Review

Effect of Castration Procedure and Management on Production Health of Pigs: A Review

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Abstract | Castration is one of the most ancient swine production practices, and it was started to avoid boar taint as an unpleasant odor and flavor in pork, the result of excessive buildup of androstenone and skatole in adipose tissue. In addition to its influence on meat quality, castration affects growth performance, carcass characteristics, behavior, reproductive control, and animal welfare. As a worldwide concern grows regarding animal welfare and consumer demand, the swine trade is moving away from surgical castration as practiced for decades and towards more welfare-friendly practices, including immunocastration. Here we summarize recent studies on biochemical influences on boar taint, contrast castrating techniques and assess the effects on performance, carcass quality and welfare. Surgical castration is still a practice with much of its use because it is simple, effective and often used to remove boar taint; nonetheless, it leads to acute pain, increased stress responses, and if not performed with anesthesia or analgesia, the risk of complications. Immunocastration via gonadotropin-releasing hormone (GnRH) vaccination provides a second course that retains full male growth until finishing phase of testicular functioning is effectively achieved. According to the study, there is evidence from several studies and meta-analyses that immunocastrated males exhibit generally higher feed conversion, reduced aggression and sexual behavior, and higher carcasses with negligible risk of boar taint. These two alternatives have economic and management implications, each of which needs to be weighed by producers. The review further highlights knowledge gaps for long-term welfare effects, environmental impacts, consumer acceptance, and possible nutrition and genetic interactions. Taken as a whole, the implementation of optimal castration strategies are achieved by a combination of welfare standards and production objectives with market demands and sustainable and ethical pork production.

Keywords | Boar taint, Surgical castration, Immunocastration, Growth performance, Carcass quality, Swine welfare

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INTRODUCTION

Castration remains a key factor of commercial swine production and is considered an effective method of preventing boar taint and reducing aggressive and sexual behaviours in male pigs and is now one of the main aspects of commercial swine production. Boar taint as an unwanted smell or unpleasant taste when eating pork is mainly associated with two compounds, androstenone (testicular steroid pheromone) and skatole (a microbial metabolite produced from tryptophan degradation in the hindgut) and occurs in cooking pork primarily due to accumulation during pork cooking (Duarte *et al.*, 2021; Squires *et al.*, 2020).

The concentrations of these compounds rise as intact males

reach puberty, hence producing pork from entire males remains a quality and consumer acceptance hurdle for much of markets. However, the expression of boar taint can be determined depending on genetics, diet composition, gut microbiota, housing hygiene, and management practices (Bee *et al*., 2020; Duarte *et al*., 2021). Historically, surgical castration has been the most established approach to control boar taint (Duarte *et al*., 2021; Pereira-Pinto *et al*., 2025). When done early, it inhibits testicular androstenone production and indirectly decreases skatole accumulation. Yet, surgical castration, without analgesia and anaesthesia, has faced increasing criticism owing to substantial welfare concerns (Duarte *et al*., 2021; Pereira-Pinto *et al*., 2025; Squires *et al*., 2020). Despite some young age procedures, piglets still have acute pain, stress responses, and postoperative distress (Borell *et al*., 2020). Furthermore, the castrated pigs exhibit low feed efficiency, high fat storage, and a greater environmental footprint than entire males or immunocastrated pigs (Bee *et al*., 2020). Due to increased welfare-led regulations and expectations from consumers, some countries are trending toward limiting, or eliminating surgical castration performed without pain relief (Duarte *et al*., 2021; Pereira-Pinto *et al*., 2025). Over the last years, immunocastration as vaccination against gonadotropin-releasing hormone (GnRH) was seen as a good alternative tool, compared with the surgical castration in pig studies (Wang *et al*., 2023). Immunocastration, when given after the second dose of vaccine, suppresses testicular function and results in reduced concentrations of androstenone and skatole, which are in line with those found in surgically castrated pigs (Djurkin Kušec *et al*., 2021; Wang *et al*., 2023). It should be noted that an immunocastrated pig will show the well-documented growth performance and leaner carcasses during the early finishing phase (Borell *et al*., 2020), while with a difference in behavior and reduced aggression after immunization the pigs still display the highest growth and leanest carcasses during the early finishing period for entire males and decreased aggression after vaccination (Werner *et al*., 2021). This is the double advantage of performance enhancement for the animal pre-second dose, with improved welfare afterward, which in a very few areas has encouraged the rapid application of immunocastration in recent years. Further promising options to modify or substitute physical castration are optimised diets (such as modified feeding methods (more fermentable fiber), better sanitary housing systems to lower skatole production; genetic screening for boar-taint–associated traits and improved livestock breeding (Pereira-Pinto *et al*., 2025; Werner *et al*., 2021).

In a further investigation of pork chains available to the industry and within the field of commercial pork, it was discovered that despite the general high prevalence, these may be relatively low under controlled detection thresholds and proper selection systems. There is a need for new synopses, which will account for recent scientific and regulatory advancements in this field. Thus, this review provides a summary of recent studies that study the factors associated with boar taint formation, compares surgical castration with immunocastration, and examines their relevance to growth performance, carcass and meat quality, and welfare. It also emphasizes the remaining knowledge gap and future research priorities as the industry transitions to more welfare-oriented and cost-effective castration alternatives.

Literature search strategy

This review was undertaken to synthesize the existing scientific evidence relating to castration techniques, means of boar taint, and productive and welfare outcomes of various management strategies in male pigs. The key objective of the manuscript was to compare surgical castration and immunocastration and discuss the biochemical basis of boar taint and its consequences for pigs' performance, meat quality, and welfare, which guided the selection of literature. To perform this, a systematic literature search was performed over the main scientific databases: Google Scholar, PubMed, ScienceDirect, and Scopus. These databases were chosen as they collectively index the largest number of peer-reviewed animal science, veterinary, and meat science journals that publish evidence on castration and boar taint research. Specific keywords that we searched were: "boar taint," "androstenone," "skatole," "surgical castration pigs," "immunocastration," "GnRH vaccine pigs," "testicular steroids," "growth performance boars," "meat quality pigs," and "welfare castration pigs." Boolean queries including "boar taint AND androstenone," "immunocastration AND performance," and "castration AND welfare pigs" were used for maximum search sensitivity and specificity. Foundational studies on the biochemical and physiological basis of boar taint were examined in this review as well as recent studies of castration regimens, immunocastration effectiveness, as well as production effects. Articles were included if they reported data about boar taint compounds, hormonal responses, behavior, growth, or carcass characteristics of entire males, surgically castrated pigs or immunocastrated pigs. The studies were directly applicable to pig production systems. Research selection decisions were made with regard to experimental trials on clear methodology with measurable, castration method validated results. Review papers and meta-analyses were included as well, strengthening synthesis and providing larger context. The final references comprise a blending of the biochemical mechanisms, actionable issues (practical management, welfare considerations, and evidence of applied production), reflecting the content which the author listed in the manuscript.

Boar taint: Biochemistry, formation, and risk factors

Boar taint is a specific sensory defect in pork, characterized primarily by the presence of bad smells of urine and/or feces when meat from entire male pigs is heated. It is thought to be caused by two androstenone and skatole compounds that deposit in adipose tissue with increasing sexual maturity in the animal (Duarte *et al.*, 2021; Squires *et al.*, 2020). Androstenone is a testicular steroid pheromone made in Leydig cells, regulated by luteinizing hormone. Its major physiological functions are sexual signaling and reproductive behavior; however, owing to its lipophilic structure it is deposited and preserved on fat deposits, leading to high levels of boar taint (Squires *et al.*, 2020). While liver metabolism does process androstenone into more water soluble metabolites for excretion, pathways for their production have not been well defined and enterohepatic recycling is suspected to play a role in prolonged tissue accumulation (Squires *et al.*, 2020). Skatole, in contrast, is a consequence of the microbial breakdown of tryptophan in the pig's large intestine (Xu *et al.*, 2025). Its content is controlled by protein fermentation, intestinal epithelial turnover, and the ratio of beneficial to skatole producing bacteria. Once absorbed, skatole is processed in the liver by cytochrome P450 enzymes (Wiercinska *et al.*, 2012); nevertheless, entire males, particularly during puberty, generally have impaired hepatic clearance due to down-regulation of important enzymes such as CYP2A and CYP2E1 (Andresen, 2006). That diminished metabolic ability explains why concentrations of skatole typically increase with increased testicular steroid production. Skatole accumulation is highly dependent on both environmental and managerial parameters. Poor hygienic conditions, wet bedding, and high manure contact together increase skatole production due to increased bacterial fermentation in the hindgut (Morales *et al.*, 2017; Parois *et al.*, 2018). Seasons also contribute, with the prevalence of boar taint being higher during warmer months, also possibly correlating with diet and behavior or microbial activity or hygiene levels (Botelho-Fontela *et al.*, 2023). Nutrition strategies like incorporating fermentable fiber or particular plant extracts (like chicory, rosemary, etc.) have been demonstrated to reduce skatole through the alteration of microbial populations and improvement of intestinal health.

A key factor in the risk of boar taint is genetic variation. Some genetic lines have naturally low production of androstenone or highly successful hepatic skatole metabolism, indicating that selection programs could greatly decrease prevalence of boar taint (Dugué *et al.*, 2020; Parois *et al.*, 2015). Age at slaughter is also of critical importance because the levels of boar taint compounds increase significantly as entire males pass puberty (Borell *et al.*, 2020). By and large, boar taint is due to an amalgam of endocrine function, microorganism metabolism, hepatic excretion, genetic inheritance, and environmentally related processes. These are interrelated mechanisms which are critically important to explain for assessing the efficacy of castration interventions, both surgical and immunologic, in reducing taint and increasing consumer acceptance of pork.

Castration procedures

Surgical castration

Surgical castration is the most conventional and most popular surgery to control boar taint, aggressive behavior, and behavior of male pig. Typically, both testicles are removed through an incision into the scrotum during the first week of life (Hötzel *et al.*, 2020). This early timing is preferred as younger piglets are usually less resistant, and the smaller testicles and blood vessels make the operation easier. However, although surgical castration is usually carried out without anesthesia in most commercial processes, it has been shown in a great deal of clinical work that the surgical technique leads to intense acute pain, physiological stress, and behavioral pain. Piglets may demonstrate marked vocalizations, escape attempts, shaking as well as leg movements during the procedure, which reflects a high degree of nociception (Lou *et al.*, 2022). From a physical point of view, increased cortisol, catecholamines, and heart rate variability immediately following castration has been well established as an acute result (Byrd *et al.*, 2020; Prunier *et al.*, 2013). Postoperative complications are a further burden on welfare. Hemorrhage, wound edema, swelling on the wound, delayed healing or secondary infections may occur, in particular, when castration is performed with poor hygiene practice or when surgery is performed in the postoperative period. The absence of proper hand hygiene or proper surgical technique often leads to such issues, such as hematoma (Morales *et al.*, 2017) could lead to hemorrhaging, bleeding, swelling of the wound, delayed recovery and infection secondary to the wound itself. Open wounds can cause abscess formation and/or systemic infection by environmental pathogens and other pathogens if these entered into the skin can progress through the wound and become abscessed or acquired in a systemic infection. And, since the increase in the testes involved is attributed to aging pigs, older animals have more vascular tissue and hence castration becomes more invasive and has a greater chance of complications (Morales *et al.*, 2017). Aware of these welfare problems, some European countries have introduced anesthesia and analgesics to castration (Scollo *et al.*, 2021). However, these methods raise overall production costs and require trained workers, restricting implementation where labor or veterinary services are limited. These are some of the drawbacks of surgical castration but it remains common

to avoid boar taint and reduce aggressive behavior of the animal throughout their life. Surgical castration leads to consistent effects on growth and carcass composition from a production point of view. Compared to entire males, castrated males often have lower lean deposition and feed efficiency, because the removal of testicular steroids drives metabolism down to a higher fat level. Producers thus need to balance the benefits of welfare, meat quality, and feed efficiency to determine castration. However, if all testicular steroid production ceases, there is a simple and inexpensive way to obtain consumer adoption and acceptance that provides a powerful incentive for the utilization of the steroid product in other markets.

Immunocastration

Immunocastration is a biological alternative that aims to suppress testicular function without actually removing the testes. It accomplishes this by stimulating the pig's immune system to produce antibodies against gonadotropin-releasing hormone (GnRH), and then this hormone's activity is cancelled out. This inhibits secretion of luteinizing hormone (LH) from pituitary gland and subsequently restricts the synthesis of testosterone and androstenone in Leydig cells (Squires *et al*., 2020; Wang *et al*., 2023). The commercially available GnRH vaccine has undergone clinical evaluation and demonstrated efficacy in the reduction of boar taint compounds and also enhanced welfare outcomes compared to surgical castration (Werner *et al*., 2021). Commercial immunocastration protocols include two vaccinations given at different physiological stages, not short ones that occur in fixed intervals. The first vaccination is usually administered around 8 to 12 weeks in age to provide the immune system with the initial stimulation while failing to substantially impair testicular steroid production. The second vaccine is given 4 to 6 weeks before slaughter typically at 16 to 20 weeks of age, depending on the way animals are produced. The first dose primes the immune system, but does not affect steroid production, meaning that pigs during the early finishing period show similar growth performance to entire males. The second dose results in rapidly ascending antibody levels, reducing testicular steroidogenesis, leading to rapid depletion of testosterone and androstenone concentrations (Einarsson *et al*., 2011; Werner *et al*., 2021). This suppresses sexual and aggressive behaviors, calms temperament, and improves handling. Boar taint compounds drop to the level of surgically castrated pigs with many studies demonstrating a low risk of the production of tainted carcasses after complete immunization (Morales *et al*., 2017). One of immunocastration benefits is that pigs develop as healthy entire males before the second immunization process, are higher in feed efficiency, gaining lean, gaining less fat, and showing less fat deposition (Škrlep *et al*., 2012), and are physiologically closer to castrate characteristics. And it increases production efficiency in meat production as well as its quality. Furthermore, a no-surgery wound situation removes the possibility for pain, infection, or inadequate healing and immunocastration is thus considered a more ethical practice (Lou *et al*., 2022). However, there are documented challenges. Among them are different antibody responses in a small percentage of animals, timing of the second injection and doubts from consumers given the limited understanding of the technology. In light of these concerns, it should be noted that immunocastration is gradually emerging as a realistic and empirically based option, that would harmonize the welfare, production and quality goals of the study.

Comparative considerations

Surgical castration and immunocastration should be contrasted, and there are advantages and disadvantages for each. Surgical castration enables a long-term, permanent reduction of testicular steroids but comes with obvious welfare problems and reduced feed efficiency. Immunocastration also shows a reversible transient suppression of hormone-producing ability enabling producers to gain advantage from the growth potential of entire males during early stages of life and avoid boar taint complications down the line. Immunocastration approaches have been shown to also result in increased growth rate, carcass leanness and welfare benefits, consistently outperforming traditional castration (Einarsson *et al*., 2011; Werner *et al*., 2021). Nevertheless, surgical castration persists in most regions because of consumer familiarity with the procedure, fear of vaccine residues (vaccine-derived residues have been disproved in the literature despite such concerns), and due to the ease of implementation without the need to precisely target injections (Werner *et al*., 2021). Castration modality is regulated by welfare, market preferences, labor, production, and consumer attitudes. Both techniques should be well known, for informed decisions to be made as swine industry approaches a more ethical and more sustainable production system.

Although immunocastration has been shown to be efficient, it also poses several practical and operational challenges that must be recognised. Economically, the total cost of a two-dose vaccination program may surpass the direct labor cost of surgical castration, especially in situations of low labour force costs (Bonneau and Weiler, 2019; Borell *et al*., 2020). Furthermore, immunocastration demands the timing of the second vaccination to be timed accurately relative to slaughter which results in the management being complex with trained manpower being needed. Another key limitation is occupational health and safety concerns. Risk to the reproductive health and safety of farm workers of accidental self-injection of GnRH vaccines is significant, with the risk of reproductive health, including temporary infertility, a reproductive health hazard (Wang *et al*., 2023),

thus, proper handling and staff training should be adhered to. Also, immunocastration effectiveness is not as assured. A small proportion of animals may be at the mercy of poor immune responses or may fail the second vaccination and be left with residual boar taint at slaughter. In other commercial practice, such a failure represents a major threat to processors and promotes the ongoing industry scepticism (Batorek *et al*., 2012a; Werner *et al*., 2021; Squires *et al*., 2020). Barriers related to the market continue to remain. Some slaughterhouses, and export markets, are still wary to accept immunocastrated pigs because of consumer perception problems or worried that the bacon could get harder to chew as a result of reduced belly fat content. These explain partly how immunocastration, beneficial in terms of biological and welfare, has not yet gained widespread acceptance on the global production chains in pork.

Effects of castration methods on growth performance of male pigs

The physiological status of the animal, mainly the presence (or not) of testicular steroids, profoundly affects growth performance in male pigs. Hormonal differences between entire males, surgically castrated pigs, and immunocastrated pigs have a significant influence on feed intake, average daily gain, feed efficiency, and body composition, which all regulate protein accumulation, fat accumulation, and metabolic rate (Zhdanov *et al*., 2025). Testosterone and other testicular steroids promote protein synthesis, muscle hypertrophy, and lowered lipogenesis, which is why entire males tend to show generally higher growth efficiency compared with castrates (Bonneau and Weiler, 2019; Zamaratskaia *et al*., 2008; Zhdanov *et al*., 2025). It should be noted that growth performance is dependent on the metric used to study the subject. In most commercial situations, surgically castrated pigs (barrows) exhibit greater voluntary feed intake and higher mean ADG, leading to higher final body weight than intact males or females. Barrows could yield a numerically greater gain in total weight and, in some systems, comparable or even lower feed conversion ratios when measured on live weight. Nevertheless, intact males and immunocastrated pigs tend to exhibit better overall biological feed efficiency when efficiency is measured compared to lean tissue gain rather than total body mass. The presence of testicular steroids promotes protein accretion and limits fat deposition, enhancing the conversion efficiency of feed to lean mass. Thus, while barrows may outbalance intact males in absolute growth rate, intact males and immunocastrates usually have better lean gain efficiency with lower energy loss due to fat content. This distinction matters to production efficiency, carcass value and sustainability outcomes.

Conversely in removing or suppressed testicular steroids, metabolic priorities change, and it becomes more important for fat rather than lean tissue to be supplied (Zhdanov *et al*., 2025). These physiological underpinnings underlie performance between surgical castration and immunocastration. It has consistently been shown to have a lower feed efficiency and a higher voluntary feed intake for surgically castrated pigs with respect to intact males. This has been well reported: castration reduces testosterone production and is associated with diminished anabolic drive and decreased ability to absorb lean muscles (Zamaratskaia *et al*., 2008; Zhdanov *et al*., 2025). Castrates compensate, so they consume more, but still retain fat and slaughter carcasses with lower lean percentages (Batorek *et al*., 2012b). Average daily gain in surgically castrated pigs is generally modest at the expense of poor feed conversion ratio. This dis-efficiency is even more exacerbated when it comes to increasing a maintenance energy consumption, as the fat tissues would accumulate faster. It is also well documented that castrated pigs may take longer to achieve the market weight (Zhdanov *et al*., 2025) than castrated pigs on account of lower potential growth, and in turn, the cost of production is raised, and the environmental gases produced as a result of per unit pork production are also increased. The feed conversion ratios, lean gain and nitrogen utilisation are higher with entire males than those with castrates (Bonneau and Weiler, 2019; Zamaratskaia *et al*., 2008). Anabolic effects of testosterone contribute to increased protein retention, decrease in fat build-up and increase metabolic efficiency (Bonneau and Weiler, 2019; Zhdanov *et al*., 2025). These pigs may also have more competitive feeding behavior, giving them greater growth in some (competing) systems. Nevertheless, it is also more likely that the advantages of entire male production are reduced by other factors including aggressive behavior, mounting, wounds and higher risk of boar taint (Morales *et al*., 2017). Such behavioural problems that contribute to decreased feed efficiency at the herd level and to decreased welfare may take place. Thus, entire males give advantages in biological-growth but production can't follow their performance potentials. For example, for immunocastrated pigs, immunocastration offers a distinct 2 phase advantage in growth, where pigs can grow male-like at first before receiving the second vaccination, and as surgically castrated pigs until after (Zhdanov *et al*., 2025). By the end of early finishing, immunocastrated pigs retain high levels of lean deposition, generally higher FCR, and relatively low fat deposition (Škrlep *et al*., 2012; Zhdanov *et al*., 2025) due to preserved testosterone levels, which are comparable to those of intact males. Subsequent to the second dose, the generation of antibodies counteracts GnRH, inhibiting testicular steroidogenesis, leading to slow evolution of growth into castrate pig (Zhdanov *et al*., 2025). Yet unlike castrated pigs injected at birth, immunocastrated pigs have been able to achieve several weeks of steroid-induced

anabolic growth. This leads to higher aggregate lean yield, improved FCR and better final carcass composition than in surgically castrated pigs. In multiple studies, immunocastrated pigs exhibited growth comparable to or slightly higher than castrates, with well-documented feed system efficiency, and better carcass fat deposition (Škrlep *et al*., 2020). Indirectly supporting production efficiency, immunocastration also reduces aggressive and sexual behavior post-immunocastration (Zhdanov *et al*., 2025), which contributes to better group stability. Decreased competition and stress lead to improved conditions for prolonged growth in group-oriented conditions (Škrlep *et al*., 2012). Although the proportion of pigs who have a delayed or indolent immune response to vaccination is a minority, there is generally performance enhancement over surgical castration in terms of efficiency performance with sufficient timing and control with minimal welfare costs of physical testicular removal. Altogether, performance information regarding growth tends to show that entire males better immunocastrated males, and immunocastrated males better surgically castrated males in feed efficiency, lean growth, and metabolic productivity. Nevertheless, entire males have many limitations due to boar taint and issues with behavior. Therefore, immunocastration is a natural compromise; it gains much of the biological efficiency of entire males during early growth and lowers boar taint and improves welfare at finishing. At the same time, surgical castration is still a reliable way of removing boar taint, but it has serious performance penalties. For producers concerned about maximising economic return while trying to maintain a welfare and quality of meat, immunocastration presents a biologically and logistically favourable alternative suited to many production aims.

Effects of castration methods on carcass traits and meat quality

Carcass structure and quality of meat differ widely between entire males, surgically castrated males, and immunocastrated males on the basis of physiological differences in anabolic hormone profiles, fat deposition, and metabolic pathways (Škrlep *et al*., 2020). Testosterone and androstenone, two testicular steroid hormones, have a very powerful impact on muscle mass accumulation, lipid metabolism, and behavior, all of which determine carcass characteristics and meat quality (Škrlep *et al*., 2020; Zhdanov *et al*., 2025). Knowing these relationships is essential for assessing the practical relevance of the various castration approaches. Of surgically castrated pigs, surgically castrated pigs tend to exhibit higher carcass fatness, lower lean percentage, and reduced dressing yield compared with entire males. Early termination of the use of testicular steroids results in diminished anabolic stimulation of the muscle and a move towards sharing of energy in the direction of the deposition of adipose tissue (Škrlep *et al*., 2020; Zamaratskaia *et al*., 2008; Zhdanov *et al*., 2025). Therefore, surgically castrated pigs have more subcutaneous fat (and intramuscular fat) and usually have thicker backfat and a higher carcass fat cover when slaughtered. Although an enhanced degree of fatness may be advantageous in some niche markets with high marbling intensity, overall, the production is generally inefficient and reduces the chance of success of the trimming process for commercial processing (Zhdanov *et al*., 2025). As reported, surgical castrate-derived meat is observed as softer and fatter, with slightly more intramuscular fat than meat from entire males, which can improve tenderness, but an overload of fat can have adverse effects on yield and carcass value. Furthermore, surgically castrated pigs are more feed- and time-consuming to reach slaughter weight and thus have higher capital intensity for production purposes (Zhdanov *et al*., 2025). Nevertheless, elimination of boar taint is a great advantage, as surgical castration does suppress testicular androstenone secretion effectively, and it may indirectly decrease skatole via hepatic metabolism enhancement. For immunocastrated pigs, carcass characteristics are intermediate between entire males and surgically castrated pigs according to the second dose schedule. They grow as entire males with large amounts of lean material and low fat accretion before the immunization is completed. After the second injection, inhibition of testicular steroidogenesis results in higher intake of feed and fat accumulation for pigs, at least partially resembling that of castrates (Dunshea *et al*., 2001; Zhdanov *et al*., 2025). However, in the meantime their final carcasses generally feature a more streamlined appearance and less fat because the pigs benefit from weeks of intact-male growth in normal lifespan before castration-like hormonal suppression occurs (Zhdanov *et al*., 2025). Research consistently shows increased carcass leanness, decreased backfat, and higher muscle-to-fat ratios in immunocastrated pigs compared with surgically castrated males. These characteristics increase dressing yield and production efficiency. Importantly, immunocastration reduces androstenone and skatole to an acceptable level after the second vaccination, producing pork with a low risk of boar taint (Squires *et al*., 2020). Therefore, it merges the workability of entire males for the early stages with the meat quality stability of castrates for the final phase. The meat quality characteristics of tenderness, juiciness, water-holding capacity, pH, and color differ according to the animal's physiological state, pre-slaughter stress, and carcass characteristics. Surgically castrated pigs tend to have somewhat improved tenderness and juiciness due to a high amount of intramuscular fat content (Zhdanov *et al*., 2025), while the high fat content in surgical castrates leads to a decrease in lean yield. Immunocastrated pigs usually produce a well-balanced quality product (in terms of meat quality) such as leaner meat, whereas surgically

castrated pigs are likely to show stress-related problems, where the overall condition of the castrate will always be affected in the meat. Reduced sexual and aggressive behaviors post second dose yield tranquil pigs who are easier to pre-slaughter and have high pH stability and reduced number of carcass defects (Zhdanov *et al*., 2025). Several animal studies have found immunocastration to not be detrimental to significant quality attributes such as water-holding capacity, drip loss, and cooking loss and can produce meat equal to or potentially better than that of surgical castrates (Batorek *et al*., 2012a). Boar taint is still the primary factor indicating the acceptability of carcasses compared to entire males and castrated males. Surgically castrated pigs demonstrate negligible androstenone levels and reduced skatole attributable to improved hepatic clearance. Both are well documented to decrease rapidly in immunocastrated pigs following second doses of vaccine with plasma concentrations typically comparable to that of surgical castrates. However, entire males vary greatly, and boar taint can remain despite optimal management strategies (Andresen, 2006).

Welfare and behavioral effects

Castration-related animal welfare issues are now more visible than ever in swine production since consumers and policymakers now expect systems of production that create less pain, less stress and less suffering. Surgical castration and immunocastration are also of great value, although divergent, for the behavioural expression and general welfare in male pigs (Einarsson *et al*., 2011; Werner *et al*., 2021). Stress-reactivity physiology, perception of pain, pathophysiological healing, aggression, sexual behaviour and social organization in group-housed animals play a role in welfare outcomes (Broom, 1991; Ohl and Van der Staay, 2012). Assessing these factors provides an important perspective on the level of compatibility between methods of castration and welfare expectations and economic farm management. Surgical castration is one of the most painful routine surgeries in commercialized pig operations (Lou *et al*., 2022). There are studies identifying the acute pain reaction during and after operation (even in very young piglets) after castration. Piglets usually exhibit high vocalization, leg movements, escape attempts, shaking, and changes in respiration that suggest intense nociceptive input and physiological distress (Borell *et al*., 2020; Duarte *et al*., 2021; Prunier *et al*., 2013). These behavioral manifestations correspond to detectable increases in cortisol, catecholamines, and other stress biomarkers that can linger for hours following the procedure (Byrd *et al*., 2020; Prunier *et al*., 2013). Apart from acute pain, surgical castration is associated with risks of postoperative complications, such as swelling, bleeding, infection and delayed wound healing. These challenges are exacerbated whenever castration is done in a nonhygienic manner or at older ages, when tissue vascularization and the size of testes widen (Morales *et al*., 2017). These problems not only compromise welfare they can also compromise growth and immunity. Behavioral discomfort such as diminished nursing, lethargy, huddling, and changed positions are often noted in the days post-procedure (Borell *et al*., 2020; Byrd *et al*., 2020; Duarte *et al*., 2021; Prunier *et al*., 2013). Accordingly, several states have adopted laws which mandate anaesthetics and analgesia requirements for surgical castration (Duarte *et al*., 2021; Pereira-Pinto *et al*., 2025; Squires *et al*., 2020). However, adoption is still not widespread in many places due to cost, manpower requirements, and veterinary scarcity, and many piglets are still castrated in nonpatients without effective analgesia. Moreover, immunocastration is a welfare-promoting alternative to surgical castration since it does not involve tissue clearance; thus, it avoids acute pain and morbidity from surgical wounds. After the first vaccination, all physiological and behavioral characteristics of intact males are present in pigs. However, following the second vaccination, the significant reduction in testicular steroids produced a marked reduction in a range of aggressive and sexual behavior (Einarsson *et al*., 2011; Werner *et al*., 2021). When immunocastrated males undergo full immunological suppression time, fights and biting and mounting among these males are consistently reduced. Such a behavior change provides a more stable group, reduced stress factor, lower trauma incidence ratio and welfare boost in the end of the competition period of the animal. Besides behavioral changes, immunocastration minimizes physiological stress by preventing surgical trauma, promoting recovery. No open wounds have developed, whereas pigs have no unpleasant consequences other than slight transient skin swelling following injection. Social behaviors return to normative levels during declines in group aggression, and pigs show calmer temperaments that ease handling and transport. Due to these welfare benefits, immunocastration represents an attractive approach for production systems trying to meet performance objectives alongside societal requirements for humane practice.

CONCLUSION

For pork producers, boar taint control is of great importance today. Despite its success in preventing boar taint through surgical castration, the process also has a cost in growth efficiency and significant welfare issues. Entire male production offers best-in-class performance and leaner carcasses; however, its use at that level is limited by aggression, sexual behavior, and variability in boar taint levels. Immunocastration provides a more moderate alternative with both the initial growth benefits of intact males and the carcass quality with low taint levels as compared to castrated pigs, without the suffering

of surgery. With an eye toward a practical approach and a fair treatment scheme that is biologically efficient and meets contemporary production and ethical standards, immunocastration offers much practical value.

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NOVELTY STATEMENT

This study evaluated the harms as well as the benefits of two methods of castrating pigs. It is one of the first studies to compare these two methods in detail.

AUTHOR'S CONTRIBUTION

NHQ and NTL designed the experiment. NHQ and NTL collected and analyzed data. NHQ and NTL synthesized data and drafted the manuscript. NHQ and NTL edited the manuscript. All authors carefully read and approved the manuscript for publication.

Generative AI and AI-assisted technology statement

The study did not use any AI technology for even grammar check or writing support.

Conflict of interest

The authors have declared no conflict of interest.

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