition. These results are in line with the literature and reinforce the negative effect of low temperatures on younger pigs (Martins, 2020; Prunier et al., 2014), as previously demonstrated by the fact that animals in this period and under this environmental condition exhibited a slightly lower but similar feed intake , along with lower average daily gain compared to the TNZ condition (thermal comfort), consequently resulting in a decrease in feed efficiency.

During the **finishing period** the summer condition continued to demonstrate the lowest feed conversion rate. The FCR recorded in the W condition remained less efficient compared to the TNZ condition, although this difference was marginal. This result aligns with the literature and indicates a differential response of pigs to cold conditions during the finishing period. Heavier pigs are less sensitive to low temperatures (Bus et al., 2021; Quiniou et al., 2000), as animals housed in colder environments tend to exhibit fattier carcasses due to increased adiposity resulting from higher food intake as a response to the cold (Cruz, 1997).

6.3. Behavioural data

6.3.1. Feeding behaviour

It is not entirely clear how changes in feed intake, provoked by the environmental factors, are mediated by underlying feeding behaviours. However, there is general agreement the daily duration of feeding decreases with increasing temperature (Collin et al., 2001; Fraga et al., 2019; Gertheiss et al., 2015). Furthermore, pigs adjust their mealtimes in response to changes in temperature, preferring to feed during cooler periods, such as early morning and late evening, to avoid heat stress (Bus et al., 2021; Cross et al., 2020; Santos et al., 2018; Quiniou et al., 2000). Moreover, high ambient temperatures can lead to decreased feed intake, changed meal patterns and reduced feeding duration, ultimately affecting overall feed efficiency (Bus et al., 2021; Cross et al., 2020; Gertheiss et al., 2015).

There are not many studies that have looked at the impact of cold on feeding behaviour since the main problem with the pigs is the heat stress. However, conversely to heat stress, cold stress can result in an increased feed intake and longer feeding durations as pigs attempt to maintain body temperature (Gertheiss et al., 2015).

Traditionally, animal feeding behavior has been observed through direct human supervision or the use of time-lapse video recording techniques. However, these methods are time-consuming and may cause stress (Brown-Brandl et al., 2013). Because of that, PLF technologies have been used to monitor feeding and drinking behaviour (Maselyne et al., 2014; Maselyne et al., 2015a). By utilizing PLF technologies, producers can enhance data collection and analysis, leading to improved management practices and ultimately, better productivity and profitability.

The results of feeding behaviour presented on Table 15 are discussed in the following sections:

(i) *Number of meals*

Across the trials, the animals consumed an average of 14 meals per day in the TNZ and W conditions and 16 meal/d in the S condition. In the TNZ condition, the average values recorded in this study are higher than that identified by Salgado et al. (2021), who recorded an average of 7 meals per day under thermoneutral conditions (18-22°C). Since this type of feeding stations have mostly been used for sows (Maselyne et al., 2015a), there are not many studies on the feeding behaviour of growing-finishing pigs. In this sense, this parameter alone may not fully represent the adaptive behaviour of pigs to thermal conditions or their weight gain. Therefore, this parameter will next be analysed in relation to other aspects of feeding behaviour.

When compared to the TNZ condition, the number of meals in the W condition was not affected by low temperatures. These results align with some literature where the effect of ambient temperatures on the number of meals was not observed (Bus et al., 2021). However, since few studies have investigated the impact of cold on feeding behaviour, as heat stress is one of the main concern for pigs (Gertheiss et al., 2015), no comparative studies on the number of daily meals under cold stress conditions were found. On the other hand, in the S condition the animals exhibited an increase (14%) in the number of daily meals. This result is consistent with the fidings of Renaudeau et al. (2006) that, although not significant, observed an increase in the daily number of meals from 7 to 8 meals/d with rising temperatures (28°C).

During the **growing period**, the number of meals remained relatively consistent between the TNZ and S conditions, with animals consuming an average of 15 meals per day. This result support the previous performance's results and are in line with the literature since pigs in this stage of growth (younger) are less sensitive to high temperatures compared to heavier pigs (Noblet et al., 2000; Van Heugten, 2010).

In contrast, a slight decrease of 6% was observed in the W condition compared to the TNZ condition. As mentioned previously, given that heat stress is the primary concern with pigs, there are few studies that have investigated the effects of cold temperatures on feeding behaviour. In the experiments of Quiniou et al. (2000) for similar conditions, the daily number of meals was not affected by temperature and these authors attributed this to the fact that pigs, when subject to thermal stress conditions, adjust their mealtimes.

During the **finishing period**, variations in the number of meals across the different environmental conditions were observed. The highest number of meals was recorded in the S condition, with animals consuming an average of 18 meals/d, while the lowest number of meals was observed in the TNZ condition, with 13 meals/d.

Compared to the TNZ condition, animals in the W condition exhibited a 15% increase in feed intake. This result can be explained by the literature, which indicates that pigs increase their feed intake under colder environmental conditions (Bus et al., 2021; Gertheiss et al., 2015; Quiniou et al., 2000). This increased intake may also influence the number of meals consumed. However, further investigation is needed to confirm this hypothesis.

Conversely, animals in the S condition presented an increase of 38%. This trend may explain that, in order to dissipate heat, growing-finishing pigs adjust their feeding behaviour as a thermoregulatory mechanism, resorting to a feed intake distributed over a greater number of meals. This result is in accordance with the study conducted by Renaudeau et al. (2006), which recorded, although not significant, an increase in the number of daily meals with rising temperatures.

Despite these variations, no significant differences were identified when comparing each environmental condition between the two periods. However, there was an observed trend of increased meal frequency in the W (7%) and S (20%) conditions. This increase is anticipated as the animals typically exhibit higher voluntary feed intake as their body weight increases (Godyń et al., 2020; Renaudeau et al., 2012; Santos et al., 2018). However, the particular case of the S condition highlights the impact of high temperatures on heavier pigs, further possible supporting that the number of meals tends to rise in this environmental setting.

In the case of the TNZ condition, a decrease of 13% was identified. It is possible that this decrease is because the animals are already in their thermal comfort zone, which may lead to a more stable and possibly reduced feeding pattern compared to more extreme conditions where their metabolism is working to either generate or dissipate heat. This may also be related to the amount of feed intake, as the animals in this condition increased their FI during this period (Table 11). This means that if they decreased the number of meals, they increased the amount of feed consumed per meal. This could be an adjustment that growing-finishing pigs make with increased body weight under thermal comfort conditions. The amount of feed consumed per meal will be a parameter analyzed in more detail later in this study. However, further research with a larger sample size is needed to confirm this hypothesis.

(ii) *Time per meal*

Animals spent longer periods feeding in the W condition (8.1 min/meal) and shorter in the summer condition (5.8 min/meal). When compared to the TNZ condition, the animals presented a decrease in the duration of their daily meals by 21% in the S condition and an increase of 11% in the W condition.

The meal durations recorded in this study under **thermal comfort conditions** (7.3 min/meal) were similar to those reported by Salgado et al. (2021) (7.4 min/meal).

The heat stress conditions (**summer condition**) resulted in a decrease of 1.5 minutes in the amount of time spent per meal. This value was slightly lower than that reported by Renaudeau et al. (2006), which observed a decrease of 2.3 min/meal at an ambient temperature of 28ºC. In contrast, Cross et al. (2020) did not identify variations in the total time spent at feeders across their study, except in the most extreme case (> 38.9ºC), where a decrease of about 4 minutes per meal was noted. This difference observed may be justified by the fact that in the present study, the recorded average temperature did not reach the emergency values observed in the work of Cross et al. (2020). However, these results underscore that, despite the lack of complete clarity on how feed intake changes with temperature, there is a general consensus that the daily feeding duration decreases with increasing temperature (Collin et al., 2001; Fraga et al., 2019; Gertheiss et al., 2015).

Santos et al. (2018) reported a 15% decrease in the feeding time of pigs raised under heat stress conditions compared to those raised under TNZ conditions. This decrease was slightly lower than that observed in our study (21%), although the difference is not substantial.

In the **winter condition**, the recorded average value for the time per meal was 8.1 min, representing a 11% increase compared to the TNZ. This result aligns with some literature where it is stated that the higher feed intake under these conditions corresponds to a consequent longer daily feeding duration (Gertheiss et al., 2015; Quiniou et al., 2000).

The analysis of meal duration across both the **growth and finishing periods** revealed significant differences influenced by the environmental conditions.

Notably, during the **growing period**, meal duration increased 21% in the W condition and decreased 14% in the S condition compared to the TNZ condition. This pattern aligns with the overall trends observed in the average results. However, the pronounced impact observed in the W condition, with a 21% increase in meal duration, further underscores the detrimental effect of low temperatures on younger pigs. Moreover, it may provide additional support to the previous findings in this study regarding the number of meals, suggesting that animals in this growth stage may exhibit a tendency to reduce the frequency of meals while increasing the duration of each meal.

Similarly, there was a notable 25% decrease in meal duration observed in the S condition and an 8% increase in the W condition compared to the TNZ condition during the **finishing period**. This pattern contrasts with that observed during the growing period, which was expected. Under heat stress conditions, animals typically reduce the daily feeding duration to minimize heat production (Collin et al., 2001; Fraga et al., 2019; Gertheiss et al., 2015). Additionally, in this stage of growth, animals are heavier and as mentioned previously, they are more sensitive to high ambient temperatures (Noblet et al., 2000; Van Heugten, 2010). Consequently, this effect was more pronounced during the finishing period, with a 25% decrease compared to 14% during the growing period.

Although not statistically significant, when comparing each environmental condition between the two periods, a more pronounced decrease in meal duration (15%) was observed during the **summer condition** compared to the other environmental conditions. This result, combined with the findings related to the number of meals, suggests a trend where animals under heat stress increase their number of meals and consequently, reduce the time per meal to cope with the effects of high temperatures. However, since it is not entirely clear how changes in feed intake are mediated by underlying feeding behaviors and there is only a general agreement regarding reductions in daily feed intake (Godyń et al., 2020; Huynh et al., 2005a; Ma et al., 2019; Pearce et al., 2015) and feeding duration (Collin et al., 2001; Fraga et al., 2019; Gertheiss et al., 2015) when temperatures rise, further research is necessary.

During the **winter condition**, a decrease (11%) in meal duration was also observed. This result may suggest an inversely proportional relationship between meal duration and the age of the animals. In other words, at the growing period (lower body weight), probably the animals found it more difficult to cope with cold temperatures, which led to longer meal duration. This reinforces the previous results and that animals increase their feed intake when exposed to thermal stress at low ambient temperatures, in order to use the energy available in food to maintain body temperature rather than for growth (Bus et al., 2021; Gertheiss et al., 2015; Quiniou et al., 2000). This effect seems to have been minimized, as expected, over time with increasing body weight (finishing period). This result is in line with the literature, as indicated by Martins (2020) and Prunier et al. (2014), regarding young pigs that are extremely sensitive to cold environmental conditions.

(iii) *Feed intake per meal*

Environmental conditions had a significant impact on feed intake per meal (P < 0.001).

The observed decrease in feed intake per meal during the **summer condition** (85 g), compared to the TNZ condition, is consistent with findings from Renaudeau et al. (2006), who reported a similar decrease when temperatures exceeded 28°C. Interestingly, this study presented a higher percentage decrease (36%) compared to the findings of Santos et al. (2018) under heat stress conditions (15%), indicating potentially greater sensitivity to temperature changes in this study population due to the significance difference identified in the results.

In contrast, during the **winter condition**, although not statistically significant, a decrease of 20% in feed intake per meal was observed. This finding aligns with the previous results, considering the unexpected lower feed intake recorded in this environmental condition compared to the TNZ condition (Table 10). Despite the increase in meal duration and the maintenance of the number of meals, the total feed intake decreased, resulting in a reduction in the amount of food ingested per meal.

Throughout both the **growing and finishing periods**, environmental conditions had a significant impact on the feed intake per meal of the animals.

During the **growing period**, smaller animals would theoretically exhibit comparable feeding patterns between the S and TNZ conditions, as suggested by literature indicating a lesser impact of high temperatures on young animals (Martins, 2020; Prunier et al., 2014). However, this study identified a significant decrease in feed intake per meal in the S condition compared to the TNZ condition.

When analysing this parameter alongside the number of meals, it becomes evident that despite the decrease in feed intake per meal when compared with the TNZ condition (190 g/meal vs 139 g/meal), the number of meals remained unchanged. Consequently, total feed intake was lower in this period (TNZ: 15 meals x 190 g = 2850 g; S: 15 meals x 139 g = 2085 g), resulting in higher feed efficiency (TNZ FCR: 2.58 kg/kg vs S FCR: 2.38 kg/kg). This observation might suggest that young animals under heat stress conditions tend to decrease the amount of food consumed per meal while maintaining their daily meal frequency. This behaviour potentially improves feed efficiency, which may help justify the lower FCR identified in this environmental condition.

Conversely, in the winter condition, it was anticipated that young animals, being more susceptible to low temperatures (Bus et al., 2021; Quiniou et al., 2000), would exhibit an increased feed intake (Gertheiss et al., 2015; Quiniou et al., 2000) and consequently, a greater amount of food per meal, but this anticipated outcome was not observed, as previously discussed. In contrast, animals in this condition reduced their feed intake per meal, although to a lesser extent compared to the S condition (174 g/meal vs 139 g/meal). When comparing this parameter with the number of meals, it is evident that despite this reduction in feed intake per meal and fewer meals compared to the TNZ condition, animals consumed more feed overall (W: 14 meals x 174 g = 2436 g; S: 15 meals x 139 g = 2085 g). However, their feed efficiency was lower (W FCR = 2.97; S FCR = 2.38). These results, combined with the ADG findings throughout the growth and finishing periods (Table 13), suggest that a part of the energy provided by the feed was used for maintaining body temperature rather than for growth.

Upon analyzing the **finishing period**, the substantial reduction in feed intake per meal in the S condition compared to the TNZ condition underscores the impact of high temperatures on heavier pigs (Noblet et al., 2000; Van Heugten, 2010). Conversely, in the winter condition, although a decrease in food intake per meal was observed compared to the TNZ condition, as previously discussed, this decrease was not significant. This reinforces that heavier animals are better prepared to cope with low temperatures (Bus et al., 2021; Quiniou et al., 2000).

When analyzing the results of this period alongside the number of meals, it can be observed that in the S condition, animals reduced their feed intake per meal but increased the number of meals (18 x 156 g = 2808 g), whereas the inverse trend was observed in the TNZ condition (13 x 227 g = 2951 g). This observation might suggest that animals adjusted their feeding behaviour as a mechanism to cope with thermal stress. Furthermore, there appears to be a recurring trend where an increase in the number of meals and a decrease in feed intake per meal lead to improved feed efficiency (S FCR = 2.66; TNZ FCR = 3.50). Additionally, these findings may indicate that animals in the TNZ condition consumed food amounts that surpassed their metabolic requirements.

Moreover, it's noteworthy that there was an increase in the amount of food ingested per meal from the growing to the finishing period across all environmental conditions, with this difference being significant in the TNZ condition. This increase is likely related to the increase in live weight and the consequent greater voluntary feed intake capacity (Godyń et al., 2020; Renaudeau et al., 2012; Santos et al., 2018). Although there was an increase in the amount of food per meal during the S condition, this increase was minimal. This suggests that the animals achieved better outcomes during the growing period compared to the finishing period, reinforcing the previously discussed greater impact of high temperatures on heavier pigs (Noblet et al., 2000; Van Heugten, 2010).

(iv) *<u>Summary of Feeding Behaviour Patterns</u>*

From a general perspective, there appears to be a trend in the TNZ condition where animals decrease the number of meals and increase the duration of each meal and the amount of food consumed per meal over time, resulting in an overall increase in total feed intake in this condition.

In the summer condition, an analysis of this parameter alongside the number of meals and meal duration reveals a tendency for animals subjected to heat conditions to increase the number of meals and reducing its duration, while maintaining a relatively constant food intake per meal. This trend appears to be directly associated with thermoregulatory adaptations observed in pigs to cope with heat stress and is in line with the literature (Cruz, 1997; Godyń et al., 2020; Mayorga et al., 2019; Quiniou et al., 2000; Renaudeau et al., 2012; Santos et al., 2018).

Conversely, in the winter condition, there seems to be a trend towards an increase in both the number and duration of meals, while feed intake per meal decreases. Surprisingly, this reduction in feed intake per meal contradicts hypothetical expectations, as it would be logical to assume that the amount of food per meal would also increase with the other parameters.

Overall, despite some disparities with existing literature, these findings provide valuable insights to better understand the feeding behaviour of pigs under different environmental conditions – particularly facilitated by the use of precision feeding throughout the automated feeding system adopted in this study – underscoring the need for future research.

6.3.2. Lying and resting behaviour

The lying and resting behaviour results obtained are derived from software developed in the project and because of that, there are no other values that can be used to numerically compare these results. However, since the index represents the animals' proximity or distance during their lying and resting periods, it is possible to observe and confirm that, in **summer condition**, as reported in the literature, the animals increase their surface area of exposure to heat exchanges, adopting a more relaxed posture and moving away from other animals, thus also allowing the air to circulate around them (Cruz, 1997; Huynh et al., 2005b; Kim et al., 2021; Olczak et al., 2015; Shi et al., 2006).

During **winter condition**, the opposite is observed, as the obtained values are very close to 1. This pattern aligns with the literature, as in this scenario, animals try to reduce the surface area exposed to heat exchanges, firstly changing their posture by adopting a huddled position, building “nests” and reducing the area of contact with the floor (Govindasamy et al., 2022; Hayne et al., 2000; Olczak et al., 2015).

In order to better understand the interaction between temperature and resting behaviour, the following relation was determined:

$$\boldsymbol{PI(T) = 1,289 - 0,031T} \qquad \textbf{(n=71, } \mathbf{R^2} \textbf{ = 0,74, RSME = 0,07)} \qquad \textbf{(eq. 11)}$$

Note: PI is the proximity index and T (ºC) is the ambient temperature.

Based on this equation, the following graph was generated:

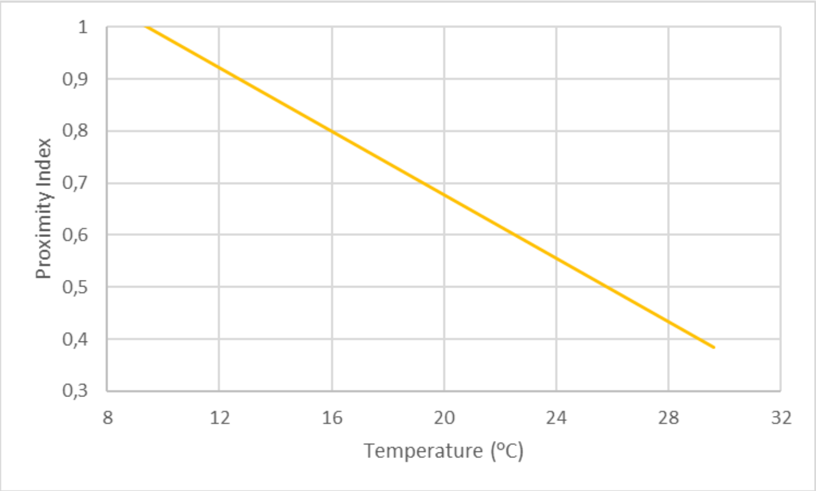


Figure 21 - Evolution of proximity index with the ambient temperature over the trials

According to equation 11, the proximity index decreases linearly with increasing temperature (Figure 21), which reinforces the previously mentioned adaptive resting and lying behaviours of pigs when subjected to thermal stress conditions.

Based on the discussion of the lying and resting behaviour results and the analysis of the PI across **different environmental conditions and periods**, several insights can be drawn.

During the **growing period**, significant differences in the PI were observed across environmental conditions, with higher values recorded in the W condition and lower values in the S condition compared to the TNZ condition. These results are consistent with the animals' lying and resting behaviour in response to temperature variations, as mentioned previously.

The patterns observed in the PI during the growing period were similarly reflected in the **finishing period**. The W condition exhibited a 27% increase in PI, while the S condition presented a 48% decrease compared to the TNZ condition. This suggests that pigs maintained similar lying and resting behaviours across both periods, with responses consistent with the prevailing environmental conditions.

Additionally, the difference in PI between the W and S conditions during the growing period was 0.46 and during the finishing period, it was 0.58. This 12% difference highlights the negative impact of environmental conditions on the animals' growth, reinforcing the apparent trend that animals tend to converge in behaviour under cold stress conditions and diverge under heat stress conditions.

However, upon examining **each condition throughout the animals' growth**, despite no significant differences, there appears to be a trend indicating that in W and TNZ conditions, animals tend to gather for lying and rest, while in S conditions, they tend to disperse. This trend reinforces the influence of high temperatures in pigs, particularly evident when the animals are heavier (Noblet et al., 2000; Van Heugten, 2010). This observation, as mentioned previously, underscores the behavioural adjustments made by pigs in response to environmental conditions, with higher temperatures stimulating animals to seek greater separation, likely to facilitate heat dissipation and mitigate thermal stress. Conversely, in cooler conditions, animals tend to aggregate, potentially to conserve body heat and maintain thermal comfort.

The integration of precision livestock farming tools, such as the PI, not only enhances the ability to differentiate subtle behavioural nuances, but also provides valuable insights into how animals respond to varying environmental stimuli. This underscores the importance of precision livestock farming technologies in clarifying complex animal behaviours and informing management practices aimed at optimizing animal welfare and performance.

Moreover, the utilization of such tools in behavioural studies, as demonstrated in the analysis of the PI in this research, highlights their significance in modern animal production systems. By providing producers with valuable insights, precision livestock farming technologies empower them to make informed decisions that can enhance animal welfare, productivity, and overall farm management practices.

7. CONCLUSIONS & FUTURE RESEARCH DIRECTIONS

This study presented a detailed analysis of the impact of environmental conditions on the performance and behaviour of growing-finishing pigs, highlighting the significant contribution of precision livestock farming to the advancement of animal production practices. The established objectives were achieved, namely:

Objective 1: To develop and update study about the impact of environmental conditions on the performance and welfare of growing-finishing pigs.

This study reaffirms that despite significant advancements in swine production – genetics, nutrition, housing systems, equipment, etc. – over recent years, environmental conditions still play a crucial role in the performance and welfare of growing-finishing pigs. While these advancements have enabled pigs to better adapt to environmental conditions, particularly heat, it is evident that the impacts of environmental housing conditions on performance and welfare persist.

The research conducted has shown that pigs continue to be affected by both heat and cold stress, which can influence their feeding behaviour, growth rates and overall health. This underscores the need for ongoing improvements and innovations in managing environmental conditions to ensure optimal performance and welfare outcomes for pigs.

Objective 2: Test and validate PLF technologies developed within the framework of the project.

In this study, several PLF (Precision Livestock Farming) technologies developed within the project framework were successfully tested and validated. Among the validated technologies, the innovative development of the proximity index stands out, proving effective in analysing the resting and lying behaviour of pigs as an indicator of animal welfare. This innovation allowed for a detailed and accurate assessment of the welfare conditions of pigs throughout the growing-finishing period.

Additionally, the innovative adaptation of the feeding machine for growing-finishing pigs was validated, significantly contributing to the study of feeding behaviour. This adaptation enabled continuous and precise monitoring of feed intake, providing valuable data for controlling and improving the growth performance of the pigs.

From the perspective of environmental condition control, the implemented technologies allowed for rigorous monitoring and adjustment of the installation's environmental parameters. This precise control was crucial to ensure that the pigs were kept in optimal conditions, minimizing thermal stress and improving their overall welfare.

The validation of these technologies demonstrates the potential of precision livestock farming tools to provide detailed and real-time data that can be used to enhance the management and housing conditions of pigs, resulting in improvements in both performance and animal welfare.

Objective 3: Realise the potential contribution of precision livestock farming tools for measurement of the impacts of environmental conditions on the performance and welfare of growing-finishing pigs.

In this study, PLF tools played a significant role in measuring the impacts of environmental conditions on the performance and welfare of growing-finishing pigs. These tools demonstrated their capability to automatically and accurately collect data on different variables and indicators, which would be challenging to monitor without their assistance.

The PLF technologies enabled precise monitoring of some behavioural patterns, performances and environmental conditions, providing valuable insights into the interactions between these factors and animal welfare. This automated and precise data collection allows for a more comprehensive understanding of how different environmental conditions affect the animals, contributing to more informed decisions regarding their care and management.

However, considering the complex interaction between animals, their environment and welfare, these tools are always subject to new potentialities and functionalities. As technology advances, there is a continuous opportunity to enhance the precision, scope and application of PLF tools, making them even more effective in capturing the intricate dynamics of animal-environment interactions.

Objective 4: To evaluate how the precision livestock farming tools can help improving the growing-finishing pig's performances and welfare.

In this study, it was confirmed that PLF technologies enhance performance and animal welfare by providing comprehensive monitoring and optimization of different aspects of animal management. The individual monitoring of animals allows for early detection of health issues and behavioural problems, enabling timely interventions that can prevent more serious complications.

The technologies used to monitor and control environmental conditions play a crucial role in improving housing conditions, thereby reducing thermal stress and ensuring optimal welfare. By maintaining a stable and comfortable environment, these tools help mitigate the negative effects of extreme temperatures on animal health and productivity. Additionally, PLF tools facilitate precise and individualized feeding strategies that optimize feed efficiency and growth rates, further contributing to improved performance. The ability to collect and analyse detailed data on feeding behaviour, growth patterns, and environmental conditions enables more informed and effective management decisions.

Overall, this study demonstrates that the integration of PLF technologies in pig production systems not only supports in monitoring but also actively improves the performance and welfare of growing-finishing pigs. The continuous and precise data collection provided by these tools ensures that animals receive the best possible care, enhancing both their performance and welfare.

Regarding the **experimental study**, the main conclusions are the following:

In the **thermoneutral condition**, characterized by ambient temperatures within the thermoneutrality zone, pigs exhibited higher feed intake and the lower number of meals and higher feed intake per meal. The performance results demonstrated greater average daily gain and although the feed conversion ratio was not optimal in this study, it remained within expected ranges for these genetics. In general, pigs in thermoneutral condition demonstrated overall better performance and growth compared to other environmental conditions.

During the **summer condition**, with ambient temperatures approaching the upper critical limit, pigs presented lower feed intake but achieved a better feed conversion ratio, indicating higher feed efficiency compared to other conditions. A feeding behaviour pattern related to heat stress was identified, resulting in an increased number of meals and reduced meal duration and feed intake per meal. Additionally, the lowest value of the proximity index was also noted during this period, suggesting possible heat stress effects. Overall, despite these animals being subjected to thermal stress conditions, which led to a decrease in their feed intake, the adjustments in feeding behaviour were apparently sufficient to minimize these effects under the experimental environmental conditions, as evidenced by the observed FCR.

In contrast, the **winter condition**, characterized by ambient temperatures near or below the lower critical limit, resulted in a decrease in feed intake and average daily gain, leading to a higher feed conversion ratio, indicating reduced feed efficiency. Additionally, there was a slight increase in the number of meals, with each meal having a longer duration and involving less feed intake per meal compared to the S condition. Moreover, the lowest value of the proximity index was also noted during this period, likely due to behavioural adjustments to cope with cold stress. Overall, the results observed in this condition indicated that environmental conditions had a negative impact on the animals' performance and welfare, prompting behavioural adaptations to cope with these effects.

In **summary**, some of these findings corroborate the existing literature, while others were less consistent and somewhat contentious. This could be attributed to a diversity of reasons discussed, including, for instance, the fact that the simulated environmental conditions were not extreme or the limited number of animals used in this study.

However, it is clear that additional research is imperative, particularly in the areas of Genetics and Breeding, Nutrition, Environmental Management, Animal Welfare, Technology and Data Analysis and Design and Methodology:

Genetics and Breeding studies:

- Explore the impact of environmental conditions on different genetic lines, focusing on breeding efficiency. Research could involve testing different genetic strains under extreme temperature conditions, aiming to select breeds with optimal performance and welfare outcomes.

Nutrition studies:

- Investigate the effects of different diets on pig's performance and welfare. This includes comparing different nutritional regimes under the same environmental conditions to assess their impact on performance and overall health.

Environmental Management studies:

- Evaluate the suitability of Temperature-Humidity Index (THI) in cold stress conditions to refine environmental management strategies.
- Examine the ecological footprint of pig production systems and develop strategies for sustainable waste management to minimize environmental impacts.

Animal Welfare studies:

- Conduct detailed analyses of behavioural responses and long-term welfare implications of environmental and dietary conditions. This includes studying the effects of different environments on social behaviours, stress levels and overall life quality.

Technology and Data Analysis studies:

- Analyse different advanced technologies such as artificial intelligence, IoT or machine learning to enhance data management, traceability and real-time monitoring capabilities.
- Develop and test technologies and equipment for monitoring and controlling animal welfare in a commercial farming context.
- Analyse the impact of PLF tools in a commercial farming context. This study includes identifying and mitigating challenges associated with this production systems.

Design and Methodology studies:

- Address the need for larger sample sizes and more repeated trials to increase the robustness and reliability of research findings. This is crucial for generalizing results and enhancing the scientific validity of studies.

The research directions highlighted above cover a diverse set of fields and disciplines, requiring the collaboration of experts from different specialties. These include precision livestock farming, animal welfare scientists and environmental housing specialists and experts in genetic and nutrition, among others. The complexity and interdisciplinary nature of these studies exceed the capabilities of any single researcher.

In future work, particular attention will be given to investigating additional environmental parameters and their impacts on animal and human health, alongside exploring behavioural and physiological aspects through the use of advanced technologies such as artificial intelligence and machine learning. These efforts aim to deepen our understanding and refine practices to promote both animal welfare and sustainable agricultural practices.

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