UNIVERSIDADE FEDERAL DE UBERLÂNDIA
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIAS VETERINÁRIAS

RENATA VIEIRA CHAVES GABRIEL

SUPLEMENTAÇÃO COM MAGNÉSIO NA ÁGUA DE BEBIDA DURANTE JEJUM PRÉ-ABATE DE SUÍNOS: POTENCIAL PARA REDUÇÃO DE FRATURAS E MELHORIA NO APROVEITAMENTO E QUALIDADE DA CARNE

Uberlândia
2025

RENATA VIEIRA CHAVES GABRIEL

SUPLEMENTAÇÃO COM MAGNÉSIO NA ÁGUA DE BEBIDA DURANTE JEJUM PRÉ-ABATE DE SUÍNOS: POTENCIAL PARA REDUÇÃO DE FRATURAS E MELHORIA NO APROVEITAMENTO E QUALIDADE DA CARNE

Dissertação apresentada ao Programa de Pós-graduação em Ciências Veterinárias da Universidade Federal de Uberlândia como requisito parcial à obtenção do título de mestre em Ciências Veterinárias.

Área de concentração: Produção Animal

Orientador: Prof. Dr. Robson Carlos Antunes

Coorientador: Prof. Dr. João Paulo Rodrigues Bueno

Uberlândia

2025

Ficha Catalográfica Online do Sistema de Bibliotecas da UFU
com dados informados pelo(a) próprio(a) autor(a).

G118 2025

Gabriel, Renata Vieira Chaves, 1988-
Suplementação com magnésio na água de bebida durante jejum pré-abate de suínos: potencial para redução de fraturas e melhoria no aproveitamento e qualidade da carne [recurso eletrônico] / Renata Vieira Chaves Gabriel. - 2025.

Orientador: Robson Carlos Antunes.
Coorientador: João Paulo Rodrigues Bueno.
Dissertação (Mestrado) - Universidade Federal de Uberlândia, Pós-graduação em Ciências Veterinárias.
Modo de acesso: Internet.
DOI http://doi.org/10.14393/ufu.di.2025.493
Inclui bibliografia.

1. Veterinária. I. Antunes, Robson Carlos,1968-, (Orient.). II. Bueno, João Paulo Rodrigues,1987-, (Coorient.). III. Universidade Federal de Uberlândia. Pós-graduação em Ciências Veterinárias. IV. Título.

CDU: 619

Bibliotecários responsáveis pela estrutura de acordo com o AACR2:
Gizele Cristine Nunes do Couto - CRB6/2091
Nelson Marcos Ferreira - CRB6/3074

RENATA VIEIRA CHAVES GABRIEL

SUPLEMENTAÇÃO COM MAGNÉSIO NA ÁGUA DE BEBIDA DURANTE JEJUM PRÉ-ABATE DE SUÍNOS: POTENCIAL PARA REDUÇÃO DE FRATURAS E MELHORIA NO APROVEITAMENTO E QUALIDADE DA CARNE

Dissertação apresentada ao Programa de Pós-graduação em Ciências Veterinárias da Universidade Federal de Uberlândia como requisito parcial à obtenção do título de mestre em Ciências Veterinárias.

Área de concentração: Produção Animal

Uberlândia, 02 de setembro de 2025.

Banca Examinadora:

____

Prof. Dr. Robson Carlos Antunes
(Orientador – UFU)

____

Prof. Dr. Sérgio Eustáquio Lemos da Silva – UNITRI
(Examinador - UNITRI)

____

Prof. Dra. Fernanda Gatti de Oliveira Nascimento – UNITRI
(Examinadora - UNITRI)

UNIVERSIDADE FEDERAL DE UBERLÂNDIA
Secretaria da Coordenação do Programa de Pós-Graduação em Ciências Veterinárias
BR 050, Km 78, Campus Glória , Uberlândia-MG, CEP 38400-902
Telefone: (34) 2512-6811 - www.ppgcv.famev.ufu.br - mesvet@ufu.br

ATA DE DEFESA - PÓS-GRADUAÇÃO

Programa de Pós-Graduação em:	Ciências Veterinárias				
Defesa de:	Dissertação de Mestrado Acadêmico PPGCVET Nº 17/2025				
Data:	02 de setembro de 2025	Hora de início:	14h:00	Hora de encerramento:	16:00
Matrícula do Discente:	12412MEV021				
Nome do Discente:	Renata Vieira Chaves Gabriel				
Título do Trabalho:	Suplementação com magnésio na água de bebida durante jejum pré-abate de suínos: potencial para redução de fraturas e melhoria no aproveitamento e qualidade da carne				
Área de concentração:	Produção Animal				
Linha de pesquisa:	FORRAGICULTURA, MANEJO E EFICIÊNCIA NA PRODUÇÃO DOS ANIMAIS E DE SEUS DERIVADOS				
Projeto de Pesquisa de vinculação:	Investigação científica dos fatores que afetam e influenciam o desempenho e eficiência dos suínos nas várias fases de produção e qualidade da carcaça e carne				

Reuniu-se na Sala 1CCG216, Campus Glória, da Universidade Federal de Uberlândia, a Banca Examinadora, designada pelo Colegiado do Programa de Pós-graduação em Ciências Veterinárias, assim composta: Professores Doutores: Sérgio Eustáquio Lemos da Silva - (UNITRI); Fernanda Gatti de Oliveira Nascimento - (UNITRI) e Robson Carlos Antunes - (FMVZ/UFU), orientador da candidata.

Iniciando os trabalhos o presidente da mesa, Dr. Robson Carlos Antunes, apresentou a Comissão Examinadora e a candidata, agradeceu a presença do público, e concedeu à Discente a palavra para a exposição do seu trabalho. A duração da apresentação da Discente e o tempo de arguição e resposta foram conforme as normas do Programa.

A seguir o senhor presidente concedeu a palavra, pela ordem sucessivamente, aos examinadores, que passaram a arguir a candidata. Ultimada a arguição, que se desenvolveu dentro dos termos regimentais, a Banca, em sessão secreta, atribuiu o resultado final, considerando a candidata:

Aprovada.

Esta defesa faz parte dos requisitos necessários à obtenção do título de Mestre.

O competente diploma será expedido após cumprimento dos demais requisitos, conforme as normas do Programa, a legislação pertinente e a regulamentação interna da UFU.

Nada mais havendo a tratar foram encerrados os trabalhos. Foi lavrada a presente ata que após lida e achada conforme foi assinada pela Banca Examinadora.

Documento assinado eletronicamente por **Robson Carlos Antunes**, **Professor(a) do Magistério Superior**, em 02/09/2025, às 16:01, conforme horário oficial de Brasília, com fundamento no art. 6º, § 1º, do Decreto nº 8.539, de 8 de outubro de 2015.

Documento assinado eletronicamente por **Fernanda Gatti de Oliveira Nascimento**, **Usuário Externo**, em 02/09/2025, às 16:03, conforme horário oficial de Brasília, com fundamento no art. 6º, § 1º, do Decreto nº 8.539, de 8 de outubro de 2015.

Documento assinado eletronicamente por **Sérgio Eustáquio Lemos da Silva**, **Usuário Externo**, em 02/09/2025, às 16:03, conforme horário oficial de Brasília, com fundamento no art. 6º, § 1º, do Decreto nº 8.539, de 8 de outubro de 2015.

A autenticidade deste documento pode ser conferida no site https://www.sei.ufu.br/sei/controlador_externo.php?acao=documento_conferir&id_orgao_acesso_externo=0, informando o código verificador **6602521** e o código CRC **BABCBD44**.

Referência: Processo nº 23117.056933/2025-14 SEI nº 6602521

AGRADECIMENTOS

A caminhada até aqui foi desafiadora, mas repleta de aprendizados. Por isso, minha gratidão se estende a todos que, de alguma forma, fizeram parte dessa jornada.

Ao meu esposo Sandro, meu companheiro de vida, que sempre acreditou em mim mesmo quando eu mesma duvidei. Obrigada por sua paciência, incentivo e amor incondicional — sua presença foi o meu porto seguro nos dias mais difíceis.

Aos meus ex-professores - na verdade eternos - que foram responsáveis por acender em mim a chama do conhecimento e por plantarem as primeiras sementes dessa trajetória acadêmica. Suas palavras e ensinamentos ecoaram em muitos dos meus passos até aqui.

Ao meu orientador Robson, pela escuta atenta, pela sabedoria compartilhada e pela confiança no meu potencial. Sua orientação foi fundamental para que este trabalho tomasse forma com consistência e profundidade.

Aos colegas de pesquisa, Wander, Ana Vitória, Geancarlo e Alexandre pela troca constante, pelo apoio mútuo e por tornarem os desafios do cotidiano acadêmico mais leves e possíveis. Cresci com vocês — como pesquisadora e como pessoa.

A todos vocês, o meu mais sincero obrigado. Este trabalho também é de vocês.

"O destino dos animais está intimamente
ligado ao destino dos homens."
— Albert Schweitzer**.**

RESUMO

A ocorrência de fraturas vertebrais em suínos durante a insensibilização elétrica representa um desafio para a indústria, comprometendo o bem-estar animal e a qualidade da carne. A suplementação de magnésio no período pré-abate surge como estratégia prática para atenuar o estresse, reduzir a excitabilidade neuromuscular e minimizar a ocorrência dessas lesões. Este estudo avaliou os efeitos da suplementação de magnésio via água de bebida de suínos no pré-abate. Foram analisados 2.080 animais, igualmente distribuídos entre dois grupos: controle (C) e tratamento (T). A análise de razão de chances (*odds ratio* – OR) indicou redução significativa na incidência de fraturas vertebrais, com o grupo tratamento apresentando 52% menos chance de ocorrência de fratura (OR = 0,66; $p < 0{,}001$). A capacidade de retenção de água (CRA) da carne foi maior em animais sem fratura, independentemente do grupo experimental ($p < 0{,}05$). Os resultados demonstram o potencial do magnésio como ferramenta prática para otimizar o manejo pré-abate, promover o bem-estar animal e melhorar a qualidade tecnológica da carne, agregando valor à cadeia produtiva suinícola.

Palavras-chave: capacidade de retenção de água; carne suína; fraturas vertebrais; insensibilização elétrica; bem-estar animal.

ABSTRACT

The occurrence of vertebral fractures in pigs during electrical stunning represents a challenge for the industry, compromising both animal welfare and meat quality. Pre-slaughter magnesium supplementation has emerged as a practical strategy to attenuate stress, reduce neuromuscular excitability, and minimise the occurrence of such injuries. This study evaluated the effects of magnesium supplementation via drinking water for pigs during the pre-slaughter period. A total of 2,080 animals were equally distributed between two groups: control (C) and treatment (T). The odds ratio (OR) analysis revealed a significant reduction in the incidence of vertebral fractures, with the treatment group exhibiting a 52% lower likelihood of fracture occurrence (OR = 0.48; $p < 0.001$). Meat water-holding capacity (WHC) was higher in animals without fractures, regardless of the experimental group ($p < 0.05$). The results demonstrate the potential of magnesium as a practical tool to optimise pre-slaughter management, promote animal welfare, and improve meat technological quality, adding value to the pork production chain.

Keywords: electrical stunning; pork; vertebral fractures; water-holding capacity;

LISTA DE ILUSTRAÇÕES

LISTA DE TABELAS

LISTA DE ABREVIATURAS E SIGLAS

Amps	Amperes
ANOVA	Analysis of Variance
C	control
°C	Degrees Celsius
CI	confidence interval
cm^2	Square centimeters
CN	Control without fracture
CS	Control with fracture
Hz	Hertz
ID	Identification
kg	kilogram
L	liters
m^2	square meter
No.	number;
OR	odds ratio
Ph	potential of hydrogen
ppm	parts per million
PSE	pale, soft, and exudative
T	treatment
TN	Treatment without fracture
TS	Treatment with fracture
UFU	Federal University of Uberlândia
WHC	water holding capacity

SUMÁRIO

1 CAPÍTULO 1 – CONSIDERAÇÕES GERAIS

1.1 INTRODUÇÃO

A suinocultura brasileira apresenta crescimento contínuo, consolidado em 2024 por meio de uma oferta estável de animais, fortalecimento do consumo interno e incremento nas exportações. Esses fatores impulsionaram a valorização do suíno vivo e da carne suína no varejo, ao mesmo tempo em que a redução dos custos de produção favoreceu a recomposição das margens de lucro do setor (EMBRAPA, 2024).

É imprescindível que a cadeia produtiva suinícola atenda simultaneamente à demanda quantitativa e às exigências crescentes por qualidade da carne e bem-estar animal, do nascimento até o abate. O bem-estar animal passou a ocupar papel central nas discussões técnicas, econômicas e éticas da cadeia suinícola, com destaque para o manejo pré-abate. Esta etapa da produção de suínos, envolve situações potencialmente estressantes para o suíno, como: transporte, jejum, espera no frigorífico e insensibilização, que podem desencadear respostas fisiológicas adversas, como aumento dos níveis de cortisol e catecolaminas (Blokhuis et al., 2010; La Lama; Villarroel; María, 2014). Essas alterações repercutem negativamente na homeostase muscular, favorecendo a ocorrência de carnes com defeitos como a pálida, flácida e exsudativa (PSE) (Rosenvold e Andersen, 2003).

Quando conduzidas de forma inadequada, as etapas pré-abate podem comprometer não apenas a qualidade da carne, mas também a integridade física dos animais, especialmente na etapa de insensibilização, onde falhas técnicas podem resultar em lesões graves, como fraturas de coluna vertebral. Contrações musculares violentas associadas a elevados índices de fraturas vertebrais, geralmente estão associados ao sistema de insensibilização elétrico de três eletrodos (Channon et al., 2003).

Entre os métodos de insensibilização aplicados ao abate de suínos, o elétrico destaca-se como o mais amplamente utilizado em todo o mundo, sobretudo em unidades de pequeno e médio porte. (Sindhøj, Lindahl e Bark, 2021). A insensibilização elétrica em suínos pode ser realizada por dois métodos principais: dois eletrodos na cabeça, que induz uma convulsão generalizada e inconsciência temporária, e três eletrodos, incluindo um no tórax ou dorso), que adiciona a indução de fibrilação ventricular cardíaca, resultando em parada cardíaca irreversível (AHAW; Nielsen *et al.*, 2020).

A escolha do método de insensibilização exerce impacto direto tanto sobre a qualidade da carne quanto sobre o bem-estar dos animais. No caso da insensibilização elétrica, a passagem da corrente pelo corpo pode provocar contrações musculares intensas e ocasionar fraturas ósseas, o que compromete a segurança do produto final, ao representar riscos físicos e microbiológicos à carne destinada ao consumo (Bertoloni et al., 2006).

As fraturas de coluna durante a insensibilização elétrica em suínos não apenas comprometem o bem-estar do animal, como também resultam em perdas econômicas por condenações e menor rendimento de carcaça. Tais fraturas geralmente ocorrem devido a respostas musculares exacerbadas ao estímulo elétrico, agravadas por fatores como estresse, manejo inadequado e condições musculares desfavoráveis. Neste contexto, estratégias que reduzam o estresse fisiológico dos animais no período pré-abate têm sido estudadas, incluindo a suplementação com Magnésio (Mg) (Cui et al., 2025; Bushby et al., 2021).

A suplementação de magnésio surge como estratégia promissora, uma vez que este mineral exerce efeito modulador sobre o sistema nervoso e a contração muscular, reduzindo a excitabilidade neuromuscular e a secreção de corticosteroides e catecolaminas. Evidências recentes demonstraram que a suplementação dietética de sulfato de potássio e magnésio em suínos de terminação submetidos ao estresse pré-abate foi capaz de reduzir significativamente as concentrações séricas de cortisol e norepinefrina, além de aumentar a atividade antioxidante e melhorar parâmetros de qualidade da carne (Cui et al., 2025). Esses achados reforçam a hipótese de que a suplementação com magnésio pode contribuir para a mitigação do risco de fraturas associadas à insensibilização elétrica, ao mesmo tempo em que promove benefícios à qualidade do produto final.

Sendo assim, a suplementação de magnésio via água de bebida tem ganhado destaque como uma alternativa promissora para minimizar perdas econômicas, garantir a qualidade da carne e promover o bem-estar animal. A suplementação hídrica de (Mg) é relativamente simples de implementar e pode ser aplicado para qualquer período de tempo antes do transporte (Frederick et al., 2006).

Contudo, apesar dos avanços na compreensão dos efeitos do estresse pré-abate sobre a qualidade da carne suína, poucos estudos investigaram a relação entre a suplementação com magnésio via água de bebida nas horas que antecedem o abate e a ocorrência de fraturas na coluna durante a insensibilização. Assim, com este estudo objetivou-se avaliar os efeitos da suplementação de magnésio na água de bebida durante o jejum pré-abate sobre a ocorrência de fraturas vertebrais e a qualidade da carne suína.

1.2 REVISÃO DE LITERATURA

1.2.1 A produção de suínos e o bem-estar animal no pré-abate

A suinocultura é uma das principais atividades pecuárias do Brasil, caracterizada por alta produtividade e crescente inserção em mercados internacionais que impõem rigorosas exigências quanto ao bem-estar animal e à qualidade da carne. Nas sociedades contemporâneas, o bem-estar dos animais de produção deixou de ser uma preocupação meramente técnica, assumindo posição central nas discussões éticas, econômicas e de segurança alimentar (Estévez-Moreno et al., 2025).

A Organização Mundial da Saúde Animal (WOAH, anteriormente OIE) conceitua o bem-estar animal como o estado físico e mental do animal em relação às condições em que vive e morre (WOAH, 2018). Dessa forma, a avaliação do bem-estar envolve a análise da capacidade do animal em responder a desafios do ambiente, por meio de diferentes indicadores que consideram o próprio animal como referência (Blokhuis et al., 2010).

Práticas que reduzam o estresse e preservem a integridade física dos animais são cada vez mais valorizadas. Na suinocultura, a etapa de pré-abate envolve diversas situações potencialmente estressantes, sendo assim, os suínos apresentam modificações bioquímicas musculares consideráveis que podem interferir na qualidade de sua carne (Costa et al., 2002).

O transporte, jejum, manejo e métodos de insensibilização são pontos críticos para o bem-estar animal. O estresse nesse período está diretamente relacionado a prejuízos zootécnicos, sanitários e econômicos, além de afetar indicadores como pH, cor, exsudação e presença de lesões musculares e ósseas. Mesmo quando as condições no frigorífico são adequadas, os suínos ainda estão sujeitos a diversos fatores estressantes que podem comprometer seu bem-estar (La Lama; Villarroel; María, 2014).

1.2.2 Fraturas de coluna em suínos durante a insensibilização

Durante a etapa de insensibilização elétrica no abate, fraturas vertebrais podem ocorrer nos suínos, devido às intensas contrações musculares causadas pela corrente elétrica. Esse método elétrico de atordoamento é amplamente utilizado em frigoríficos de suínos, e visa garantir perda de consciência imediata e humanitária. Porém, as contrações epilépticas causadas pelo atordoamento elétrico aumentam o risco de fraturas e hemorragias, enquanto que, suínos atordoados com CO_2 demonstraram ter menos carcaças condenadas devido a fraturas e lesões em comparação com o atordoamento elétrico (Marcon et al., 2019).

Diversos estudos têm demonstrado que a insensibilização elétrica e erros no manejo durante esse processo podem resultar em lesões severas à carcaça dos suínos, com destaque para fraturas vertebrais, aumentando a condenação de carcaças por esse tipo de lesão (Bertoloni, et al., 2006; Marcon et al., 2019; Von Wenzlawowicz et al., 2023).

A insensibilização elétrica, quando mal aplicada, pode desencadear contrações musculares intensas, promovendo lesões como hemorragias musculares e fraturas de coluna. A implementação adequada do abate humanitário é essencial para garantir o bem-estar, uma vez que, enfatiza práticas que minimizem o sofrimento dos suínos (Ludtke et al., 2010).

A anatomia dos animais e a intensidade do estímulo elétrico influenciam diretamente a incidência dessas lesões. O atordoamento elétrico comumente causa hemorragias musculares devido à intensa contração muscular generalizada, que causa a ruptura dos pequenos capilares enquanto o sistema circulatório ainda está intacto (Gregory, 2005). Tais lesões resultam em condenação parcial ou total da carcaça, uma vez que os respingos de sangue decorrentes comprometem a qualidade do produto e o valor comercial da carne. (Velarde et al., 2000).

A intensidade da corrente elétrica, o posicionamento inadequado dos eletrodos e o estado fisiológico do animal — especialmente a excitabilidade neuromuscular — também estão entre os principais fatores de risco para a ocorrência dessas fraturas. O atordoamento elétrico, em comparação com o atordoamento com CO2, leva a um estresse fisiológico mais grave no suíno e aumenta a taxa de metabolismo energético pós-morte devido ao aumento da atividade muscular e à liberação elevada de catecolaminas no sangue (Troeger e Woltersdorf, 1990, 1991). Animais com maior sensibilidade ao estresse tendem a apresentar respostas musculares mais abruptas, o que favorece lesões estruturais durante o choque elétrico (Ludtke et al., 2010).

Durante a insensibilização de suínos, especialmente quando realizada por choque elétrico, podem ocorrer microfraturas vertebrais associadas às intensas contrações musculares desencadeadas nesse processo (Gregory, 2005). De acordo com Dich-Jørgensen et al. (2017), a identificação de células da medula óssea e fragmentos de cartilagem nos músculos adjacentes, como o filé mignon e a parte superior do pernil, é um forte indicativo de fraturas vertebrais ocorridas durante essa etapa. Tais lesões comprometem a integridade da carcaça, configurando-se como problema relevante tanto para o bem-estar animal quanto para a qualidade final do produto.

Embora o sistema de três eletrodos promova melhor bem-estar ao impedir a recuperação da consciência mesmo com atraso na sangria, está associado a maior ocorrência de fraturas ósseas, especialmente quando o eletrodo torácico é posicionado caudalmente. Por outro lado, o método com dois eletrodos apresenta menor incidência de fraturas, mas requer sangria imediata e precisa, pois, sem fibrilação cardíaca, o animal pode recobrar a consciência em até 30 segundos após o choque (Wotton et al., 1992).

1.2.3 Papel fisiológico do magnésio

O magnésio é um mineral essencial à homeostase neuromuscular, atuando como cofator enzimático e modulador tanto da excitabilidade neuronal quanto da contração muscular. Seu efeito primário consiste na redução da excitabilidade neuromuscular por meio da ação antagonista ao cálcio, o que contribui diretamente para o controle dos níveis de cálcio intracelular (Laver et al., 1997; Rosenvold e Andersen, 2003).

Durante situações de estresse agudo, como o período que antecede o abate de suínos, observa-se uma redução nas concentrações plasmáticas de magnésio, favorecendo estados de hiperexcitabilidade. Esse quadro pode intensificar reações exacerbadas durante a insensibilização elétrica, elevando o risco de lesões e comprometendo o bem-estar animal. Nesse contexto, a suplementação de magnésio no pré-abate surge como uma estratégia promissora, por contribuir para a estabilização das membranas celulares, modular o sistema nervoso e diminuir a excitabilidade neuromuscular. Além disso, o magnésio participa de diversas reações enzimáticas envolvidas no metabolismo energético e proteico e, sob estresse, auxilia na atenuação dos efeitos das catecolaminas, o que reduz a resposta aguda ao manejo pré-abate (Kietzmann e Jablonski, 1985).

Somado a esses efeitos fisiológicos, o magnésio também apresenta ação ansiolítica, por interferir em receptores do sistema nervoso central, promovendo maior estabilidade comportamental nos animais. Esses benefícios têm incentivado pesquisas voltadas à sua suplementação, especialmente via água de bebida, nos dias que antecedem o abate. Estudos demonstraram que essa prática, mesmo a curto prazo, resulta em melhorias significativas na qualidade da carne suína — como o atraso no início da glicólise pós-morte, a preservação de fosfatos de alta energia, além de melhorias na capacidade de retenção de água, na coloração e na textura da carne (Moesgaard et al., 1993; D'Souza et al., 1998; Caine et al., 2000; Frederick et al., 2006).

1.2.4 Suplementação de magnésio no pré-abate

Diversos estudos, como os de Peeters et al. (2006), Alonso et al. (2012) e Bushby et al. (2021), investigaram a administração de magnésio via dieta ou água de bebida no pré-abate, relatando benefícios como redução nos níveis de cortisol, menor incidência de lesões, e melhor qualidade da carne (pH, cor e capacidade de retenção de água).

Peeters et al. (2006) avaliaram diferentes suplementos nutricionais com efeito antiestresse, incluindo o magnésio, e observaram que a suplementação por cinco dias pré-abate promoveu redução significativa nos níveis plasmáticos de cortisol e lactato, além de aumentar o teor de glicogênio muscular. Dessa forma, promoveu benefícios sobre a qualidade da carne suína, como o atraso no início da glicólise pós-morte, contribuindo para a melhora na capacidade de retenção de água, na coloração e na textura da carne (Moesgaard et al., 1993; D'Souza et al., 1998; Caine et al., 2000; Frederick et al., 2006).

Alonso et al. (2012) compararam formas de apresentação distintas de magnésio (óxido, sulfato e quelato) e observaram que a suplementação de Quelato de Magnésio melhorou a qualidade da carne, com menores perdas por exsudação e menor oxidação lipídica durante o armazenamento. Tais achados reforçam a ideia de que o magnésio pode contribuir para preservar a integridade muscular e a estabilidade bioquímica da carcaça.

Mais recentemente, em uma revisão sistemática que envolvia 16 estudos sobre suplementação de magnésio em suínos, Bushby, et al., (2021) concluíram que, na maioria dos casos, a suplementação resultou em benefícios comportamentais e fisiológicos, como menor reatividade, redução do cortisol e melhor qualidade de carne. Os autores alertam, no entanto, que os efeitos do magnésio são dependentes da dose, forma química, tempo de suplementação e manejo pré-abate.

Ao minimizar a resposta motora exacerbada durante a insensibilização elétrica, o magnésio pode contribuir para reduzir a intensidade das contrações involuntárias, limitando as forças mecânicas aplicadas à coluna vertebral e, consequentemente, a ocorrência de fraturas. Estudos como os de Peeters et al. (2006), Alonso et al. (2012) e Bushby et al. (2021) fornecem base científica relevante para a aplicação dessa estratégia, embora mais pesquisas direcionadas especificamente às lesões de coluna vertebral no abate ainda sejam necessárias.

Contudo, apesar de poucos estudos abordarem especificamente a relação entre magnésio e fraturas de coluna, os dados que relacionam sua ação ao controle muscular, os efeitos relatados sobre a modulação do sistema nervoso, a melhoria no estado de relaxamento dos animais, sugerem que o magnésio pode desempenhar papel preventivo frente a esse tipo de lesão, especialmente quando suplementado horas antes do abate.

Apesar dos avanços na compreensão dos efeitos do estresse pré-abate sobre a qualidade da carne suína, poucos estudos investigaram a relação entre a suplementação imediata com magnésio via água de bebida nas horas que antecedem o abate. Essa prática demonstra potencial em reduzir a ocorrência de fraturas na coluna durante a insensibilização, melhorar a qualidade da carne e atender às crescentes exigências do mercado em relação ao bem-estar animal, configurando-se como uma medida inovadora e de aplicação direta na rotina industrial. Sendo assim, são necessários mais estudos para entender essa temática.

REFERÊNCIAS

(AHAW), Efsa Panel On Animal Health And Welfare; NIELSEN, Søren Saxmose; ALVAREZ, Julio; BICOUT, Dominique Joseph; CALISTRI, Paolo; DEPNER, Klaus; DREWE, Julian Ashley; GARIN-BASTUJI, Bruno; ROJAS, Jose Luis Gonzales; SCHMIDT, Christian Gortázar. Welfare of pigs at slaughter. Efsa Journal, v. 18, n. 6, 113 p., jun. 2020. DOI: http://dx.doi.org/10.2903/j.efsa.2020.6148.

ALONSO, Verónica; PROVINCIAL, Laura; GIL, Mario; GUILLÉN, Elena; RONCALÉS, Pedro; BELTRÁN, José A. The impact of short-term feeding of magnesium supplements on the quality of pork packaged in modified atmosphere. *Meat Science*, v. 90, n. 1, p. 52-59, jan. 2012. DOI: http://dx.doi.org/10.1016/j.meatsci.2011.05.028.

BERTOLONI, William; SILVEIRA, Expedito Tadeu Facco; COSTA, Marcela de R.; LUDTKE, Charlí B.. Avaliação de diferentes híbridos suínos submetidos à insensibilização elétrica e gasosa (CO2). Parte 3: mensurações visuais de qualidade**.** *Ciência e Tecnologia de Alimentos***,** v. 26, n. 3, p. 555-563, set. 2006. FapUNIFESP (SciELO). DOI: http://dx.doi.org/10.1590/s0101-20612006000300012.

BLOKHUIS, H. J.; VEISSIER, I.; MIELE, M.; JONES, B.. The Welfare Quality® project and beyond: safeguarding farm animal well-being. *Acta Agriculturae Scandinavica*, Section A - Animal Science, v. 60, n. 3, p. 129-140, set. 2010. Informa UK Limited. DOI: http://dx.doi.org/10.1080/09064702.2010.523480.

BUSHBY, Emily V.; DYE, Louise; COLLINS, Lisa M.. Is Magnesium Supplementation an Effective Nutritional Method to Reduce Stress in Domestic Pigs? A Systematic Review. *Frontiers In Veterinary Science*, v. 7, p. 1-8, 12 jan. 2021. Frontiers Media SA. DOI: http://dx.doi.org/10.3389/fvets.2020.596205.

CAINE, W. R.; SCHAEFER, A. L.; AALHUS, J. L.; DUGAN, M. E. R.. Behaviour, growth performance and pork quality of pigs differing in porcine stress syndrome genotype receiving dietary magnesium aspartate hydrochloride. *Canadian Journal Of Animal Science*, v. 80, n. 1, p. 175-182, 1 mar. 2000. Canadian Science Publishing. DOI: http://dx.doi.org/10.4141/a99-068.

CHANNON, Heather A.; PAYNE, Ann M.; WARNER, Robyn D.. Effect of stun duration and current level applied during head to back and head only electrical stunning of pigs on pork quality compared with pigs stunned with CO2. *Meat Science*, v. 65, n. 4, p. 1325-1333, dez. 2003. DOI: http://dx.doi.org/10.1016/s0309-1740(03)00053-6.

COSTA, L Nanni; LOFIEGO, D.P; DALL'OLIO, S; DAVOLI, R; RUSSO, V. Combined effects of pre-slaughter treatments and lairage time on carcass and meat quality in pigs of different halothane genotype. *Meat Science,* v. 61, n. 1, p. 41-47, maio 2002. DOI: http://dx.doi.org/10.1016/s0309-1740(01)00160-7.

CUI B, XIONG Y, WEN X, WU S, HUANG Y, XIAO H, CAO S, JIANG Z, WANG L, HU S. Preliminary research on dietary supplementation of potassium magnesium sulphate on transport stress in finishing pigs prior to slaughter. Animals, v. 15, n. 3, p. 362, 2025. DOI: https://doi.org/10.3390/ani15030362.

DICH-JØRGENSEN, Kristine; LARSEN, Helle Daugaard; LEIFSSON, Páll S.; JENSEN, Henrik Elvang. Characterization of hemorrhages in the ham topsides and tenderloins of slaughter pigs. *Meat Science*, v. 124, p. 34-38, fev. 2017. DOI: http://dx.doi.org/10.1016/j.meatsci.2016.10.016.

D'SOUZA, D N; WARNER, R D; LEURY, B J; DUNSHEA, F R. The effect of dietary magnesium aspartate supplementation on pork quality. *Journal Of Animal Science*, v. 76, n. 1, p. 104, 1998. Oxford University Press (OUP). DOI: http://dx.doi.org/10.2527/1998.761104x.

EMBRAPA. Panorama da suinocultura. In: ANUÁRIO SUINOCULTURA INDUSTRIAL 2025, n. 06, 2024. Disponível em: https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1172717/1/final10397-panorama-da-suinocultura.pdf . Acesso em: 10 jun. 2025.

ESTÉVEZ-MORENO, Laura X.; VILLARROEL, Morris; LALAMA, Genaro C. Miranda-De. Do Mexican consumers really care about hen welfare? Understanding their attitudes, constraints and willingness to pay for cage-free eggs. *Food Quality And Preference*, v. 122, p. 105292, jan. 2025. DOI: http://dx.doi.org/10.1016/j.foodqual.2024.105292.

FREDERICK, B. R.; VAN HEUGTEN, E.; HANSON, D. J.; SEE, M. T.. Effects of supplemental magnesium concentration of drinking water on pork quality1. *Journal Of Animal Science*, v. 84, n. 1, p. 185-190, 1 jan. 2006. DOI: http://dx.doi.org/10.2527/2006.841185x.

GREGORY, N.G.. Recent concerns about stunning and slaughter. *Meat Science*, v. 70, n. 3, p. 481-491, jul. 2005. DOI: http://dx.doi.org/10.1016/j.meatsci.2004.06.026.

KIETZMANN, M.; JABLONSKI, H. On the blocking of stress by magnesium-aspartate hydrochloride in the pig. *Praktischer Tierarzt*, München, v. 66, p. 328–335, 1985.

LALAMA, G.C. Miranda-De; VILLARROEL, M.; MARÍA, G.A.. Livestock transport from the perspective of the pre-slaughter logistic chain: a review. *Meat Science*, v. 98, n. 1, p. 9-20, set. 2014. DOI: http://dx.doi.org/10.1016/j.meatsci.2014.04.005.

LAVER, D.R.; OWEN, V.J.; JUNANKAR, P.R.; TASKE, N.L.; DULHUNTY, A.F.; LAMB, G.D.. Reduced inhibitory effect of Mg2+ on ryanodine receptor-Ca2+ release channels in malignant hyperthermia. *Biophysical Journal*, v. 73, n. 4, p. 1913-1924, out. 1997. DOI: http://dx.doi.org/10.1016/s0006-3495(97)78222-5.

LUDTKE, C. B.**;** CIOCCA, J. R. P.**;** DANDIN, T.**;** BARBALHO, P. C.**;** VILELA, J. A.**;** DALLA Costa, O. A. Abate humanitário de suínos. Rio de Janeiro: WSPA, 2010. 132 p. ISBN 978-85-63814-00-5. Apoio: Embrapa Suínos e Aves. Disponível em: http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/920389. Acesso em: 17 jun. 2025.

MARCON, Adila V.; CALDARA, Fabiana R.; OLIVEIRA, Geyssane F. de; GONÇALVES, Liliane M.P.; GARCIA, Rodrigo G.; PAZ, Ibiara C.L.A.; CRONE, Carla; MARCON, Alex. Pork quality after electrical or carbon dioxide stunning at slaughter. ***Meat Science***, v. 156, p. 93-97, out. 2019. DOI: http://dx.doi.org/10.1016/j.meatsci.2019.04.022.

MOESGAARD, B.; LARSEN, I. Errebo; QUISTORFF, B.; THERKELSEN, I.; CHRISTENSEN, V. Grøsfjeld; JØRGENSEN, P. Fogd. Effect of Dietary Magnesium on Post Mortem Phosphocreatine Utilization in Skeletal Muscle of Swine: a non-invasive study using 31p-nmr spectroscopy. *Acta Veterinaria Scandinavica*, v. 34, n. 4, p. 397-404, dez. 1993. DOI: http://dx.doi.org/10.1186/bf03548184.
PEETERS, E.; DRIESSEN, B.; GEERS, R.. Influence of supplemental magnesium, tryptophan, vitamin C, vitamin E, and herbs on stress responses and pork quality1. *Journal Of Animal Science*, v. 84, n. 7, p. 1827-1838, 1 jul. 2006. DOI: http://dx.doi.org/10.2527/jas.2005-600.

PEETERS, E.; NEYT, A.; BECKERS, F.; SMET, S. de; AUBERT, A. E.; GEERS, R.. Influence of supplemental magnesium, tryptophan, vitamin C, and vitamin E on stress responses of pigs to vibration1. *Journal Of Animal Science*, v. 83, n. 7, p. 1568-1580, 1 jul. 2005. DOI: http://dx.doi.org/10.2527/2005.8371568x.

ROSENVOLD, Katja; ANDERSEN, Henrik J. Factors of significance for pork quality—a review. *Meat Science,* v. 64, n. 3, p. 219-237, jul. 2003. DOI: http://dx.doi.org/10.1016/s0309-1740(02)00186-9.

SINDHØJ, E., LINDAHL, C., & BARK, L. (2021). Review: Potential alternatives to highconcentration carbon dioxide stunning of pigs at slaughter. Animal, 15, Article 100164. https://doi.org/10.1016/j.animal.2020.100164 .

TROEGER, K.; WOLTERSDORF, W. Electrical stunning and meat quality in the pig. *Fleischwirtschaft,* v. 70, p. 901–904, 1990.

TROEGER, K.; WOLTERSDORF, W. Gas anaesthesia of slaughter pigs. I. Stunning experiments under laboratory conditions with pigs of known halothane reaction type: meat quality, animal protection. *Fleischwirtschaft,* v. 71, p. 1063–1068, 1991.

VELARDE, A.; GISPERT, M.; FAUCITANO, L.; MANTECA, X.; DIESTRE, A. The effect of stunning methods on the incidence of PSE meat and haemorrhages in pork carcasses. *Meat Science*, v. 55, p. 309–314, 2000. DOI: https://doi.org/10.1016/S0309-1740(99)00158-8.

VON WENZLAWOWICZ, M; VON HOLLEBEN, K; ESER, E. Identifying reasons for stun failures in slaughterhouses for cattle and pigs: a field study. *Animal Welfare*, v. 21, n. 2, p. 51-60, jun. 2023. DOI: http://dx.doi.org/10.7120/096272812x13353700593527.

WORLD ORGANIZATION FOR ANIMAL HEALTH (WOAH). Introduction to the recommendations for animal welfare. In: Terrestrial Animal Health Code. Paris: WOAH, 2018. Disponível em: https://www.oie.int/fileadmin/Home/eng/Health_standards/tahc/2018/en_chapitre_aw_introduction.htm. Acesso em: 17 jun. 2025.

WOTTON, S.B.; ANIL, M.H.; WHITTINGTON, P.e.; MCKINSTRY, J.L.. Pig slaughtering procedures: head-to-back stunning. *Meat Science,* v. 32, n. 3, p. 245-255, jan. 1992. DOI: http://dx.doi.org/10.1016/0309-1740(92)90088-l.

2 CAPÍTULO 2 – MAGNESIUM ADMINISTRATION IN PRE-SLAUGHTER DRINKING WATER REDUCES SPINAL FRACTURES IN PIGS DURING STUNNING[1]

Renata V. C. Gabriel[1], Wander S. F. Filho[1], Ana Vitória G. de Sousa[1], Geancarlo G. Degane[1], Alexandre B. do Amaral[1], Ednaldo C. Guimarães[1], João Paulo R. Bueno[2], Robson Carlos Antunes[1*]

[1]Federal University of Uberlândia (UFU), Uberlândia, MG, Brazil;

[2]Federal Institute of Goiás, Urutaí Campus, Urutaí, GO, Brazil;

** Corresponding author.*

ABSTRACT

Spinal fractures in pigs during electrical stunning are frequent and compromise animal welfare, meat quality and generate economic losses. Despite the relevance of the problem, specific preventive strategies are still little explored. This research evaluated, in an unprecedented way, the effect of magnesium supplementation in drinking water during pre-slaughter fasting on the occurrence of these fractures. A total of 2,080 pigs were evaluated, divided into a control group (CT) with 964 animals, not supplemented and a treatment group (TG) with 1,116 animals, supplemented with magnesium in drinking water, at a concentration of 300 mg/L. The supplementation reduced the proportion of fractures from 39.4% (380/964) to 30.0% (335/1,116), with an odds ratio of 0.66, suggesting a protective effect associated with muscle relaxation. Pigs with fractures had lower water holding capacity (WHC: 0.338 vs. 0.351; p = 0.0076), especially in the supplemented group (0.333 vs. 0.357; p = 0.0002), confirming the relationship between skeletal injuries and meat quality. We concluded that pre-slaughter supplementation with magnesium is practical and effective to reduce fractures and improve pork quality.

KEYWORDS: animal welfare; electrical stunning; meat quality; mineral; odds ratio; swine production; water holding capacity (WHC).

2.1 INTRODUCTION

Spinal fractures observed during the electrical stunning of pigs constitute a relevant problem in the production chain: they compromise animal welfare, reduce yield and carcass quality, and cause economic losses due to convictions. Pork has technological attributes — appearance, texture, juiciness, color, fat content, pH, and water holding capacity (WHC) — which are affected by physiological responses to stress in the pre-slaughter stage. During pre-slaughter management, handling, transport, and containment situations often trigger acute stress

---

[1] Chapter 2 — This chapter corresponds to the manuscript: Gabriel, R. V. C.; Filho, W. S. F.; Sousa, A. V. G.; Degane, G.G.; Amaral, A. B.; Guimarães, E. C.; Bueno, J. P. R.; Antunes, R.C. Magnesium administration in pre-slaughter drinking water reduces spinal fractures in pigs during stunning. Manuscript submitted to ACS Ômega in August 2025.

responses and neuromuscular excitement, increasing the chance of adverse events at the time of stunning. The passage of electric current can cause intense muscle contractions that, in extreme cases, result in vertebral fractures, often located in the lumbosacral region[1,2 e 3].

Despite the relevance of the problem, there are few studies that systematically describe the occurrence of vertebral fractures in pigs during electrical stunning[3], and there are only a limited number of studies that have evaluated the use of magnesium as a strategy to mitigate pre-slaughter stress — although the results have been varied, most have indicated beneficial effects of supplementation, mainly on meat quality parameters[5,7]. Alves et al. (2011) tested the supplementation of four minerals in the drinking water of pigs at pre-slaughter and observed that magnesium was the most effective in improving meat quality. However, none of these studies evaluated the occurrence of vertebral fractures.

In this context, magnesium supplementation administered by drinking water during pre-slaughter fasting emerges as a practical and quickly applied alternative. Previous evidence indicates that magnesium acts as a modulator of the nervous system and muscle contraction, reducing the release of cortisol and catecholamines, providing greater muscle relaxation[5,6,7]. These physiological properties justify the hypothesis that the administration of magnesium hours before slaughter can attenuate the high motor response to electric shock and, consequently, reduce the intensity of involuntary contractions responsible for fractures. In addition to that, interventions that reduce pre-slaughter excitement can have a positive impact on animal welfare and meat technology parameters such as WHC. Studies that applied magnesium for a short period of time reported beneficial effects on stress and WHC, but they are still scarce in the specific context of vertebral fractures during stunning[8,11].

This research evaluated in a direct and applied way the effect of magnesium supplementation via drinking water during pre-slaughter fasting on the occurrence of spinal fractures in pigs submitted to electrical stunning. In addition, we sought to investigate the relationship between the occurrence of fractures and subcutaneous fat thickness, as well as the possible interactions between magnesium supplementation and the water holding capacity (WHC) of meat. This article differs from previous investigations as it tests a short-term intervention, easily adopted in a commercial setting, focused specifically on the occurrence of fractures during electrical stunning. The main expected contribution is to provide practical and direct evidence of a simple strategy to reduce skeletal injuries at slaughter, with immediate implications for animal welfare and for quality and industrial efficiency of pork production.

2.2 MATERIALS AND METHODS

This research was approved by the ethics committee on the use of animals, process number 23117.017394/2025-90.

2.2.1. Location and period of research

The experiment was conducted in May 2025, over six consecutive days, in a slaughterhouse located in the city of Uberlândia, in the Triângulo Mineiro region, Minas Gerais, Brazil; under Municipal Inspection Service. The establishment has an operational capacity for the slaughter of approximately 350 pigs per day, has 16 pigsty stalls and a sequestration stall. Each one has 10 pacifiers to supply water to the animals, containing cement floors, masonry partitions with iron gates and tin roof. The structure of the slaughterhouse's pens complies with Ordinance Nº 274/94, which defines 1m² per pig with an average weight greater than 110 kg in Brazil.

2.2.2. Animals and Experimental Management

A total of 2080 finished pigs from different commercial lines were used, from the following genetic crosses: males AGPIC337 × females TN70; males LQ1250 × females DB90; and males AGPIC337 × Camborough females. All of these commercial lines are crosses originated from males of the Large White, Landrace, Duroc and Pietrain breeds; and females from Landrace and Large White breeds. Half of the animals were of males surgically castrated and the other half were females. The pigs were equally distributed among two experimental groups: control (C) and treatment (T), in order to balance genetic crosses and sex in both groups. All animals had an average weight of 120 kg and an approximate age of 178 days.

The animals were from commercial farms located in the Triângulo Mineiro region, Minas Gerais, Brazil, and were raised in intensive production systems: in conventional warehouse, with natural ventilation and stocking density compatible with the animal welfare recommendations for the finishing phase. The food offered consisted of a balanced commercial diet, provided until the beginning of the pre-slaughter fasting.

Solid fasting was started 18 hours before slaughter, according to operational protocols established between the farm and the slaughterhouse. The transport to the slaughter site was carried out by trucks, and the average travel time was less than two hours. The boarding and landing stages were conducted by trained workers aiming to minimize stress and preserve the animal's welfare.

2.2.3. Experimental Design and Treatments

At the slaughterhouse, the animals of this research (n=2,080) were divided into two experimental groups: control (C; n = 964, 482 males and 482 females) and treatment (T; n = 1,116, 558 males and 558 females). The allocation was made in a systematic way, positioning the groups on opposite sides of the pigsty, in order that one side was destined to the control group (without the addition of magnesium sulfate in the drinking water) and the other to the treated group (with the addition of magnesium sulfate in the drinking water). They arrived at the slaughterhouse pigsties approximately 12 hours before slaughter, and had free access to water from the moment of arrival.

To supply drinking water to the animals, two water tanks of 1,000 L each were allocated. For the control group the water pacifiers were supplied from the water tank containing 1,000 L of drinking water without magnesium sulfate supplementation, and for the treatment group, It was supplied from the water tank containing 1,000 L of drinking water with magnesium sulfate supplementation.

The magnesium dosage used in the experiment was defined based on the recommendations of the National Research Council (NRC, 2005), which establishes 300 ppm (or 300 mg/L of water) as the maximum tolerated level of magnesium for pigs, as described by Alves (2011). To ensure the safety and efficacy of supplementation, an inorganic source of the mineral was chosen, whose concentration of magnesium available after dissolution in water corresponds to 9.10%. In that case, the amount offered to the animals was calculated in order to reach the desired concentration in drinking water, using 3,296 kg of the supplement for every 1,000 L of water. This strategy allowed the dose to be adjusted to the recommended safe limit, optimizing supplementation and avoiding possible adverse effects resulting from excess mineral. The animals in the treated group consumed the supplemented water for a period of 10 to 12 hours before slaughter. The water consumption per group did not exceed 700 L during this pre-slaughter period.

Before the beginning of the experiment, water samples were collected from the pigsties where the research was conducted, aiming to define its mineral composition, especially the pre-existing concentration of magnesium. The analysis of chemical compounds in the water indicated an average magnesium content of approximately 80 ± 2 ppm, and it was carried out at the Chemical Analysis Center (CEAQ) at the Federal University of Uberlândia (UFU) by the method of flame atomic absorption spectrometry.

2.2.4. Data collection

2.2.4.1. Animal behaviour assessment over pre-slaughter

The behavioral analyses were all visual, monitored by the same evaluators, during the pre-slaughter time. Over the rest period it was observed that the environment remained calm and with no records of agitation events. The nocturnal vocalizations were discrete and compatible with the expected behavior for finishing pigs, without the occurrence of collective stress. The lights remained on throughout the night, favoring the observation of the animals.

The treated group showed predominantly passive behavior, remaining lying down most of the time, getting up only to consume water. Both groups remained visibly clean, with no accumulation of dirt or signs of discomfort.

The animals were taken to the slaughter line sequentially, stall by stall, and four pigs were released at a time. Three employees of the slaughterhouse, wearing standardized blue uniforms, were responsible for handling the animals, followed by a member of the research team who observed and recorded the process. The movement occurred calmly and continuously, without interruptions or the use of excessive stimuli. Before entering the stunning box, all the animals went through a shower, according to the routine practice of the slaughterhouse.

The climatic conditions during the six days of the experiment were obtained from the meteorological database of the National Institute of Meteorology (INMET), referring to the station of Uberlândia, Minas Gerais. The average air temperature was 22.3 °C, with minimum and maximum values of 21.8 °C and 22.8 °C, respectively. The relative humidity of the air averaged 62.1%, with variations between 60.1% (minimum) and 64.2% (maximum). The average dew point temperature was 14.4 °C. These conditions characterize a thermally comfortable environment for finishing pigs, favoring rest and reducing the risk of heat stress during the pre-slaughter fasting period.

2.2.4.2. Fractures assessment, Backfat Thickness Measurement, and *Longissimus Dorsi Muscle* Sample Collection

The swine was stunned by means of electric shock equipment, using two electrodes positioned in the cephalic region and a third electrode applied in the cardiac region. The operational parameters used were: voltage of 366 volts and current of 1.6 amperes at the cephalic electrodes, and current of 1.1 amperes at the cardiac point, with a frequency of 60 Hz. The time of application of the electrical stimulus was seven seconds. The mean interval between stunning and the beginning of bleeding ranged from five to eight seconds. Bleeding was conducted by cutting the carotid artery, with an average duration of three minutes, according to the routine of the slaughterhouse.

After bleeding, the carcasses were submitted to the usual stages of the slaughter process, starting with scalding in tanks with water heated between 62 °C and 65 °C, in order to facilitate the pelage removal. Then, they went through epilator machines equipped with rotating cylinders for the mechanical elimination of hair and dirt from the skin. After waxing, the carcasses were subjected to direct flame in a blowtorch to burn residual hair, followed by manual scraping (toilet). After that it was performed an evisceration opening the abdominal cavity and removing the thoracic and abdominal viscera for post-mortem inspection, according to current legal requirements.

After the post-mortem inspection stage, the occurrence of spinal fractures was identified by a member of the research team through direct visual inspection of the carcass, based on the observation of blood clots and lesions compatible with microfractures in the spinal region. Examples of carcasses with fractures are illustrated in **figure 1.**

(a) (b)

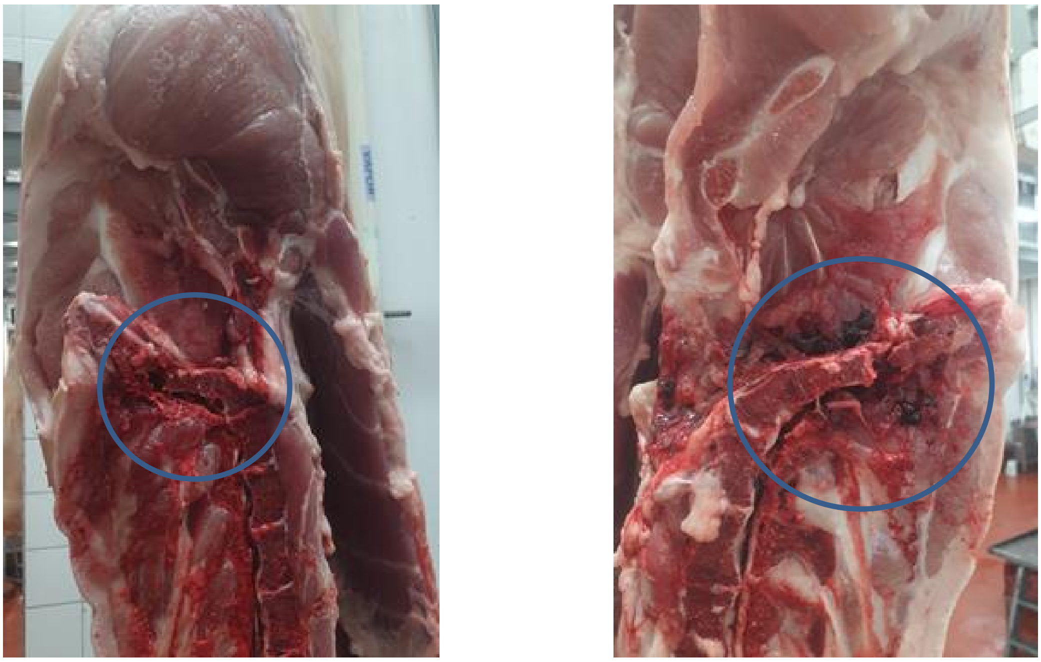

Figure 1. Examples of pig carcasses with fractures: (a) fracture in the lumbosacral region; (b) fracture with the presence of blood clots. Photos from the authors' personal archive.

The carcasses with and without fractures were recorded in a schedule, according to the number previously marked on the left palette of the animals. This method was adopted because it is the only viable way to identify fractures in real time within the slaughter line flow without interrupting the industrial process, in addition to being commonly used in field evaluations due to its speed and practical applicability.

Subcutaneous fat thickness was measured in all carcasses immediately after their longitudinal division. The measurement was performed with the aid of a millimeter flexible ruler, positioned perpendicular to the surface of the carcass, at a point located on the loin, at the height of the last rib, always on the left half carcass. This method was chosen because it is a direct, practical and widely used technique in slaughterhouses for the evaluation of carcass conformation, allowing standardization of measurements. All measurements were recorded in a schedule before the carcasses were entered for cooling, by the same previously trained observer.

Then, the carcasses were washed with potable water and sent for cooling in cold rooms, kept between 0 °C and 4 °C. After the cooling period, which means reaching a temperature ≤ 7 °C, the carcasses with fractures and without fractures were located once again by the number recorded on the left shoulder and a sample of the *Longissimus dorsi muscle* of approximately 2 cm^2 was collected from each previously selected carcass using a scalpel and sterile anatomical forceps, always from the left half carcass. The data collection was carried out by a member of the research group.

The samples were packed in plastic tubes with lids, identified with the carcass number and the day of slaughter, and transported in a thermal box containing gel ice and kept refrigerated until the end of the analyses, which occurred on the same day of collection. Collections were carried out at the same time, ensuring a sample of the carcass with fracture and another of a carcass without fracture for each group.

The identification of the experimental group each sample belonged (control (C; n = 964) or treatment (T; n = 1,116) was performed retrospectively, based on the count of animals allocated to each stall and the order of entry into the slaughter line. As the groups were kept on opposite sides of the pigsty and conducted sequentially to slaughter, it was possible to establish the correspondence between the carcass number (previously recorded on the left shoulder) and the respective group of origin. This strategy allowed the traceability of the samples without interfering in the operational routine of the slaughterhouse and ensured the correct classification of the data according to the experimental treatment.

2.2.4.3. Water Holding Capacity (WHC) Assessment

At the Meat Technology Laboratory of the Federal University of Uberlândia (UFU), the samples remained refrigerated (between 0°C and 4°C) until the WHC analyses were performed on the same day of collection. The determination of the water holding capacity (WHC) was performed using the compression method, a widely recognized technique considered the gold standard for this evaluation, as described by Grau and Hamm[11] and adopted by several recent studies[12]. The steps of the procedure are illustrated in **figure 2.**

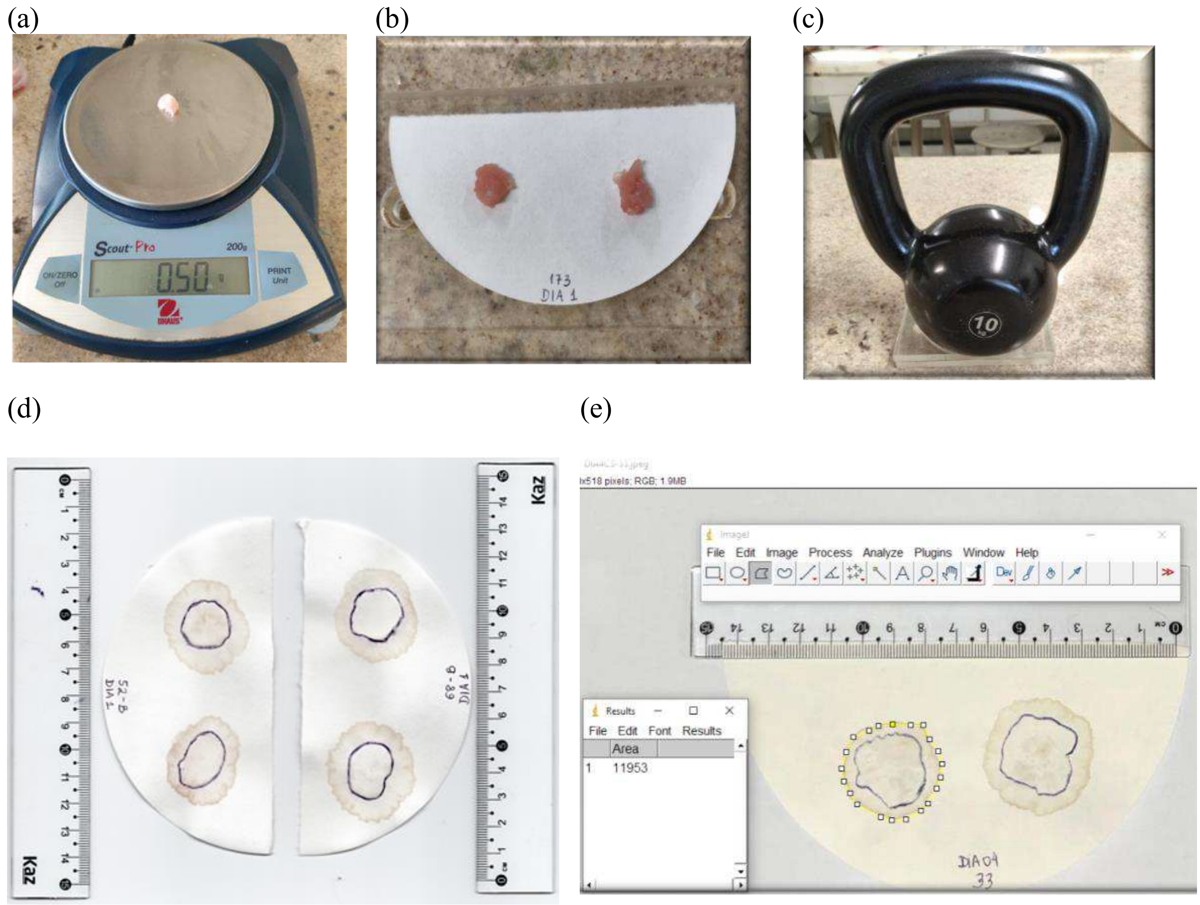

Figure 2. Stages of the water holding capacity (WHC) analysis: (a) standardization of the weight of the samples; (b) *Longissimus dorsi* sample on filter paper; (c) compression method with standardized weight; (d) image of the post-compression sample; (e) analysis of WHC images in the *ImageJ software*. Photos from the authors' personal archive.

The analysis of the water holding capacity (WHC) was performed in 495 samples of *the Longissimus dorsi muscle* of pigs. They were conducted in duplicate, totaling 990 determinations. For each sample, the mean of the values obtained in the duplicates was considered as representative of the WHC. The determination of the results was expressed by the ratio between the pressed meat area and the total area of the impression, indicating the capacity of the sample to hold water under pressure.

The samples were standardized in portions of 0.5 g and weighed individually on a precision scale (OHAUS Scout Pro). For each pair, a quantitative round filter paper (Unifil brand, medium filtration, white color, diameter of 15 cm) was used, duly identified with the carcass number (animal ID) and the date of collection. The two samples were placed side by side on the filter paper and compressed between two acrylic plates, on which a standardized weight of 10 kg was applied for five minutes.

After this period, the weights and the top paper were removed simultaneously, and the filter paper showed the formation of two distinct areas: one corresponding to the pressed meat and the other to the exudate halo. This area of the meat was outlined on the back of the paper with a marker. Afterward, the papers were photographed and the images analyzed using the *ImageJ* v. 1.37 software on which the areas of pressed meat and exudate were accurately calculated. The results were expressed in the form of ratios between the areas, and the average values obtained from the two samples of each carcass were entered and organized in Microsoft® Excel 2010 schedule for later statistical analysis.

2.2.5. Statistical Analysis

Statistical analysis was conducted to assess if the proportion of fractures differed between the control (C; n = 964) or treatment (T; n = 1,116) groups, and to verify the relationship between the occurrence of fractures and subcutaneous fat thickness, as well as the possible association between water holding capacity (WHC) and magnesium use. The comparison between the proportions of fractures in groups C and T was performed using the binomial test to compare two proportions, adopting a significance level of 5% ($p < 0.05$). The association between categorical variables, such as group and presence of fracture, was analysed using the odds ratio (OR), considering group C as reference 1 (one) and group T as 0 (zero); fracture as 1 (one) and absence of fracture as 0 (zero). The OR values were followed by the respective 95% confidence intervals (CI), and were considered statistically significant when the CI limits did not include value 1.

For the quantitative variable subcutaneous fat thickness, the normality and homogeneity of the residues were initially verified using the Shapiro-Wilk and Levene tests, both with a significance level of 5%. As the data did not attended the assumptions required for analysis of variance (ANOVA), after data transformation, we opted for the application of the non-parametric Kruskal-Wallis test. The analysis of the WHC was also performed by calculating the odds ratio (OR), considering the same group and fracture codings, with a CI of 95%.

All statistical analyses were performed using the R software (R Core Team, 2025), version 4.3.1, using the statistical programming language and environment of the R Foundation for Statistical Computing, Vienna, Austria. Available at: https://www.R-project.org.

2.3. RESULTS

2.3.1. Occurrence of Vertebral Fractures in pigs

The group (C) consisted of 964 pigs had 380 that suffered fractures and 584 that did not suffer fractures whereas group (T) consisted of 1,116 pigs had 335 with fractures and 781 that did not suffer fractures. The binomial test for two proportions (odds ratio – OR) indicated that the incidence of fractures was significantly higher in the control group (39.4%) compared to the treated group (30.0%) (p = 0.000008; 95%CI: 5.2% - 13.6%). The odds ratio analysis indicated that pigs supplemented with magnesium had a lower probability of fractures, with an OR of 0.66 (95%CI: 0.55 - 0.79), which corresponds to a 52% reduction in the chance of fracture compared to the animals in the control group.

2.3.2. Association between Fracture Occurrence, Experimental Group and Subcutaneous Fat Thickness

Subcutaneous fat thickness was significantly associated with the occurrence of fractures. Pigs with fractures had a lower average thickness of subcutaneous fat (1.98 cm), while those without fractures had an average of 2.14 cm. The odds ratio analyses showed that a 1 cm increase in backfat thickness was associated with a 72% reduction in the chance of fractures (OR = 0.58). When stratified by group, this reduction was 82% in the Treatment group (OR = 0.55) and 49% in the Control group (OR = 0.67). It was confirmed a statistical significance of the odds ratios for the occurrence of fractures, both as a function of the experimental group and of the thickness of subcutaneous fat, as 95% confidence intervals did not include a value of 1.

These findings indicate a real effect of these variables on the probability of fractures in pigs. The animal in group (T) has a 52% lower chance of presenting the fracture.

Based on the results of the Kruskal-Wallis test, Table 1 presents the descriptive values of subcutaneous fat thickness (cm), stratified by experimental group (C) and (T) and the occurrence or absence of fractures.

Table 1. Average thickness of subcutaneous fat (cm) in pigs with and without fractures, according to the experimental group

Group	Average thickness (cm)	
	Fracture CS; n=380; TS; n=335	No fracture CN; n=584; TN; n=781
Control (C; n = 964)	1.96^{bA}	2.07^{aB}
Treatment (T; n = 1,116)	2.00^{bA}	2.18^{aA}

Source: the authors, 2025.
Different lowercase letters (a, b) on the line indicate a significant difference between the presence and absence of fracture ($p < 0.05$). Different capital letters (A, B) in the column indicate a significant difference between groups ($p < 0.05$).

The analysis stratified by experimental group revealed that pigs with fractures had significantly lower subcutaneous fat thickness than those without fractures. In group (C), the fractured animals had an average of 1.96^{b} cm, while the non-fractured animals had 2.07^{a} cm. Similarly, in the group (T), the thickness was 2.01^{b} cm in the animals with fractures and 2.18^{a} cm in those without fractures. These results confirm a significant association between lower subcutaneous fat thickness and the occurrence of fractures in both groups ($p < 0.05$).

When comparing the experimental groups considering only the animals with fractures ("Fracture" column), there was no significant difference in the mean thickness between the Control (1.96^{A} cm) and Treatment (2.01^{A} cm) groups.

In general, the Kruskal–Wallis test indicated a highly significant association between subcutaneous fat thickness and the occurrence of fractures, regardless the experimental group ($p = 1.29 \times 10^{-11}$).

2.3.3. Water holding capacity (WHC)

The WHC was calculated by the ratio between the area of the compressed meat and the total area of the spot (meat + exudate). Higher values indicate less exudate release and, therefore, greater water holding capacity by the meat. WHC was significantly associated with the occurrence of fractures — animals without fractures had higher WHC. The animals were divided into two experimental groups: control (C; n = 238), subdivided into CS (n = 119, animals with fractures) and CN (n = 119, animals without fractures), and treatment (T; n = 257), subdivided into TS (n = 127, animals with fractures) and TN (n = 130, animals without fractures).

The odds ratio for the group (0 = Treatment; 1 = Control) was 1.47 (95%CI: 0.06–35.76), indicating no statistically significant association with WHC. However, the occurrence of fractures was strongly associated with WHC: the OR was 0.015 (95%CI: 0.0005–0.3962), suggesting that for each 1 percentage unit increase in WHC, the chance of fracture was about 66.6 times lower.

When analyzing only the group (T), the association between WHC and fracture was even more evident: the OR was 0.00015 (95%CI: 0.00000103–0.0212), indicating a strong reduction in the chance of fracture with increasing WHC. Considering increments of 1 percentage unit in the WHC, the chance of fracture was approximately 6,667 times lower for each increase. In group (C), there was no statistically significant association between WHC and fractures.

The Kruskal–Wallis test did not identify a statistically significant difference in the (WHC) between groups (C) and (T) in general (p = 0.30). However, when considering the occurrence of fractures, it was observed that pigs without fractures had significantly higher WHC than those with fractures, regardless of the experimental group (p = 0.0076), with medians of approximately 34.5 and 33.5, respectively. These results suggest an association between carcass integrity and greater water holding capacity.

The analysis stratified by experimental group revealed that this association was especially evident in the group (T), where the animals without fractures had significantly higher WHC than the fractured group (p = 0.0002). Among the pigs in group (T), the average WHC was 35.71 for those without fracture and 33.32 for those with fractures. In group (C), there was no significant difference between the animals with 34.39 and without fractures 34.43.

When comparing the Control and Treatment groups within the "no fracture" condition, it was found that the pigs in group (T) had significantly higher WHC than those in group (C) (p = 0.0126). This indicates that magnesium supplementation may have contributed positively to water holding in animals that did not suffer fractures. On the other hand, among the animals with fractures, no significant differences in WHC were observed between the experimental groups (p = 0.24).

Table 2. Water holding capacity (WHC) in pigs with and without fractures, according to the experimental group.

Group	Ratio of compressed meat area to total spot (meat + exudate)	
	Fracture	No fracture
Control C; n = 238, CS; n = 119, animals with fractures and CN; n = 119, animals without fractures.	34.39^{bA}	34.43^{aB}
Treatment T; n = 257; TS; n = 127, animals with fractures and TN; n = 130, animals without fractures.	33.32^{bA}	35.71^{aA}

Source: the authors, 2025.

Different lowercase letters (a, b) on the same line indicate a significant difference between pigs with and without fractures within the same group. ($p < 0.05$). Different capital letters (A, B) in the column indicate significant difference between groups for the same fracture condition ($p < 0.05$; Kruskal-Wallis test). WHC = water holding capacity expressed by the ratio of the area of the compressed meat to the total area of the spot (meat + exudate).

The Water Holding Capacity (WHC) of the meat was significantly different between pigs with and without fractures, regardless of the experimental group. In both groups, animals without fractures had higher WHC than those with fractures ($p < 0.05$). In addition, when comparing the experimental groups in the "non-fracture" condition, it was observed that the pigs in the group (T) had significantly higher WHC than those in the group (C) (35.71 vs. 34.43; $p = 0.0126$). This finding suggests that magnesium supplementation may exert an indirect effect on the improvement of WHC, possibly by reducing the occurrence of fractures and, consequently, the pre-slaughter stress that affects meat quality. No difference between the groups was observed between the animals with fractures.

2.4. DISCUSSION

2.4.1. The effect of magnesium supplementation on the occurrence of fractures

The magnesium supplementation via drinking water provided during the pre-slaughter period was effective in reducing the occurrence of fractures in pigs when compared to the control group. Unlike dietary supplementation, this approach allows for rapid action in fasting animals, making it a practical alternative for critical moments of pre-slaughter management.

The effects observed can be attributed to magnesium's properties as a stress modulator and muscle relaxant. The supplementation possibly reduced neuromuscular excitability and modulated the behavior of the animals, making them less reactive to external stimuli and sudden movements during electrical stunning — factors directly associated with the risk of vertebral fractures. The action of magnesium occurs, in part, due to its calcium antagonist effect, which stabilizes the cell membrane and promotes muscle relaxation, as demonstrated in previous studies[14,15].

Although physiological indicators of stress were not measured in this research, results of systematic reviews indicate that magnesium supplementation in pigs can reduce plasma cortisol levels, improve stress-related behaviors, and reduce the occurrence of traumatic injuries[5,6,13]. Furthermore, the effect of magnesium may be influenced by other minerals present in the diet, such as calcium and phosphorus, which compete for absorption and modulate muscle excitability and bone strength, although these interactions were not evaluated in this research.

2.4.2. Relationship between subcutaneous fat thickness and fracture occurrence

The results of the relationship between the occurrence of fractures and the thickness of subcutaneous fat showed that this characteristic can influence the susceptibility to bone lesions during the process of electrical stunning in pig slaughter. The fractured animals had thinner back fat thickness. This significant association between subcutaneous fat thickness and the occurrence of fractures (OR = 0.58 for each additional cm) reinforces the hypothesis that a thicker fat layer can provide mechanical protection to bones at slaughter, especially in the spinal region.

A one-cm increase in subcutaneous fat thickness was associated with up to a 72% reduction in the chance of fracture, regardless of the experimental group. The association observed between greater thickness of subcutaneous fat and lower occurrence of fractures suggests that subcutaneous fat may play a mechanical protective role during stunning at slaughter.

Anatomical differences among pigs can make them more or less susceptible to vertebral fractures[2], which reinforces the existence of individual factors involved in this injury. However, electronarcosis remains the main trigger for these fractures, and losses in meat and carcass quality are inevitable, regardless of the type of equipment, the configurations used, or the training of operators[16].

Pigs with the current genetics are genetically improved and tend to have less subcutaneous fat deposition and higher lean meat yield. Consequently, they have less fat coverage and a higher proportion of muscle mass. This characteristic can directly influence the response to electrical stunning, since more developed muscles, with less fat insulation, tend to present more intense contractions during the passage of electric current.

This intensity of response can increase the risk of vertebral fractures, especially in the absence of precise electrode placement or when there are individual variations in anatomy. In view of this scenario, the hypothesis considered is that the electrical stunning parameters currently used (voltage and amperage), developed based on previous genotypes, may not be the most appropriate for the zootechnical profile of modern pigs. Therefore, additional studies evaluating the interaction between animal biotype and electronarcosis parameters are required, aiming to minimize fracture losses and improving welfare at slaughter.

Although studies directly related to the production of commercial pigs are scarce, these findings reinforce the hypothesis that the thickness of subcutaneous fat at the level of the last rib can act as a natural shock absorber, minimizing the effects of impacts and sudden movements during management, especially in the stunning phase.

2.4.3. Relationship between fractures and WHC meat quality

WHC was significantly associated with the occurrence of fractures — animals without fractures had higher WHC, regardless of the experimental group. This suggests an association between the physical integrity (absence of fractures) of the animals at the time of slaughter and the technological quality of the meat produced. The occurrence of fractures is often associated with pre-slaughter stress and excessive movement during electrical stunning.

Stress in pigs triggers complex physiological responses involving both the hypothalamic-pituitary-adrenal (HPA) axis — with the release of corticotropin-releasing hormone (CRH), adrenocorticotropic hormone (ACTH) and cortisol — and the sympathetic nervous system, responsible for the release of catecholamines, increased heart rate and redistribution of blood flow[17]. Simultaneously, in the post-mortem period, there is an increase in glycolytic activity, which accelerates the degradation of muscle glycogen and promotes a sudden drop in pH, while the carcass temperature remains high. This condition favors the denaturation of proteins, reducing the water holding capacity of meat and negatively impacting its technological quality[14]. Consequently, there is a higher incidence of PSE (pale, soft and exudative) meat.

Thus, the lower WHC observed in animals with fractures can be explained by the alteration in muscle metabolism induced by stress and trauma, favoring the production of meat with undesirable characteristics, such as PSE. This technological condition compromises the quality of the final product and generates losses to the industry: due to the greater loss of fluids during storage, or the shorter shelf life, or even the lower sensory acceptance.

In a general basis, the results demonstrate that pork WHC was significantly associated with the occurrence of fractures, being higher in animals without fractures. This relationship was more evident in the magnesium-supplemented group ($p = 0.0002$), with the mean WHC being 35.71 for those without fractures and 33.32 for those with fractures. This result suggests that supplementation can improve meat quality, especially when there is no physical damage to the carcass.

Although magnesium supplementation did not directly alter the water holding capacity (WHC) in this experiment, the reduction in the occurrence of fractures can indirectly contribute to the maintenance of muscle integrity and meat quality**,** preventing economic losses associated with traumatic injuries.

2.5. CONCLUSION

The results of this research show that magnesium supplementation via drinking water in the hours prior slaughter can reduce the occurrence of vertebral fractures during electrical stunning of pigs, indicating a beneficial effect on the modulation of the response to acute pre-slaughter stress. The association observed between fractures and lower water holding capacity (WHC) reinforces the negative impact of these injuries on the technological quality of the meat. In addition, the relationship between lower thickness of subcutaneous fat and higher occurrence of fractures suggests that leaner animals may be more susceptible to these injuries.

This research has an innovative character by demonstrating, in a practical way, the potential of magnesium as a strategy of pre-slaughter water supplementation to improve animal welfare and preserve the quality of the final product, reducing economic and technological losses.

On the other hand, the research has limitations, such as the restricted number of parameters of meat aspects evaluated and the absence of physiological, biochemical and histological analyses that could elucidate the mechanisms involved. Future research should include different doses, durations and routes of administration of magnesium, in addition to the evaluation of physiological indicators such as (post-mortem pH, muscle glycogen, cortisol), technological (color, tenderness) and behavioral (observation protocols), to explore the understanding of its effects on the welfare and quality of pork.

Author Contributions

The article was written through contribution of all authors. Renata V. C. Gabriel, Wander S. F. Filho, Ana Vitória G. de Sousa and Geancarlo G. Degane were responsible for data collection in the slaughterhouse, laboratory analyses and the article essay. Alexandre B. do Amaral contributed with technical support in the laboratory analyses, Ednaldo C. Guimarães performed the statistical analyses. João Paulo R. Bueno and Robson Carlos Antunes participated in the experimental design, statistical analysis, interpretation and discussion of the results

Notes

The authors declare that there are no conflicting financial interests.

AKNOWLEDGMENTS

The authors would like to acknowledge the São Pedro slaughterhouse and all its employees for the opportunity to carry out the experiment; Franciele Rodrigues Duarte Borges (technical manager) and Elicéia Meireles Gomes (inspector from the Municipal Inspection Service) for their support and collaboration conducting the activities. They also aknowledge the veterinarian Jéssica Luana Guimarães de Oliveira for the fundamental teachings in the detection of fractures, the Laboratory of Inspection and Technology of Products of Animal Origin of the Federal University of Uberlândia (LITPOA/UFU) for the technical and structural support in the analyses and the professional Sandro Silvestre Gabriel for the extensive experience and knowledge shared throughout the development of the research. This research was supported by the Coordination for the Improvement of Higher Education Personnel – Brazil (CAPES), through the granting of a scholarship to the master's student of the postgraduate program in Veterinary Sciences (PPGCVET/UFU) Renata Vieira Chaves Gabriel (author) as well as the payment of the publication fee (CAPES – ROR: 00x0ma614).

REFERENCES:

1- Cornet, Steven H.V.; Snel, Silvia J.E.; Lesschen, Judith; Goot, Atze Jan Van Der; Sman, Ruud G.M. Van Der. Enhancing the water holding capacity of model meat analogues through marinade composition. *J. Food Eng., 290*, Article 110283, 2021. DOI: https://doi.org/10.1016/j.jfoodeng.2020.110283

2- Faucitano, Luigi. Preslaughter handling practices and their effects on animal welfare and pork quality. *J Anim Sci.,* v. 96, n. 2, p. 728-738, 1 Feb. 2018. Oxford University Press (OUP). http://dx.doi.org/10.1093/jas/skx064

3- Alberton, Geraldo Camilo; Moreira, Larissa Maria; Belo, Carlo Eduardo Penner; Donin, Daiane Güllich; Dornbush, Peterson Triches. Macroscopic aspects of pig vertebrae fractured during the slaughtering process. *Arch. Vet. Sci.,* v. 21, n. 3, p. 77-85, 5 Dec. 2016. Federal University of Paraná. http://dx.doi.org/10.5380/avs.v21i3.45563

4- Estévez-Moreno, Laura X.; Villarroel, Morris; Lalama, Genaro C. Miranda-De. Do Mexican consumers really care about hen welfare? Understanding their attitudes, constraints and willingness to pay for cage-free eggs. *Food Qual. Prefer.,* v. 122, p. 105292, jan. 2025. http://dx.doi.org/10.1016/j.foodqual.2024.105292

5- Bushby, Emily V.; Dye, Louise; Collins, Lisa M. Is Magnesium Supplementation an Effective Nutritional Method to Reduce Stress in Domestic Pigs? A Systematic Review. *Front. Vet. Sci.,* v. 7, p. 1-8, 12 jan. 2021. Frontiers Media SA. http://dx.doi.org/10.3389/fvets.2020.596205

6- D'souza, D N; Warner, R D; Leury, B J; Dunshea, F R. The effect of dietary magnesium aspartate supplementation on pork quality. *J Anim Sci.,* v. 76, n. 1, p. 104, 1998. Oxford University Press (OUP). http://dx.doi.org/10.2527/1998.761104x

7- Alves, Luana Ribeiro. Quality of pork. 1. Effect of the halothane gene on intramuscular fat deposition. 2. Effect of mineral supplementation on pre-slaughter. 2011. 121 f. Dissertation (Master's Degree in Veterinary Sciences – Animal Production) – Faculty of Veterinary Medicine, Federal University of Uberlândia, Uberlândia, 2011.

8- Tarsitano, Marina Avena; Bridi, Ana Maria; Silva, Caio Abércio Da; Constantino, Camila; Andreo, Nayara; Dalto, Danyel Bueno. Magnesium supplementation in swine finishing stage: performance, carcass characteristics and meat quality. *Semin., Ciênc. Agrár.,* v. 34, n. 6, p. 3105, 11 dez. 2013. State University of Londrina. http://dx.doi.org/10.5433/1679-0359.2013v34n6p3105

9- NRC. NATIONAL RESEARCH COUNCIL. Nutrient requirements of dairy cattle. 7th ed. Washington: National Academy Press, 2001. 408p.

10- NRC. NATIONAL RESEARCH COUNCIL. Mineral tolerance of animals. 2nd ed. Washington: National Academic Press, 2005. 510p.

11- Grau, R.; Hamm, R. Eine einfache Methode zur Bestimmung der Wasserbindung im Fleish. Fleischwirtschaft, Frankfurt, v.4, p.295-297, 1953.

12- Reis, Vinicius Clemente de Sousa; Ferreira, Isaura Maria; Durval, Mariah Castro; Antunes, Robson Carlos; Backes, André Ricardo. Measuring water holding capacity in pork meat images using deep learning. *Meat Sci.,* v. 200, p. 109159, June 2023. Elsevier BV. http://dx.doi.org/10.1016/j.meatsci.2023.109159

13- Alonso, Verónica; Provincial, Laura; Gil, Mario; Guillén, Elena; Roncalés, Pedro; Beltrán, José A. The impact of short-term feeding of magnesium supplements on the quality of pork packaged in modified atmosphere. *Meat Sci.,* v. 90, n. 1, p. 52-59, jan. 2012. http://dx.doi.org/10.1016/j.meatsci.2011.05.028

14- Rosenvold, Katja; Andersen, Henrik J. Factors of significance for pork quality—a review**.** *Meat Sci.,* v. 64, n. 3, p. 219-237, jul. 2003. Elsevier BV. http://dx.doi.org/10.1016/s0309-1740(02)00186-9

15- Laver, D.R.; Owen, V.J.; Junankar, P.R.; Taske, N.L.; Dulhunty, A.F.; Lamb, G.D. Reduced inhibitory effect of Mg2+ on ryanodine receptor-Ca2+ release channels in malignant hyperthermia. *Biophys. J.,* v. 73, n. 4, p. 1913-1924, out. 1997. http://dx.doi.org/10.1016/s0006-3495(97)78222-5

16- Channon, Heather A.; Payne, Ann M.; Warner, Robyn D. Effect of stun duration and current level applied during head to back and head only electrical stunning of pigs on pork quality compared with pigs stunned with CO2. *Meat Sci.,* v. 65, n. 4, p. 1325-1333, dez. 2003. http://dx.doi.org/10.1016/s0309-1740(03)00053-6

17- Martínez Miró, S.; Tecles, F.; Ramón, M.; Escribano, D.; Hernández, F.; Madrid, J.; Orengo, J.; Martínez Subiela, S.; Manteca, X.; Cerón, J. J. Causes, consequences and biomarkers of stress in swine: an update. *BMC Vet. Res.,* v. 12, art. 171, 19 Aug., 2016. DOI: https://doi.org/10.1186/s12917-016-0791-8