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Pig production systems and related effects on pre-slaughter animal welfare and meat quality

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ABSTRACT

Pre-slaughter handling practices, such as fasting, transport, mixing and human interventions affect the welfare of pigs and carcase and meat quality individually and cumulatively. Behavioural and physiological studies conducted during the pre-slaughter period revealed that producer-controlled factors at the farm, such as housing system, previous handling experience, genetics, gender, nutrition and slaughter weight can have an impact on pigs' ease of handling and sensitivity to stress, which result in loss of profits for the pork chain due to transport losses, reduced carcase value due to lesions and bruises and meat quality defects. Research has shown that pigs originating from enriched housing conditions, not over-selected for lean deposition and trained to be handled are easier to handle and more resilient to the effects of physical stress prior to slaughter. However, the effects on meat quality are not clear. The production of entire males and immunocastrates can be a valid alternative to surgical castration, provided specific practices are applied to limit aggressiveness in mixed group situations and the risk of bruised carcases. Recommendations for the transport and handling of heavier slaughter pigs must be adapted to improve ease of handling and reduce transport losses, aggressiveness and fatigue-related meat quality defects. The response of pigs to pre-slaughter physical stress and feed deprivation can be affected by ractopamine dietary supplementation, feed composition and feeding regime. The objective of this paper is to overview the effects of on-farm producer-controlled factors on pigs' response to pre-slaughter handling and meat quality, and environmental, social and economic sustainability.

HIGHLIGHTS

- On-farm factors impact pig losses
- On-farm factors impact ease of handling
- On-farm factors impact food safety; effects on meat quality are unclear

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Animal welfare; pigs; meat quality; pre-slaughter; production systems

Introduction

The pre-slaughter period consists of several stages, starting when pigs leave the finishing pen and including transport, lairage, stunning and sticking. At each stage, pigs are exposed to different stressors ranging from sorting pigs out of the home pen, feed withdrawal, transport, mixing with unfamiliar conspecifics, overcrowding, handling through ramps, bends and alleys, that, both individually and additively, can contribute to animal losses, carcase depreciation due to severe skin lesions and weight losses, and meat quality defects due to abnormal post-mortem muscle acidification (Faucitano 2018; Lebret and Čandek-Potokar 2022).

The farm of origin has been reported as a major contributor to the variation of animal losses during transport (25%; Dewey et al. 2009), with a 0.93% difference in dead-on-arrival (DOA) being recorded between the poorest and the best performing farms (Fitzgerald et al. 2009), ease of handling between batches of pigs at the slaughter plant (Grandin 1993), pigs' physiological condition at slaughter (Rocha et al. 2016), incidence of bruised carcases (Dalla Costa et al. 2007) and pork meat quality (Rocha et al. 2016).

The producer can account for approximately 50% of the variation of pork meat quality (Grandin 1994). This responsibility, which is shared with the abattoir, is in terms of producer-controlled factors, such as

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housing conditions, gender of the herd, final market weight, nutrition, genetics and handling.

The objective of this paper is to overview the effects of the on-farm conditions (i.e. housing system, feed withdrawal and handling) on pigs' physiological and behavioural response to pre-slaughter handling and its influence on meat quality variation. Aspects related to the environmental, social and economic sustainability of different farming systems will also be addressed based on the available studies.

Housing conditions

During the grow-to-finish period, pigs are normally kept under intensive, with little environmental enrichment, housing conditions, resulting in pigs showing a higher reactivity to novel stimuli, less developed social behaviour or increased fearfulness (Faucitano and Goumon 2018). In contrast, pigs raised in a semi- or full intensive enriched environment, i.e. lower stocking density, straw-bedding with or without access to an outdoor area and more frequent contacts with humans, appear easier to handle, more resilient to transport and handling stress (i.e. lower post-transport salivary cortisol and blood lactate levels at slaughter) and less aggressive in mixed group conditions than those raised under intensive barren housing conditions (Geverink et al. 1999; De Jong et al. 2000; Barton-Gade 2008; Rocha et al. 2016; Fàbrega et al. 2019). However, the results of a comparative study between 12 pig farms, featuring conventional and animal welfare-improved raising systems (AWIRS), differing in stocking density, use of bedding, and handling and production practices (i.e. electric prodding and tail-docking), showed a greater proportion of either PSE (pale, soft, exudative) or RSE (red, soft, exudative) pork meat in AWIRS compared with conventionally raised pigs (Rocha et al. 2016). The greater incidence of these meat quality defects in AWIRS loins has been associated with the significant correlations between the score for good housing, criterion of the European Welfare Quality audit guidelines (Welfare Quality® 2009) that was used to assess the raising conditions at these farms, with muscle pHu ($r = -0.75$; $p < .05$) and Minolta L^* value ($r = 0.87$; $p < .01$). The greater residual glycogen content in the muscle at slaughter resulting from the greater resilience (based on lower blood lactate levels) of AWIRS pigs to physical stress prior to slaughter was proposed as the likely cause of these meat quality defects. However, this interpretation was hardly supported by the results of previous studies, ranging from no effect to greater residual glycogen and lower loin meat pHu value to lower muscle residual glycogen and/or greater loin meat pHu values in pigs raised in enriched housing conditions, i.e. indoor straw-bedding or semi-intensive raising systems, e.g. indoor bedding plus access to outdoor area (Geverink et al. 1999; Klont et al. 2001; Lebret et al. 2006, 2011; Barton-Gade 2008; Lebret 2008; Foury et al. 2011). More recently, Faucitano et al. (2020), besides recording a greater ease of handling (i.e. less round-turns, back-up and stops, and less handler interventions at loading, all resulting in shorter loading time) and lower fatigue condition at slaughter (as shown by lower blood lactate levels), also reported a trend for a reduced loin muscle glycolytic potential, and lower pH1 and drip loss in enriched- (straw-bedding and lower stocking density) vs. conventionally housed (slatted floor and greater stocking density) pigs. The inconsistent effects of alternative production systems on pork meat quality as assessed in different muscles was previously reported (Olsson and Pickova 2005) and may be explained by the different experimental design of the studies, e.g. pre-slaughter stress intensity.

Besides the clear positive effect that all animal-friendly housing systems have on the societal aspects of sustainability (including both animal welfare and consumer perception; Boogaard et al. 2011), the consequences of these farm management strategies on the environmental and economic aspects are less consistent across studies. One of the typical conundrums concerns, for example, organic or, more generally, extensive farms. While organic farms perform better on the majority of sustainability indicators when the results are expressed per unit of land, they also tend to show less favourable indicators when expressed per unit of product (Zira et al. 2021), due to the greater land surface occupied, feed requirements and production costs, that in turn translate into a lower production efficiency compared to conventional farms. However, estimates indicate that consumers are willing to pay more for pork products showing a general animal welfare or an organic label and perceive them as having higher sensory quality (Gross et al. 2021), possibly increasing the revenue (and economic sustainability) of these farming systems. This trade-off between the three dimensions of sustainability in animal-friendly production systems warrants the need for a holistic evaluation of each production condition.

Previous handling experience

On the basis of the concept that pigs can be trained to accept some irregularities in management and thus react less vigorously to novelty (Reid and Mills 1962), a series of studies have been conducted over the last 25 years with the objective to assess the effects of previous training strategies on the later ease of handling, physiological and psychological response to pre-slaughter handling, incidence of animal losses on arrival at the abattoir and meat quality (Table 1). Overall, training pigs to be driven through the alley at the farm during the whole grow-to-finish phase or the last finishing period (from last 3 weeks to last day) appears to improve easiness of handling by increasing animal pace (80% faster pigs) and reducing moving time (1 min shorter) and the number of handler interventions at loading (Abbott et al. 1997; Lewis et al. 2008; Goumon et al. 2013), to improve the cardiovascular response to loading stress (Goumon et al. 2013) and tends to reduce the proportion of total animal losses (DOA and non-ambulatory pigs) during transport (Stewart et al. 2008) compared with pigs that had not been previously moved (0.07 vs. 0.38%; $P = .08$).

More recently, a shorter (30 vs. 60 s) loading time has been reported in finishing pigs that were exposed to a ramp when they were piglets in the nursery pen (Novak et al. 2020). However, the effects of a previous handling experience at the farm on meat quality are unclear, ranging from no effect to a slight paler colour or higher muscle pHu values in the loin muscle of pigs having experienced regular handling and human contacts at the farm (Geverink et al. 1998; Pommier et al. 1998; Terlouw et al. 2005).

Genetics

Similarly to the prior experience at the farm, the genetic background influences the way pigs evaluate their situation in slaughter contexts determining their psychological and physiological state at slaughter and, eventually, the quality of the meat they will produce (Terlouw et al. 2021).

Over-selection for a single trait, such as the higher efficiency of lean growth, applied over the last 50 years resulted in undesirable effects on behaviours and physical capacities of the animals through correlated effects on behaviours, metabolism and health (Rydhmer and Canario 2014). When compared to less selected genotypes, pigs from genetic lines selected for more lean meat deposition are reported to be more fearful, more aggressive, more reluctant to move (Rydhmer and Lundheim 2008), and, finally, more prone to die or become non-ambulatory prior to slaughter (Dalla Costa et al. 2019). Genetic-dependent changes in individual conformation can also explain the variation in skin lesions, with more conformed pigs having a more sensitive skin that can be more easily damaged (Faucitano and Raj 2022).

A specific gene, known as the Halothane gene (HAL-1843 gene), causing malignant hyperthermia syndrome (MHS), also called porcine stress syndrome (PSS), which is characterised by a generalised rigidity of the muscles, muscle lesions, respiratory distress, hyperthermia, blotchy dermal hyperaemia and

Table 1. An overview of different studies assessing the efficiency of previous handling experience on the ease to handling at loading and meat quality.

Treatment	Duration	Results	Reference
Handling in the alley	Three weeks before loading for transport	Lower percentage of slow animals and shorter loading time	Abbott et al. (1997)
1. Spontaneous exit from the pen, slow pace handling to the truck, transport, unloading and return to the home pen 2. Presence of humans in the pen, negative and positive handling at each contact	Grow-to-finish, twice/week	Faster exit from the pen and shorter loading time in pigs accustomed to the presence of humans; slightly paler loins	Geverink et al. (1998)
Regular handling	Five days before loading for transport	Higher pHu values in the loin muscle due to lower stress at loading	Pommier et al. (1998)
Handling from pen to the loading area	The day before loading for transport	Shorter loading time, lower percentage of NANI and total transport losses	Stewart et al. (2008)
Regular positive or mildly negative handling in the pen	40 days before loading for transport	No effect on meat quality	Terlouw et al. (2005)
Physical training (walk for 1.2 km) Psychological training (voluntarily access to a ramp installed in the finishing pen)	Nine days before loading 11 days before loading	Lower heart rate in psychological and/or physical training Greater ease of handling (less stops and handler interventions on the ramp) in physically trained pigs	Goumon et al. (2013)

NANI: non-ambulatory, non-injured pigs

metabolic acidosis in the tissues, PSE pork meat production and blood splashes, acute right heart failure and death, has been shown to be directly related to pigs' response to handling and transportation stress (Gispert et al. 2000; Fàbrega et al. 2002; Weschenfelder et al. 2012, 2013), and stunning, both electrical and CO_2 gas (Velarde et al. 2001, 2007). Since 1990s, pigs have been identified as normal (Hal^N), heterozygous (Hal^{Nn}) or homozygous (Hal^n) for the PSS mutation using a DNA-based test (Fujii et al. 1991). This PSS mutation occurs at a high frequency in specific breeds, such as Piétrain (Gispert et al. 2007), whose terminal sires are still used in the selection programs to get more efficient and leaner crossbreds, tailored to specific market requirements (Weschenfelder et al. 2012, 2013). However, in transportation trials where different Piétrain crosses (50% Pietrain Hal^{Nn}, 50% Piétrain Hal^{NN} and 25% Piétrain Hal^{NN} genotypes) were shipped to slaughter (45 min trip) using two trailer types (one featuring internal steep ramps and the other semi-hydraulic decks), Weschenfelder et al. (2013) reported a lower ease of handling (overlaps and jamming) at unloading in 50% Piétrain crossbreds, regardless of the presence of the Hal gene, and more exudative loins and hams in 50% Piétrain Hal^{Nn} crossbreds compared with 50 and 25% Piétrain Hal^N crossbreds. The general conclusion from this study was the crossbred type contributed more to animal welfare and meat quality than the trailer type, but this effect may be exacerbated by the trailer model (presence of internal ramps) used for their transport to the abattoir. More recently, a greater occurrence of severe lesions in the posterior part of the carcase was recorded in Hal^{Nn} pigs, likely resulting from their lower ease of handling and increased handler interventions (e.g. electric prodding; Čobanović et al. 2023).

However, it appears that the HAL-1843 mutation was not associated with the occurrence of DOA and non-ambulatory pigs on arrival at the abattoir in US transport trials (Ritter et al. 2008), which suggests that mutations of other genes (e.g. dystrophin gene; Nonneman et al. 2012) could account for these transport losses.

Differences in pigs' response to pre-slaughter handling and transport and meat quality have also been reported for other commercial and local breeds. Lepron et al. (2003) observed that Meishan crossbreds and Large White pigs were easier to handle than a synthetic breed selected for muscle development, while Terlouw and Rybarczyk (2008) found that Duroc were less fearful towards human approach and less reactive to slaughter conditions than Large White pigs, which resulted in less exudative pork meat in the Duroc pigs. A couple of studies also assessed the response of local pig breeds to transport stress and its effects on meat quality. In a 2 h transport trial, Li et al. (2008) reported a calmer behaviour (more sitting and lying) in Erhualian, prolific Chinese breed, pigs compared with Piétrain pigs that stood more during the journey. Whereas, pigs of the indigenous Italian breed Apulo-Calabrese, although they were less reluctant to move forward and vocalised less, showed a greater physiological response to short transport (1 h) stress (based on greater concentrations of lactate and urea in exsanguination blood), resulting in darker pork meat, compared to commercial crossbreds (Aboagye et al. 2018).

The main expected progress, in terms of genotype and sustainability, include selection programmes for the genetic capability of pigs to efficiently use nutrients combined with precision feeding (Pomar and Remus 2019). Other genetic selection paths may include breeding for traits improving animal welfare *per se* or at least as a method to offset the negative effect of selection for production traits. Some examples in this sense could be selecting for increased neonatal survival, reduced aggressiveness and reduced expression of tail biting (Turner et al. 2018). Despite being not immediate, this selection may help especially when effective management solutions to solve these issues still have to be found (Faucitano et al. 2022).

Gender

The response to handling and transport effects of the most common genders in swine production, i.e. gilts and barrows or castrated males, is unclear, ranging from no difference in transport losses, physiological response (based on blood acid-base parameters or rectal temperature) and carcase lesions to greater transport losses, rise in rectal temperature after handling and proportion of bruised carcases after mixing in barrows than in gilts or more carcase bruises in gilts than in barrows (Dokmanović et al. 2017; Faucitano and Raj 2022; Čobanović et al. 2023).

While the worldwide production of castrated males remains dominant (31.5% of the market pig population in Europe; IFIP 2022), that of entire males that are traditionally raised in some countries (e.g. Spain and UK) is increasing in number of other EU countries, reaching the current 17% of the European market pig population (IFIP 2022), and in Brazil (MAPA 2020). This trend is in response to the welfare concern due to the pain and stress associated with the surgical castration procedure, which also has led several countries to adopt the practice of surgical castration carried out with local anaesthesia and analgesia (Faucitano et al. 2022; IFIP 2022). The use of entire male pigs is raising interest because they improve the productivity and sustainability of swine production, thanks to a higher growth rate (+13%) and feed conversion (+14%), lower feed consumption (−9.5%) and greater carcase lean yield (+9–40%) (Gispert et al. 2010; Squires et al. 2020). This production is also associated with a lower environmental impact due to reduced energy costs and manure production (EFSA 2004).

In an economic analysis of the alternatives to traditional surgical castration, castration carried out with local anaesthesia would be economically more beneficial to producers, while the production of entire males would be only profitable if the percentage of pigs with boar taint is not above 2.5% (de Roest et al. 2009). This latter objective looks quite achievable considering that the production of compounds responsible for boar taint (androstenone and skatole) is highly heritable making the genetic selection for low boar taint possible (Guatteo 2012; Merks et al. 2012).

Besides the need to monitor entire male carcases for boar taint, an off-odour and off-flavour in cooked pork meat, greater levels of aggression and skin lesions have been reported for this pig gender after mixing with other unfamiliar pigs compared with castrated males and gilts (Warriss and Brown 1985; Teixeira and Boyle 2014). However, handling strategies have been proposed to limit fighting and skin lesions in entire males after mixing on the truck or in the lairage pen, such as keeping the group unmixed (Rydhmer et al. 2013) or by mixing boars with gilts rather than with pigs of the same gender (Van Staaveren et al. 2015).

Immunocastration through the injection of a GnRF analogue a few weeks before slaughter proved to be a valid alternative to the painful practice of surgical castration, while keeping the growth performance of boars until a few weeks before slaughter and reducing aggressions and sexual behaviours during the late finishing phase at the farm and risk of boar taint (Fàbrega et al. 2010; Batorek et al. 2012). When compared to castrates, immunocastrates are leaner (approximately +5% lean yield) and show no or minor difference in meat technological or sensory traits (Keith, 2009; Rocha et al. 2013; Li et al. 2015). For these reasons, immunocastrate males are the dominant gender in Brazil and represent 1% of the European market weight pig population (IFIP 2022), with the production concentrated in Germany (5%) and Belgium (15%). Regarding their response to pre-slaughter handling, a few studies showed that immunocastrates vocalise less during handling and loading and present no transport losses when compared with barrows and gilts (Guay et al. 2013) and do not differ in fighting behaviours when mixed with unfamiliar conspecifics of the same gender in lairage compared with barrows (Rocha et al. 2013).

The effect of immunocastration on the economic, environmental and societal dimension of sustainability are therefore a consequence of the careful fine-tuning of the vaccination calendar, with a delayed second intervention resulting in better performance on the first two dimensions (Kress et al. 2019), but higher risks for societal aspect, in terms of consumer acceptance (Aluwé et al. 2020).

Nutrition

Feed texture and meal frequency

Withdrawing feed from pigs before slaughter is a practice recommended to producers primarily to ensure empty viscera at slaughter and prevent food safety hazards due to cross-contamination between carcases (SCAHAW 2002; Faucitano et al. 2010; NFACC 2014). A further objective of this practice is to ensure the welfare of pigs during transport preventing transport losses, hyperthermia and travel sickness (Faucitano 2018). Feed withdrawal is also seen as a tool for reducing the incidence of PSE pork meat by raising muscle pHu values through the reduction of muscle glycogen stores at slaughter (Faucitano et al. 2006, 2010). The application of this practice can help the economic and environmental sustainability of the pork chain through feed saving (2 kg less for 24 fasting; Kephart and Mills 2005) and reduction of wastes to dispose for the abattoir (e.g. 10,000 kg of waste less by each 2 kg reduction in the viscera weight for an abattoir slaughtering 8000 pigs per day; Murray 2001).

Studies have shown that, regardless the application of correct fasting interval (24 h from last feed to slaughter; Faucitano et al. 2010), the gastro-intestinal tract (GIT) emptying rate influences hunger-related behaviours, such as lower ease of handling and increased fighting and drinking (Brown et al. 1999; Saucier et al. 2007; Dalla Costa et al. 2016), of fasted pigs and the weight and content (solid or liquid) of the viscera at slaughter is dependent on the feed texture (pellet vs. mash) provided at the last meal and the meal frequency (restricted vs. *ad libitum*). Saucier et al. (2007) reported that, as expected, full stomach and content weights decreased with increasing fasting time in pigs fed mash and up to 14 h fasting in pigs fed pellets, but in the latter pigs full stomach and water content weights increased again after 24 h of fasting. This increase was explained by the greater hunger of pigs fed pellets during lairage as GIT emptying rate was faster due to the greater digestibility of this feed type (Fekete et al. 1983). The positive correlation ($r = 0.40$; $p < .01$) between the weight of water content in the stomach and drinking behaviour (total water use) in the lairage pen indicates that these pigs needed to drink water to fill their stomach and feel satiated. In the same study, when compared with restricted feeding (two meals/day), *ad libitum* feeding (five meals/day) reduced the weights of stomachs and their content (Saucier et al. 2007). This difference can be explained by the intake of smaller feed portions at each meal in pigs with *ad libitum* access to feed, which favours food digestion and consequently accelerates GIT emptying (Faucitano et al. 2010). In a companion study, the combined effect of pellet feeding in two meals per day and 24 h feed withdrawal raised the pHu value of the *Adductor* muscle as a result of hunger-related muscle glycogen stores depletion at slaughter (Faucitano et al. 2006).

Dietary ractopamine supplementation

The feed additive ractopamine is a ß-adrenergic agonist that, when fed to pigs (5–10 ppm/kg of feed) during the last 28 days of the finishing period, increases growth rate (+10–15%) and carcase leanness (+11%), while producing acceptable pork meat quality (Schinckel et al. 2001; Patience et al. 2009). However, there is evidence that ractopamine feeding also increases the heart rate of pigs during handling and transport (Marchant-Forde et al. 2003; Poletto et al. 2010), fighting rate and intensity in mixed groups (Poletto et al. 2010; Rocha et al. 2013) and handler interventions (Rocha et al. 2013). Interestingly, Rocha et al. (2013) reported that feeding ractopamine to immunocastrates increased the number of fights when they were mixed with pigs of the same gender in lairage. For these reasons, although it appears that these negative behaviour and physiological responses have been mostly observed in pigs fed with doses above 5 mg/kg or 20 mg/kg (Ritter et al. 2017), the use of ractopamine is only permitted in 27 countries, including Canada, USA, Mexico and Brazil (Pacelle 2014), due to marketing issues related to concerns for possible residues in the meat.

Slaughter weight

Slaughter weight has been increasing worldwide over the last decades. For example, in Canada, the average slaughter weight increased from 105 kg in 1989 to the current weight of 130 kg achieved in 2010 (Correa 2011), while in US it was increased by approximately 10 kg from 2010 to 2022 (USDA 2023). This increase in market weight is driven by the dilution of fixed production cost through the reduction of the total number of pigs required to produce a given quantity of pork and the improvement of genetic selection for leaner and faster growing pigs (Wu et al. 2017), resulting in better carcase yields and meat to bone ratio (Ellis and Bertol 2001), reduced costs for animal health control due to lower need for vaccine protection resulting from a more developed immune system (Wu et al. 2017), and greater profits when pig prices are high or when finishing feed prices are relatively low (Morin et al. 2015). However, it has been reported that heavier pigs (131–137 kg) are less easy to handle than lighter pigs (114–124 kg) and need more handler interventions to move forward in the barn alley and on the loading ramp (Bertol et al. 2011; Rocha et al. 2016) as, because of their larger size, they get easily stuck in narrow spaces (Zurbrigg et al. 2017). Their lower ease of handling has been associated with increased salivary cortisol concentration and heart rate (Dalla Costa et al. 2009), and greater risk of transport losses and bruised carcases (Correa 2011; Passafaro et al. 2019; Čobanović et al. 2023). The increased risk for a heavier pig to die or become non-ambulatory during transport can be explained by its particular vulnerability to heat stress resulting from overcrowding or poorly ventilated environments (Renaudeau et al. 2011) as they produce more body heat (+ 2% per 5 kg body weight increase) and are less able to dissipate it compared with lighter pigs (Brown-Brandl et al. 2004). Furthermore, it has been shown that heavier pigs (140 vs. 120 kg) fight more when mixed in the lairage pen and, consequently, are more fatigued at slaughter, as shown by greater blood creatine kinase (CK) concentrations and higher pHu values in the ham muscles (Vero, 2021). Increased fighting behaviour explained the greater lesion scores in the anterior part of the carcase (where most fighting bites are observed; Faucitano 2001) of heavier pigs (121–145) compared with lighter pigs (70–100 kg) in a recent study (Čobanović et al. 2023).

Conclusions

The research findings overviewed in this chapter provide the evidence about the impact of production systems and practices on the subsequent response of pigs to pre-slaughter handling and transport and meat quality.

Similarly to other meat species, in pigs the most important welfare issues result from production systems involving close confinement, high stocking density or a barren environment, painful husbandry practices and genetic selection to increase production.

The benefits of growing-finishing pigs in indoors enriched environments, i.e. straw-bedding and lower density, in terms of greater ease of handling at loading, faster loading procedure, lower stress status at slaughter, and improved *post-mortem* muscle metabolic conditions and pork meat quality have not been consistently reported in the literature. The reason for this inconsistency between studies can be explained by the different enriched housing and environmental conditions (indoor enriched vs. semi-intensive raising systems and cold and warm, respectively) and the stress intensity (i.e. mixing vs. no mixing, gentle handling and different lairage time) applied during the grow-to-finish period and pre-slaughter period, respectively. Furthermore, a producer who wants to invest in this type of production to meet the consumers' demand must consider some related drawbacks, such as greater carcase fatness, due to increased feed intake, pig health control (in extensive housing systems), environmental issues due to the amount of wet and soiled bedding to dispose and risk of blockages in the slurry system caused by the straw falling through the floor slats.

Research has provided a clear evidence that selection for lean growth resulted in pigs more reactive to environmental stressors and less resistant to physical activity, particularly during pre-slaughter handling and transport. For this reason, robustness, described as high production potential combined with enhanced resilience to stress and greater adaptability to ambient conditions, has become one of the traits identified as important breeding goals necessary for more sustainable pork production.

The increasing market demand for the production of heavier pigs is creating challenges to handling and transportation systems, in terms of lower ease of handling and greater fighting in mixed groups and related increased proportion of bruised carcases, transport losses, fatigue condition at slaughter and DFD-like pork meat production. Existing recommendations, in terms of facilities design (e.g. ramp slope), handling system (i.e. group size) and ambient, transport and lairage conditions (i.e. thermal comfort and space allowance), are not adapted to the physical needs of these pigs that differ from those of other pigs due to their greater weight and size. More research is thus needed to provide revised science-based recommendations helping producers to reduce animal and related profit losses.

Although many countries are embracing surgical castration with pain mitigation (anaesthesia and analgesia), it is still difficult to determine whether the increased distress from the handling (and or drug injection) outweighs the pain relief it provides. Despite the risk of consumer meat unacceptance or marketing of boar-tainted carcases, the production of entire males and immunocastrates represent a valid alternative to surgical castration of piglets. However, to reduce their innate fighting behaviour and the risk of condemned carcases due to severe lesions, mixing of entire males should be avoided or at least managed during transport and lairage. Immunocastration equals the resistance to transport stress and fighting behaviour to that of surgically castrated pigs, but the latter advantage may be offset by the supplementation of ractopamine in the diet. Nutrition, indeed, plays an important role in relation to the fitness of pigs at the departure from the farm, with higher than recommended doses of ractopamine making pigs less resistant to physical stress and more prone to die or become non-ambulatory during transport, and feed composition and feeding regime increasing the capacity of pigs to cope with pre-slaughter feed deprivation and produce safer and better pork meat quality.

Due to the difficulties in investigating the three dimensions of sustainability simultaneously, research gaps persist in the evaluation of the economic and social dimension of sustainability, while environmental studies tend to be more common. In addition, trade-offs between the three dimensions are present and remain to be fully understood. In the case of animal-friendly systems, for example, the societal and animal welfare aspects are improved, but conflicting results may still arise, in terms of the environmental and economic dimensions (mainly due to lower production efficiency and uncertain economic return for the investments). Instead, if we consider the application of specific farming strategies (e.g. immunocastration, genetic selection and fasting before slaughter), the economic and environmental aspects related to lower resource use and increase efficiency may in some cases be outweighed by animal welfare issues (increased aggression, morbidity or pre-slaughter stress). Overall, understanding these conundrums and consequently fine-tuning farming strategies will be the key for the development of a more sustainable pig production.

Disclosure statement

No potential conflict of interest was reported by the authors.

Data availability statement

The data presented in this review are available on request from the corresponding author upon reasonable request.

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