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DISSERTAÇÃO

AJUSTE DIÁRIO NA ALIMENTAÇÃO DE SUÍNOS NAS FASES DE CRESCIMENTO E TERMINAÇÃO: IMPACTOS ECONÔMICOS, PRODUTIVOS E AMBIENTAIS

Yann Malini Ferreira

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UNIVERSIDADE FEDERAL RURAL DO RIO DE JANEIRO
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Sob a Orientação do Professor
Luan Sousa dos Santos

e Coorientação do Professor
Tadeu Eder da Silva

Dissertação submetida como requisito parcial para obtenção do grau de **Mestre(a),** no Curso de Pós-Graduação em Ciência Animal, Área de Concentração Zootecnia

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YANN MALINI FERREIRA

Dissertação submetida como requisito parcial para obtenção do grau de Mestre(a) no Programa de Pós-Graduação em Ciência Animal, área de Concentração em Zootecnia.

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RESUMO GERAL

FERREIRA, Yann Malini. **Ajuste Diário na Alimentação de Suínos nas Fases de Crescimento e Terminação: Impactos Econômicos, Produtivos e Ambientais.** 2024. 70p. Dissertação (Mestrado em Ciência Animal). Instituto de Zootecnia, Programa de Pós-Graduação em Ciência Animal, Universidade Federal Rural do Rio de Janeiro, Seropédica, RJ, 2024.

A suinocultura a nível mundial se encontra em constante crescimento e desenvolvimento, mesmo enfrentando diversos desafios de produção, como o constante aumento dos preços de matérias-primas e a necessidade de adequação às novas demandas do mercado consumidor. Os maiores desafios estão nos altos custos com alimentação e na preocupação em ser mais sustentável. A aplicação de práticas de nutrição de precisão e modelagem matemática são excelentes aliadas neste quesito. Principalmente por causar uma redução dos custos de produção, redução de nutrientes fornecidos e menor impacto ambiental. Portanto, no presente projeto foram propostos dois modelos, um para o sistema de alimentação convencional de fases (CON) e outro para um sistema com ajuste diário das dietas para os suínos (DFM). O DFM foi criado para otimização do fornecimento de nutrientes aos animais o mais próximo das suas exigências nutricionais, com mudanças dos níveis nutricionais diariamente. A partir dos modelos desenvolvidos, foram elaboradas simulações usando três cenários de formulação de dietas: tabelas brasileiras (BT-2017), NRC (NRC-2012) e AGPIC (AGPIC-2021). Os modelos foram alimentados com as informações de custos de ração, taxa de consumo de ração e quantidade de fases utilizadas, sendo utilizado 5 fases. Para a simulação proposta, foi utilizado dados de consumo de ração, ganho de peso e exigências nutricionais de suínos castrados durante um período de 120 dias nas fases de crescimento e terminação. A partir das exigências nutricionais dietas foram formuladas e aplicadas nos modelos para posterior comparação entre os mesmos. A partir dos custos em cada sistema de alimentação, foi avaliado o potencial de redução nos custos da ração e o consumo de nutrientes como lisina e fósforo. Outra análise empregada foi a Análise de Ciclo de vida (ACV) empregando uma abordagem do berço à porteira. A ACV avaliou o impacto ambiental dos modelos propostos considerando fatores como acidificação, mudanças climáticas, ecotoxicidade, eutrofização, toxicidade humana, uso da terra, uso de água, uso de recursos minerais, metais e fósseis. O software OpenLCA e o método de avaliação de impacto Environmental Footprint (EF) 3.0 foram empregados. Os resultados revelaram que o modelo DFM apresentou uma redução significativa no impacto ambiental durante as fases de crescimento e terminação, com reduções nos custos dos suínos e na ingestão de nutrientes, como proteína bruta, lisina e fósforo digestível. Essa abordagem simplificada de alimentação de precisão mostrou-se promissora para minimizar o impacto ambiental e promover práticas sustentáveis na suinocultura. Além disso, o estudo enfatizou a importância da adoção de técnicas de alimentação de precisão e estratégias alternativas para mitigar os efeitos adversos na produção de suínos. Ao destacar o papel crítico da produção de alimentos na condução dos impactos ambientais, este estudo contribui para o avanço do conhecimento sobre práticas sustentáveis na suinocultura, promovendo o gerenciamento ambiental e a viabilidade de longo prazo na indústria.

Palavras-chave: Alimentação de precisão, Nutrição de precisão, Suinocultura

GENERAL ABSTRACT

FERREIRA, Yann Malini. **Daily Adjustment in Swine Feeding During Growing-finishing Phases: Economic, Productive, and Environmental Impacts.** 2024. 70p. Dissertation (Master Science in Animal Science) Institute of Animal Science, Animal Science Graduate Program, Federal Rural University of Rio de Janeiro, Seropédica, RJ, 2024.

The swine industry worldwide is experiencing continuous growth and development despite various production challenges, such as the constant increase in raw material prices and the need to adapt to new consumer market demands. The significant challenges lie in high feed costs and the imperative to be more sustainable. The application of precision nutrition practices and mathematical modeling proves to be excellent allies in this regard, primarily due to their ability to reduce production costs, nutrient supply, and environmental impact. Therefore, this project proposes two models: one for conventional phase feeding systems (CON) and another for a system with daily adjustment of swine diets (DFM). The DFM model aims to optimize the nutrient supply to animals to be as close as possible to their nutritional requirements, with daily changes in nutritional levels. Simulations were conducted using three diet formulation scenarios: Brazilian tables (BT-2017), NRC (NRC-2012), and AGPIC (AGPIC-2021). The models were fed with information on feed costs, feed consumption rate, and number of phases used, employing 5 phases. For the proposed simulation, data on feed consumption, weight gain, and nutritional requirements of castrated pigs were utilized over 120 days in the growth and finishing phases. Diets were formulated based on dietary requirements and applied to the models for subsequent comparison. Evaluations were made regarding the potential reduction in feed costs and nutrient consumption, such as lysine and phosphorus. Another analysis employed was Life Cycle Assessment (LCA) using a cradle-to-gate approach. LCA assessed the proposed models' environmental impact, considering factors such as acidification, climate change, ecotoxicity, eutrophication, human toxicity, land use, water use, and the use of mineral, metal, and fossil resources. OpenLCA software and Environmental Footprint (EF) 3.0 impact assessment method were utilized. Results showed that the DFM model significantly reduced environmental impact during the growth and finishing phases, along with reduced pig costs and nutrient intake, such as crude protein, lysine, and digestible phosphorus. This simplified precision feeding approach proved promising in minimizing environmental impact and promoting sustainable practices in swine production. Moreover, the study emphasized the importance of adopting precision feeding techniques and alternative strategies to mitigate adverse effects in pig production. By highlighting the critical role of food production in driving environmental impacts, this study contributes to advancing knowledge on sustainable practices in swine farming, promoting environmental management, and long-term viability in the industry.

Keywords: Precision feeding, Precision nutrition, Swine farming

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1 INTRODUÇÃO GERAL

A suinocultura segue sendo destaque nacional e internacional. Visando atender demandas internacionais, novos desafios estão pelo caminho para tornar a suinocultura uma atividade mais sustentável. Tais medidas são necessárias, uma vez que alguns riscos estão atrelados a suinocultura intensiva, que ao gerida de forma inadequada pode causar danos ao meio ambiente. No contexto de aumentar a produtividade dos sistemas de produção levando em consideração o crescimento demográfico, desenvolvimento tecnológico, mudanças climáticas, mudanças no padrão de consumo e bem-estar animal, a nutrição de precisão aplicadaa animais de produção é uma das medidas que mitigam os principais problemas ambientais e proporcionam o desenvolvimento do setor agropecuário de forma mais sustentável.

A nutrição de precisão utiliza de diferentes técnicas que permitem que os indivíduos recebam a dieta adequada tanto quantitativamente quanto qualitativamente no momento certo para cada animal (Pomar *et al*., 2009). O emprego da modelagem permite ajustes mais precisos de acordo com a realidade do sistema de produção e dos animais (Lovato, 2013).

Dentre os benefícios das práticas de precisão podemos citar seu efeito na redução de custos, redução de perdas por desperdício e mal aproveitamento da dieta, redução excesso de nutrientes, atendimento das exigências nutricionais de cada indivíduo, promoção da sustentabilidade, aumento da eficiência do sistema de produção e redução de gases de efeito estufa (Andretta, 2014; Lovato *et al*., 2017; Pomar *et al*., 2009).

Diante disto, o presente trabalho propõe a aplicação de um ajuste diário nas dietas utilizadas para os suínos visando atingir benefícios de redução de custos, redução do excesso de nutrientes e redução do impacto ambiental.

2 REVISÃO DE LITERATURA

2.1 Custos com alimentação na suinocultura

Na cadeia suinícola nacional a alimentação é o componente dos custos mais preocupante, uma vez que ocupa quase 80,0% dos custos totais de produção de suínos (CIAS, 2023). Fatores que contribuem para esse valor envolvem os preços das matérias primas mais utilizada nas dietas dos suínos, milho e soja; entraves logísticos; questões político-sociais e sanitárias.

Os preços do milho e soja registraram altas de 100% e 60% respectivamente no período de 2020, impactando consideravelmente a cadeia suinícola (EMBRAPA, 2022). Parte disso é devido a pandemia de COVID-19 que causou grande aumento nos custos de produção, principalmente pela alta dos preços de matéria prima, queda na exportação seguida por aumento da exportação e aumento do preço da carne suína no mercado interno. Um dos mais afetados foi o milho, que é o principal cereal usado nas rações, ocupando aproximadamente 66% do conteúdo das dietas em 2020 (Zani, 2021).

Entraves logísticos interferem diretamente nos custos de produção, como a distância dos grandes centros comerciais e de portos para escoamento da produção destinada à exportação (Gameiro *et al*., 2018), localização da produção e deficiência na capacidade estática de armazenagem brasileira (ABCS, 2019). A necessidade de produção de várias dietas diferentes para atender as necessidades de cada categoria animal, transporte de insumos e animais favorecem esse aumento nos custos.

A partir de 2022 enfrentou-se queda nos preços de milho e soja (ABCS, 2022), além de aumento do faturamento e da produção (CNA & CEPEA, 2021). Além de se tornar uma atividade mais economicamente viável, há diversas exigências do mercado consumidor para desenvolver uma suinocultura mais sustentável. E não apenas como o principal gerador de custos na produção a alimentação dos suínos também tem grande participação no impacto ambiental. Novas estratégias alimentares e nutricionais podem ser utilizadas visando mitigar esses efeitos e atender demandas comerciais.

2.2 Sistemas de alimentação para suínos nas fases de crescimento e terminação

O sistema de alimentação para suínos mais empregado nas fases de crescimento e terminação é o de alimentação por fases. Onde uma mesma dieta é fornecida ao lote de animais durante um determinado período, a fase. O número de fases é variável, sendo sistemas de 3 a 5 fases mais comuns nessas etapas. Essas fases são mais preocupantes no quesito custo com alimentação, uma vez que cerca de 70% do rebanho está nessas fases e consomem maior parte da ração (Hauschild, 2010).

O sistema de alimentação por fases, por alimentar os animais em lotes com a mesma dieta, não leva em consideração diferenças individuais nas exigências nutricionais dos animais. Ignorando fatores como idade, sexo e genética, que são os principais responsáveis pela variação de exigência nutricional entre os indivíduos (NRC, 1998). As dietas empregadas são formuladas levando em consideração as exigências do animal médio da população (Hauschild *et al*., 2010), ocasionando na subalimentação, e mais frequentemente a superalimentação dos demais animais. Atender as exigências individuais dos animais é uma tarefa difícil, justamente porque as exigências mudam constantemente conforme a idade (Hong *et al*., 2016; NRC, 1998). O aumento no número de fases pode se aproximar da exigência real dos animais, porém problemas de armazenamento e logísticos são enfrentados (Pomar *et al*., 2014).

A superalimentação resulta em problemas metabólicos. Por exemplo níveis de proteína bruta além da exigência podem resultar em aumento da concentração de ureia no plasma sanguíneo (Fuller *et al*., 1987). Há relatos de que suínos nas fases de crescimento e terminação recebem 26% de lisina além do que realmente necessitam (Andretta *et al*., 2016). O excesso de lisina acima de 4% pode comprometer o ganho de peso em 16% e a eficiência alimentar em 5%, com cerca de 26% da lisina sendo eliminada na urina (Edmonds; Gonyou; Baker, 1987). Excesso e deficiência de fósforo (P) tem efeitos negativos na mineralização e saúde óssea (Sørensen *et al*., 2018) e um maior suprimento de cálcio e P pode resultar em menor ingestão de ração, menor ganho de peso e pior conversão alimentar (Oster *et al*., 2018). No geral, o excesso de nutrientes pode levar a queda do ganho de peso, do consumo de ração e redução da retenção de nutrientes, levando a diminuição da produtividade (Edmonds; Gonyou; Baker, 1987; Toue *et al*., 2006; Van Milgen *et al*., 2008). Ajustes na alimentação para atender as exigências mais corretamente tem o potencial de melhorar a eficiência de utilização dos nutrientes (Ferket *et al*., 2002; Pomar *et al*., 2014).

Diferenças nutricionais dependem de fatores como o sexo e a genética do animal. Na produção de suínos existem distintos grupos sexuais, o macho inteiro, macho castrado, macho imunocastrados, fêmeas inteiras e fêmeas imunocastradas. Quanto ao potencial de crescimento e deposição de proteína na carcaça machos inteiros possuem maior potencial do que fêmeas (Aymerich *et al*., 2020) e de que machos castrados (Noblet; Shi; Dubois, 1994). Consequentemente possuem uma maior exigência em lisina, justamente pelo maior potencial de deposição de proteína na carcaça. Outra classe sexual utilizada é a de machos imunocastrados, que se comportam como macho inteiro no início e como macho castrado após a aplicação da segunda dose de imunocastração (Škrlep *et al*., 2010), além de apresentarem melhor conversão e maior ganho de peso que os machos castrados cirurgicamente (Demori *et al*., 2015). Estes possuem maior exigência em lisina em comparação a machos castrados (Muniz *et al*., 2019), e maior consumo de energia e ganho de peso diário que machos castrados, fêmeas e machos inteiros (Broeke *et al*., 2022). Levar em consideração essas e outras diferenças não é tarefa fácil, no entanto ajuste ao sistema convencional de fases como o fornecimento de dietas personalizadas e ajustadas diariamente permite mitigar seus principais problemas da alimentação por fase (Pomar; Andretta; Hauschild, 2017).

2.3 Nutrição de precisão e modelagem matemática na nutrição de suínos

A nutrição de precisão consiste na aplicação de técnicas que permitem que os indivíduos (animais) recebam a dieta adequada tanto quantitativamente quanto qualitativamente no momento certo para cada animal (Pomar *et al*., 2009). Esse conceito complexo não considera apenas aspectos específicos da nutrição, mas outros, como a produção e armazenamento dos alimentos, monitoramento da qualidade e da composição nutricional dos ingredientes, infraestrutura e mão de obra qualificada para aplicar os conceitos, além de manejo alimentar (Branco & Harmon, 2012).

Para atender as demandas da nutrição de precisão, o conhecimento das exigências nutricionais de suínos é necessário. Nas fases de crescimento e terminação as exigências nutricionais podem ser estimadas pelos métodos empírico e fatorial. O método empírico segue uma metodologia de dose-resposta onde as exigências nutricionais para um determinado nutriente são estimadas avaliando a resposta de uma população de suínos alimentados com dietas contendo níveis crescentes de um nutriente estudado em determinado espaço de tempo e são estabelecidas para maximizar ou minimizar um ou vários parâmetros de desempenho (Hauschild, 2010b; Sakomura; Rostagno, 2007). Como as exigências nutricionais variam em função do genótipo, sexo, idade, peso vivo ou capacidade de consumo, o método empírico apresenta respostas adequadas somente para condições semelhantes às quais as curvas de exigências nutricionais foram determinadas (Siqueira, 2009).

O método fatorial estima as exigências com a soma das exigências de mantença e produção de uma população com base em um único indivíduo com o uso de modelos. O método leva em consideração as diferenças de pesos, composição corporal, potencial de crescimento e de produção dos animais, assim como o ambiente de criação. Por considerar os diferentes estados metabólicos dos animais, a abordagem fatorial permite a elaboração de modelos capazes de estimar as exigências nutricionais para diferentes linhagens e idades, em diferentescondições de produção (Sakomura; Rostagno, 2007).

Os modelos matemáticos tradicionais utilizam o suíno médio do grupo que recebe a mesma dieta que os demais para estimar a sua exigência em aminoácidos (Möhn *et al*., 2000). Ignorar as diferenças individuais resulta nos animais recebendo mais nutrientes do que realmente precisam (Hauschild *et al*., 2012). Nenhum dos métodos utilizados pelas fontes de exigências nutricionais fornece a precisão necessária para as exigências dos indivíduos. No entanto, fornecer dietas ajustadas diariamente utilizando técnicas de alimentação de precisão para os suínos permite diminuir o excesso de nutrientes fornecido na dieta (Pomar; Andretta; Hauschild, 2017).

2.4 Aspectos econômicos e ambientais

Dentre os benefícios da alimentação de precisão podemos citar a redução de custos, do impacto ambiental e melhoria produtiva. Alimentar os suínos com dietas personalizadaspermite redução de custos, principalmente na fase de crescimento e terminação (Hong *et al*., 2016; Pomar *et al*., 2011). Reduções consideráveis nos nutrientes podem ser alcançadas com baixo custo de implementação (Dubeau; Julien; Pomar, 2011), podendo chegar cerca de 10% dos custos com alimentação (Pomar *et al*., 2011). Práticas de precisão aplicadas na granja e nas fábricas de ração permite resultados economicamente interessantes e ambientalmente mais favoráveis.

O benefício econômico se dá principalmente pela redução do excesso de nutrientes na dieta, principalmente dos mais onerosos, como proteína (aminoácidos) e P. A redução de lisina em programas de alimentação de precisão pode chegar a 26% (Andretta *et al*., 2016) e de P pode chegar a 29% (Pomar *et al*., 2011). Esses nutrientes em excesso são associados a quedas na produtividade dos animais.

O excesso de nutrientes, especialmente nitrogênio (N) e P, no ambiente é fonte importante de poluição aquática e do solo (European Commission, 2020). A alimentação de precisão é um grande avanço na nutrição de suínos principalmente por seu impacto ambiental em reduzir cerca de 60% das perdas de nutrientes via excreta e dejetos (Pomar; Remus, 2019).

Em sistemas de alimentação de precisão a menor ingestão de N reduziu a excreção de N no ambiente em aproximadamente 12% (Pomar *et al*., 2007), 30% sem comprometer o desempenho dos suínos (Andretta *et al*., 2016) e mais de 38% (Pomar *et al*., 2011). Utilizando estratégias de redução dos níveis de proteína na dieta, a redução da excreção de N pode chegar a 35% (Monteiro *et al*., 2017). Segundo Dourmad & Jondreville (2007), a redução dos níveis de proteína na dieta, aliados ao melhor equilíbrio de aminoácidos na dieta são estratégias para melhorar a eficiência da utilização de N em suínos e, consequentemente, reduzir a excreção de N.

No caso do P, sua menor ingestão na dieta também ocasiona menores teores na excreta. Cerca de 45% do P ingerido é absorvido pelo animal, destes 30% é adsorvido e 15% são excretados por urina (Poulsen *et al*., 1999). No geral 70% do P ingerido é excretado através das fezes ou da urina. A utilização de fontes mais digestíveis e biodisponíveis de P além dos ajustes mais precisos das exigências de P na dieta são estratégias para reduzir o excesso nas excretas (Dourmad; Jondreville, 2007). A redução de P na dieta é reportado na faixa de 9,7% (Zhang; Pomar; Yang, 2011) e 4,4% (Pomar *et al*., 2014). Alinhando com redução na excreção de 6,6% (Pomar *et al*., 2014) e 30% (Zhang; Pomar; Yang, 2011). O P do dejeto suíno pode representar riscos de poluição ambiental e contribuir para a eutrofização de cursos d'água (Lautrou *et al*., 2021). Portanto, as estratégias precisas de estimativa e alimentação podem melhorar a utilização e a sustentabilidade da atividade suinícola.

O fornecimento de nutrientes insuficientes limita o crescimento potencial e a produção de animais, enquanto a alimentação com nutrientes em excesso reduz a lucratividade econômica e causa poluição ambiental (Hong *et al*., 2016). Além disso, a alimentação de precisão pode utilizar margens de segurança mais baixas do que a alimentação convencional (Pomar; Remus, 2019) gerando menor impacto ambiental, resultados econômicos e produtivos positivos.

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CAPÍTULO I: A SIMPLIFIED MATHEMATICAL MODEL TO REDUCE COSTS AND NUTRIENT INTAKE IN GROWING-FINISHING PIGS

RESUMO

A alimentação de precisão emerge como uma excelente alternativa aos sistemas convencionais de alimentação em fases para suínos em crescimento e terminação, especialmente com o aumento dos custos de alimentação e preocupações com a sustentabilidade ambiental. No entanto, as estratégias de alimentação de precisão às vezes requerem tecnologias avançadas, como dispositivos eletrônicos e a modernização das instalações de suínos. Além da implementação de hardware, a alimentação de precisão frequentemente está relacionada a dificuldades matemáticas devido à falta de profissionais treinados em tomada de decisão. Portanto, este estudo compara dois modelos, um modelo convencional de alimentação em fases (CON) e um modelo de ajuste diário (DFM) com uma abordagem simplificada para o uso consciente de nutrientes na produção de suínos. Um estudo de simulação foi conduzido usando curvas de crescimento de suínos machos castrados, seguindo três recomendações nutricionais para alimentação em fases convencionais, Tabelas Brasileiras para suínos e aves, NRC e AGPIC, uma linhagem comercial de suínos. Uma vez determinados os requisitos nutricionais para o CON, essas dietas foram usadas para o DFM antecipando uma porcentagem proporcional da próxima fase da dieta na dieta atual. Este ajuste simples não prejudica o desempenho de crescimento dos suínos. No entanto, neste estudo, o DFM mostrou-se promissor durante as fases de crescimento e terminação para reduzir os custos dos suínos e a ingestão de nutrientes, como proteína bruta, lisina e fósforo digestível, em até 5,58, 7,11 e 9,13%, respectivamente. Em conclusão, o DFM pode reduzir custos, minimizar o impacto ambiental e promover práticas sustentáveis. Além disso, esta estratégia simplificada de alimentação de precisão desempenha um papel vital nos desafios enfrentados pelos criadores de suínos.

Palavras-chave: Alimentação de precisão, Gerenciamento de nutrientes, Nutrição de suínos, Suinocultura sustentável

ABSTRACT

Precision feeding emerges as an excellent alternative to conventional phase feeding systems for growing-finishing pigs, especially with increasing feeding costs and environmental sustainability concerns. However, precision feeding strategies sometimes require advanced technologies such as electronic devices and the modernization of pig facilities. Besides hardware implementation, precision feeding is frequently related to mathematical difficulties due to a lack of professionals trained in decision-making. Therefore, this study compares a conventional phase feeding model (CON) and a daily fit model (DFM) with a simplified approach to the conscious use of nutrients for pig production. A simulation study was conducted using growth curves of barrow pigs, following three nutritional recommendations for conventional phase feeding, Brazilian Tables for swine and poultry, NRC, and AGPIC, a commercial lineage of pigs. Once the nutrient requirements for CON were determined, these diets were used for the DFM by anticipating a proportional percentage of the next phase diet in the current diet. This simple adjustment does not impair the growth performance of pigs. However, in this study, the DFM showed promising during the growing-finishing phases to reduce pigs' costs and nutrient intakes, such as crude protein, lysine, and digestible phosphorus, up to 5.58, 7.11 and 9.13%, respectively. In conclusion, the DFM can reduce costs, minimize environmental impact, and promote sustainable practices. Also, this simplified precision feeding strategy plays a vital role in the challenges swine farmers face.

Keywords: Feed Cost Reduction, Nutrient Management, Precision Feeding, Sustainable Pig Farming, Swine Nutrition

4 INTRODUCTION

Precision feeding (PF) is a strategic approach to curtailing feed expenditures, setting itself apart from the conventional phase feeding system. This approach aims to provide the pigs with the correct quantity and composition of feed at the right moment (Pomar *et al*., 2009). Conversely, phase feeding entails altering the nutrient content of pig diets during various stages or phases of their growth to better align with their evolving daily nutritional needs (McBride & Key, 2007). This strategy causes a nutrient oversupply, especially in pigs with lower nutrient requirements (Misiura *et al*., 2021). The economic advantages of precision feeding are substantial, particularly within growing-finishing pig facilities (Brossard *et al*., 2014; Niemi *et al*., 2010; Pomar *et al*., 2011, 2009). Variability among individual pigs due to factors such as age (NRC, 1998), sex, and genetics leads to significant differences in their nutritional requirements (Brossard *et al*., 2009).

Despite advanced research on the benefits of PF for pigs, some challenges still need to be addressed. Challenges like the high cost of adoption, technology-related difficulties, lack of professional support, and lack of supporting policies. These are the farmers' main concerns regarding adopting precision technologies (Mizik, 2023). Complex technologies face difficulties in being adopted adequately, especially because some technicians and owners need to be trained to use these tools and evaluate the data collected (Tekin *et al*., 2021). With PF approaches to financial and logistics challenges (Pomar and Remus, 2023), strategic decisions must be made to adopt these technologies.

In growing-finishing pig facilities, phase feeding is the most common feeding strategy. Its disadvantage is the excess of nutrients provided in the diet due to its higher security margins during the formulation of diets. A daily adjustment to the diet can draw nearer to the pigs' actual nutritional requirements, reducing the intake of nutrients in excess. PF reduces the surplus nutrients in pig diets (Pomar *et al*., 2011). Reduction of nutrients like phosphorus (P) and crude protein (CP) results in decreased P (Rodehutscord *et al*., 1999) and nitrogen (N) excretion (Andretta *et al*., 2016; Pomar *et al*., 2014).

This article aims to compare a conventional feeding system (CON) with a daily adjustment model (DFM). This modeling framework was applied to evaluate the effectiveness of the DFM over the CON. These evaluations were conducted by considering the response of a barrow. The specific objectives were to: (1) determine the economic vantage of the DFM in reducing costs; (2) determine the vantage of the DFM in reducing nutrient intake by the pigs; (3) simulate the results of these models in three scenarios of feed formulation, using the Brazilian tables for poultry and pigs (Rostagno, 2017), the NRC (2012) and AGPIC (2021).

5 MATERIAL AND METHODS

5.1 Data collection and scenario definition

Data from 11 feeding curves of pigs from four distinct sex categories, with varying initial weights and daily feed intakes, were collected. These feed intake and growth curves were obtained from a comprehensive database containing records of over 1,000,000 animals. Three operational pig farms provided commercial data. Pigs were kept in commercial conditions (ad-libitum access to water and feed, group housing, ambient room temperature of 20-24°C) for 120-150 days.

Information on average daily feed intake (ADFI), average daily gain (ADG), breed, gender, initial weight, final weight, and age from barrows was selected for the simulations. With an initial body weight of 20.61 ± 0.85 kg, they reached a final body weight of 138.94 ± 0.90 kg over a 120-day growing-finishing period. All collected data were tabulated for subsequent analysis and modeling purposes.

Three distinct scenarios were divided, adhering to the barrow requirements outlined in the Brazilian tables for poultry and swine (Rostagno, 2017), the National Research Council (NRC, 2012), and the commercial lineage AGPIC (PIC, 2021). These scenarios assessed and compared two feeding models: the conventional 5-phase feeding model (CON) and the daily fit model (DFM).

For each scenario, ADFI and ADG data from the barrows were employed to evaluate the two feeding systems: the 5-phase system, which entails supplying the same diet to all pigs within the group during each proposed phase, and the daily feeding system, which adjusts the diet based on the nutritional requirements of pigs as they age. The daily feeding system anticipates the subsequent diet through daily adjustments. In the simulations, five feed phases were considered, each with varying durations in days, determined by the weight range of the animals (Table 1).

Table 1. Specifications of the simulations

Phase	Duration of the phase (days)	Weight range (kg)
1	24	20-35
2	29	35-60
3	29	60-90
4	16	90-110
5	22	>110

5.2 Model Description

Two models were employed to facilitate a comparison of the feed systems. The first model, the conventional model (CM) (1), calculates feed costs in the CON, taking into account the duration of the feeding phase (DP), feed price (FP) within each phase, and feed intake (FI) during the respective phase (P). The total cost is derived by summing the costs of all phases, depending on the number of feeding phases employed.

$$CM = \sum_{i=P}^{N} (DP_i \times FP_i \times FI_i) \qquad (1)$$

The second model (DA; 2) computes daily feed costs by considering the total cost of feed used (TCf) and daily feed intake (DFI). Calculating the total cost value (TCf) requires knowledge of the amount of feed intake (AFI) and the corresponding feed prices (FP) (3). A summary of these models is presented in Table 2.

$$DA = \sum_{i=P}^{N} (TC_f \times DFI) \qquad (2)$$

$$TC_f = (AFI_1 x FP_1) + (AFI_2 x FP_2) \qquad (3)$$

These models can also be applied to predict nutrient reduction. Instead of price, the input is adjusted to reflect the quantity of nutrients in the diet. After model construction, results were compiled, organized, and tabulated in a Microsoft Excel® spreadsheet to create a comprehensive database and facilitate the development of models for calculating excessnutrient reduction in diets and feed costs. An automated spreadsheet was designed to enhance the practical application of these models.

Table 2. Model description

Equation	Description
DP	Phase duration in days
FP	Feed price
FI	Feed intake
P	Phase
DFI	Daily feed intake
FP_1 e FP_2	The price of feed 1 and 2 used
AF_1 =100-PD	Amount of feed 1
PD = (100/d) x (D-1)	Phase duration
d	Phase day
D	Production day
$AFI_2 = 100 – AFI_1$	Amount of feed 2

5.3 Formulation of Virtual Feeds

Diets were formulated employing the solver procedure available in Microsoft Excel. For the simulations, six diets were devised, guided by the nutrient requirements for barrows established in the Brazilian tables for poultry and swine (Rostagno, 2017), NRC (NRC, 2012), and AGPIC (PIC, 2021). The sixth feed diluted the fifth feed, with details on the diets provided in Supplementary Tables S1-S2.

5.4 Simulation Study

Three models were employed to estimate the requirements of Standard Ileal Digestible Lysine (SID Lys): BT-2017 from the Brazilian Tables, the NRC-2012 model, and the AGPIC-2021 model. The NRC-2012 model underwent slight modifications to enhance comparability between the models, akin to the approach in (Remus *et al*., 2020). The simulated Metabolizable Energy (ME) content was set at 3.4 Mcal.

Model BT-2017

SID Lys requirement (g/day) = 0.036 x BW0.75 + Y x ADG (4)Where Y= 16.664 + 0.0736 x BW – 0.0003 x BW^2

BW= body weight

Model NRC-2012

Lysine losses (g/day) = DFI x 0.417 x 0.88 x 1.1 (5)

Integument Lys losses (g/day) = 0.0045 x BW0.75 (6)

SIDLysM (g/day) = [((Eq(2)+Eq(3))/(0.75 +0.002))x (Maximum PD) – 147.7)] (7)

Lys retained in PD (g/day) & Non – ractopamine – indiced = (PD x 7.10)/100 (8)

SIDLysG (g/day) = {(Lys retained in PD)/([0.75 + 0.002 x (maximum PD - 147.7)])}/(1 + 0.0547 + 0.002215 x BW) (9)

Pd barrows (g/day) = (133) x (0.7078 + 0.013764 x BW – 0.00014211 x BW^2 + 3.2698 x 10-7 x BW^3) (10)

PD and Pd = Protein deposition

Model AGPIC-2021

SID Lys for barrows if weight is < 40 kg = 0.0000255654 × (weight,kg × 2.204622)^2 - 0.0157978368 × (weight,kg × 2.204622) + 4.4555073859 (11)

SID Lys for barrows if weight is > 40kg = Eq 11 + (- 0.0000000031 × (weight, kg + 0.0000013234 × weight, kg^3 - 0.0002087068 × weight, kg^2 + 0.0142221655 × (weight, kg - 0.3126825057] × Eq 11 (12)

In addition to SID Lys intake comparisons, weekly calculations were conducted for CP intake, assessing differences between the CON and DFM. The evaluation of SID Lys intake compared the percentage of SID Lys in the daily diet with the requirement for each scenario on the first day of each feeding phase. Moreover, Cumulative CP, Amino Acid (AA), Total N, and standardized total tract digestible Phosphorus (STTD P) were compared across the models. Finally, the disparity in feed costs ($) between the application of the CON and DFM was analyzed. The conversion from Brazilian reais to US dollars was performed using an exchange rate of 5.05 reais per dollar—value taken on 05/04/2023.

6 RESULTS

6.1 SID Lys requirements

The nutrient requirements from different recommendations between NRC-2012, BT-2017, and AGPIC-2021 showed essential variations in curves of SID Lys to calorie ratio of Metabolizable Energy (ME) (Figure 1). These factorial methods provide valuable estimations of nutrient requirements for pigs reared in large groups and subjected to extended periods of uniform feed consumption throughout their production cycle.

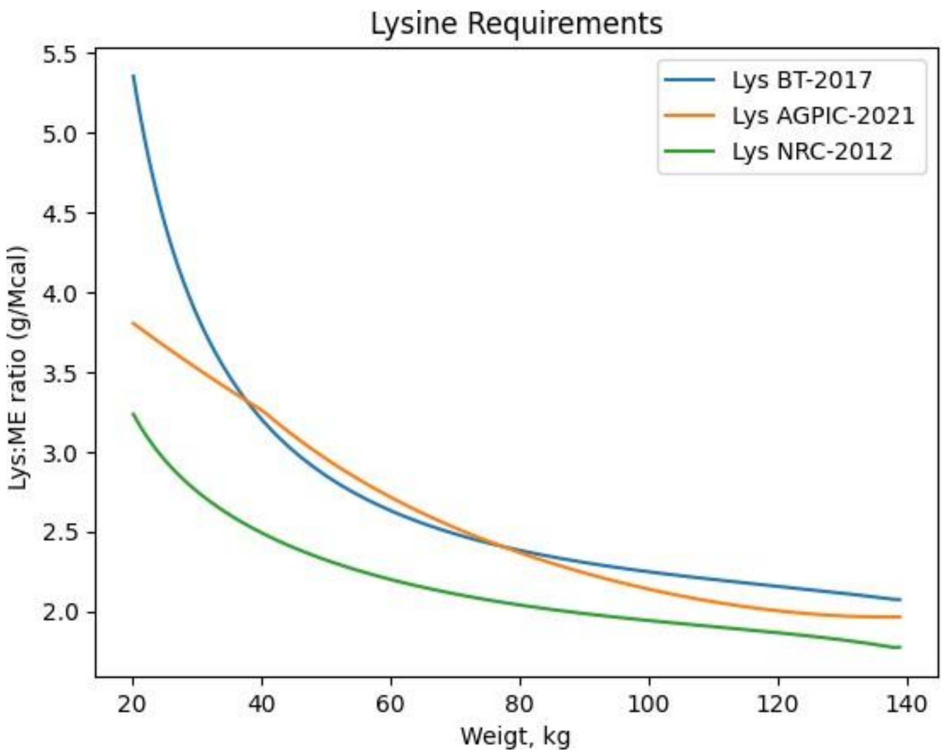

Figure 1. Lysine requirements for growing-finishing barrows follow the Brazilian Tables (BT-2017), NRC (NRC-2012), and AGPIC (AGPIC-2021) requirements. The simulated Metabolizable Energy (ME) content was set at 3.4 Mcal.

6.2 Crude protein and amino acid intake

Across all scenarios, our simulations consistently showed reduced nutrient intake when employing the DFM compared to the CON. This reduction encompassed essential components such as protein, AA, and P, ultimately decreasing feed costs.

Figure 2 illustrates changes in weekly CP consumption between DFM and CON, showing a more significant reduction in the BT-2017 compared to NRC-2012 and AGPIC-2021 scenarios. The total CP intake accumulated also shows reductions (Figure 3) for the BT-2017, NRC-2012, and AGPIC-2021 of 6.77, 4.72, and 5.38%, respectively. The period of these differences they were also varied among the modeled scenarios. The reductions of CP in the BT-2017 and NRC-2012 scenarios started from the 6th week and coincided with the transition between phase 2 and phase 3. In the AGPIC-2021 scenario, the DFM initiated CP reductions after nine weeks (during the shift from Phase 2 to Phase 3). These reductions were most pronounced during the 11th week in BT-2017 and NRC-2012, with differences of 552 g and 225 g, respectively, and during the 14th week in the AGPIC-2021 scenario, with the most substantial difference amounting to 369 g. These discrepancies corresponded with feed phases 4 and 5, where the DFM's ability to align CP requirements with the pigs' actual needs closely resulted in enhanced CP intake reduction.

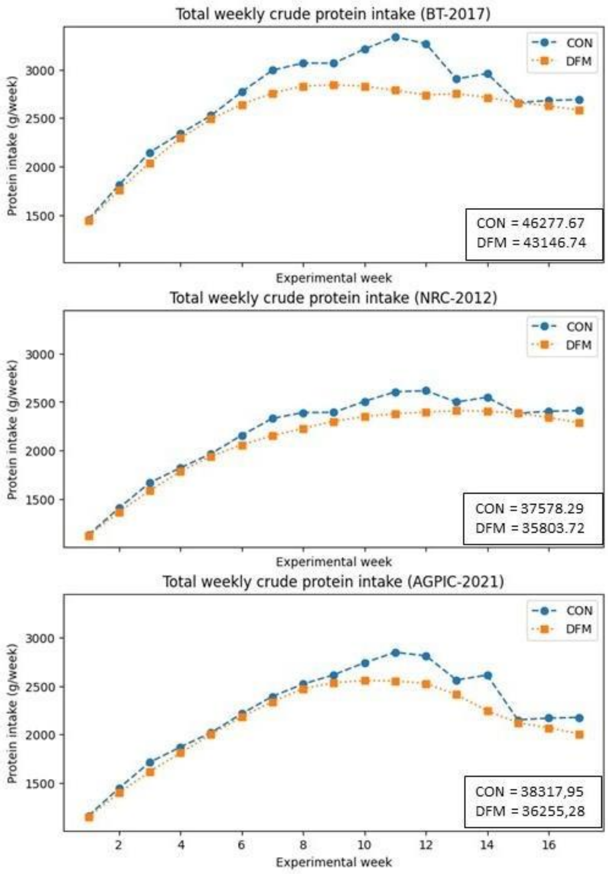

Figure 2. Total weekly crude protein intake in the proposed scenarios. A: BT-2017; B:NRC-2012; C: AGPIC-2021.

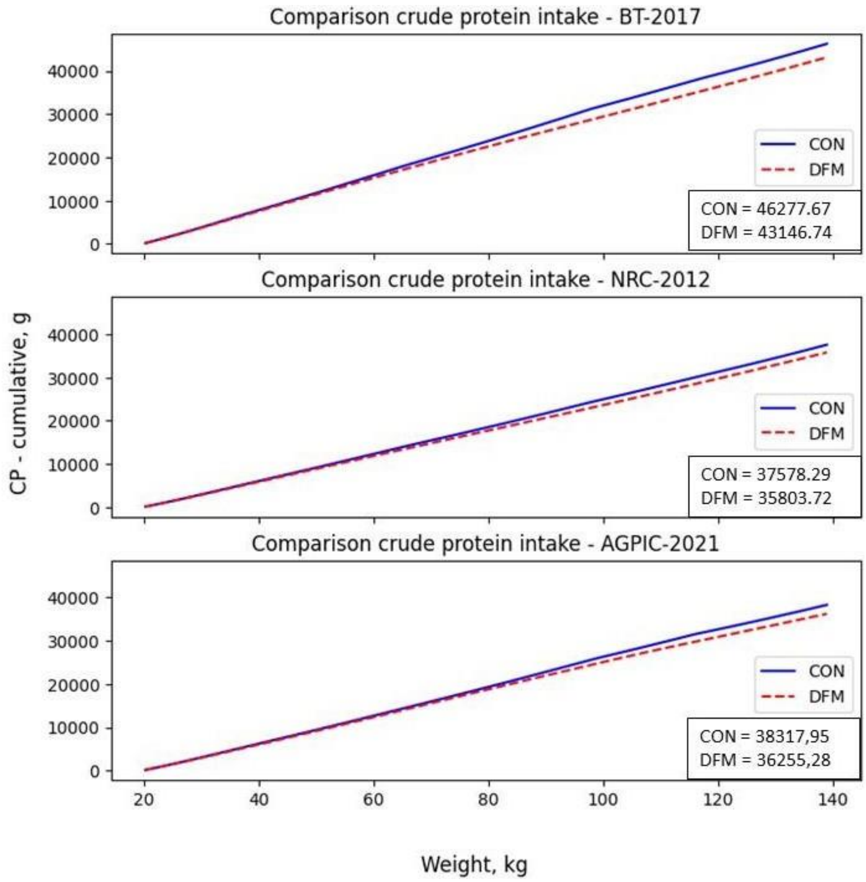

Figure 3. Cumulative crude protein intake (g) in the diet in the proposed scenarios. A: BT-2017; B: NRC-2012; C: PIC-2021.

When comparing the diets' lysine content among the scenarios (Figure 4), it becomes evident that applying the DFM consistently leads to lower lysine intake across all scenarios. Similar reductions are observed in the diet's levels of other essential AA, with a decrease in quantity evident when employing daily adjustment models (Figure 5).

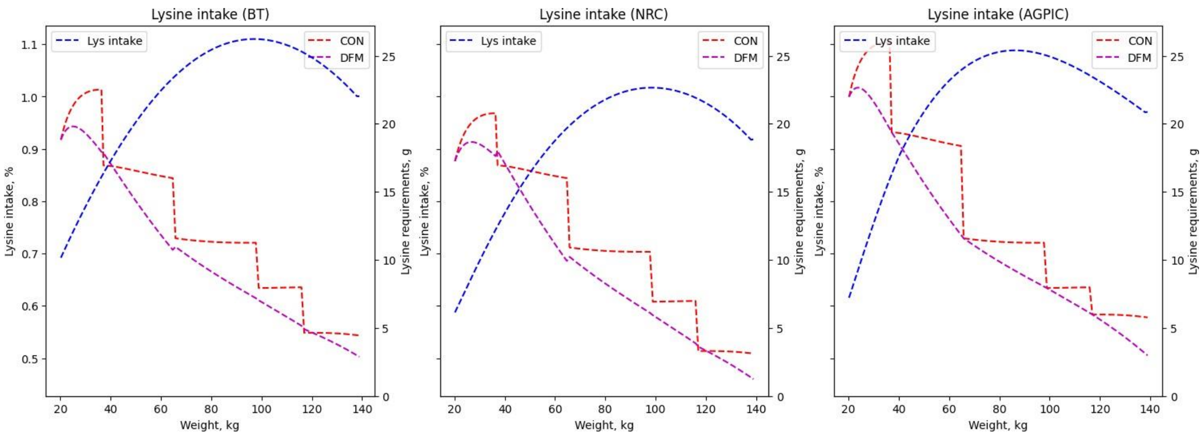

Figure 4. Lysine in the feed (%) in the proposed scenarios and lysine requirements following the Brazilian Tables (BT-2017), NRC (NRC-2012), and AGPIC (AGPIC-2021) requirements and lysine intake (g). A: BT-2017; B: NRC-2012; C: PIC-2021. Abbreviations: CON = Conventional Phase Feeding Model; DFM = Daily Fit Model; Lys intake = Lysine requirements.

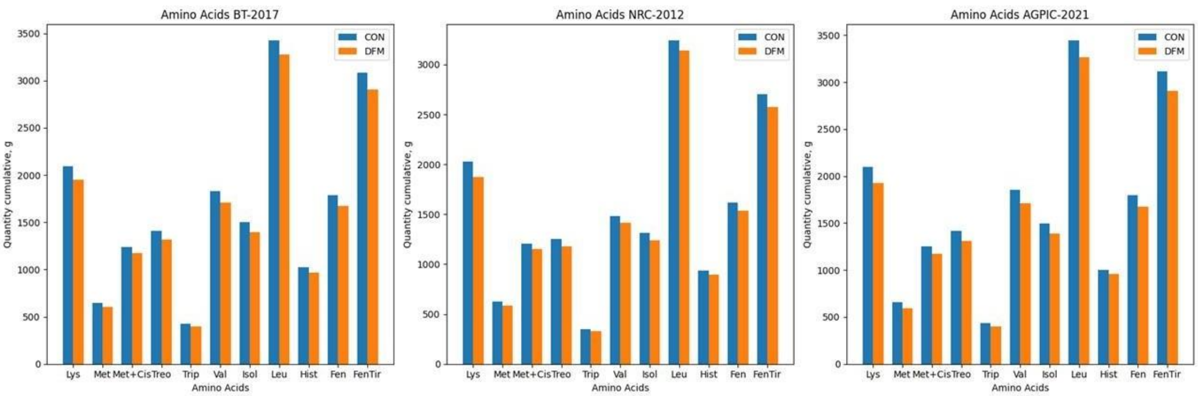

Figure 5. Cumulative amino acid intake (g) in the proposed scenarios. A: BT-2017; B:NRC-2012; C: PIC-2021. Abbreviations: CON = Conventional Phase Feeding Model; DFM =Daily Fit Model.

6.3 Total nitrogen and phosphorus intake

The CON showed that pigs consumed more CP in all scenarios. In contrast, the DFM reduced the CP in the diet and, consequently, the CP intake of pigs. In the BT-2017, NRC-2012, and AGPIC-2021 scenarios, the daily adjustment model reduced total accumulated dietary N by 6.77%, 4.72%, and 6.21%, respectively (Figure 6).

The DFM also reduced P intake in the simulation. In the BT-2017, NRC-2012, and AGPIC-2021 scenarios, the diet's STTD P content was decreased by 10.87%, 5.28%, and 6.18%, respectively (Figure 7). Notably, in the NRC-2012 and AGPIC-2021 scenarios, the differences become more prominent from 70.0 kg of BW, while in the BT-2017 scenario, these disparities become evident from 100.0 kg of BW onwards.

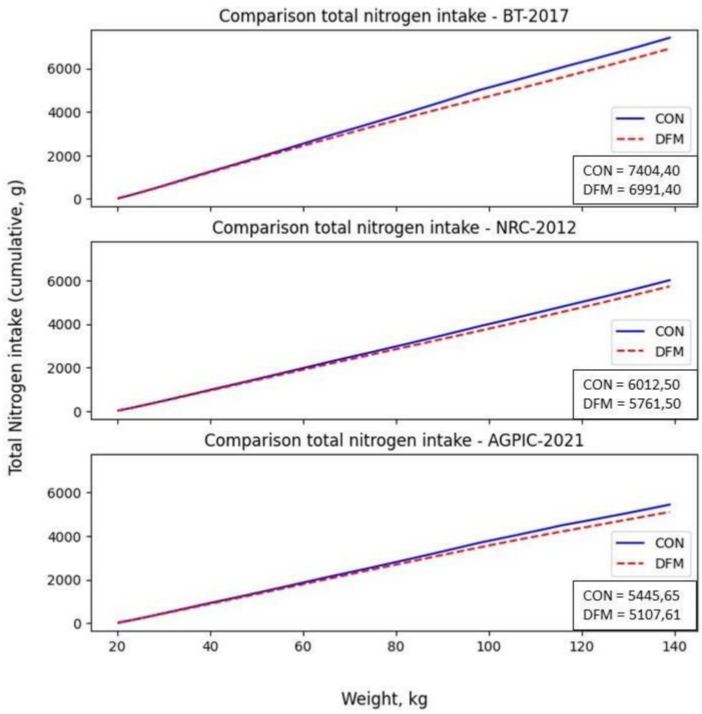

Figure 6. Total nitrogen in the diet (g) in the proposed scenarios. A: BT-2017; B: NRC-2012; C: AGPIC-2021. Abbreviations: CON = Conventional Phase Feeding Model; DFM = Daily Fit Model.

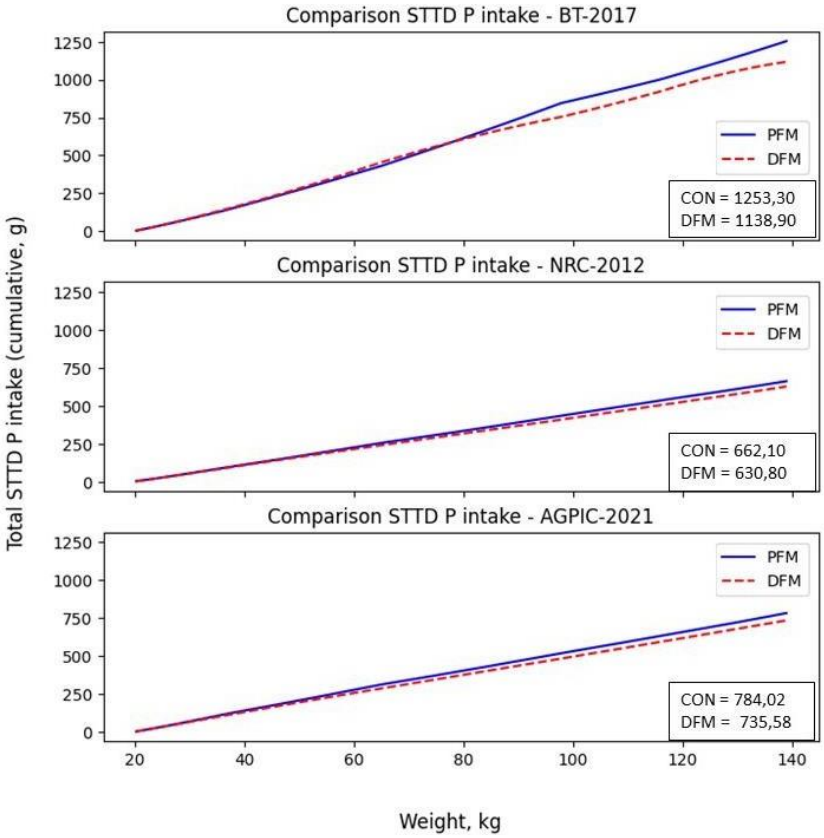

Figure 7. Total STTP intake in the diet (g) in the proposed scenarios. A: BT-2017; B: NRC-2012; C: AGPIC-2021. Abbreviations: CON = Conventional Phase Feeding Model; DFM = Daily Fit Model.

6.4 Cost reduction

Table 3 provides a comprehensive overview of the DFM cost-saving potential compared to conventional models across the three proposed scenarios. Notably, the NRC-2012 scenario yields the most substantial cost reduction, with a $2.58 decrease in feed costs. They were followed by the AGPIC-2021 and BT-2017 scenarios, with $2.27 and $2.04 respectively. The simulations underscore the considerable cost-saving potential of the DFM in optimizing feed expenditure.

Table 3. Comparison of feed costs in the proposed scenarios

Item	BT-2017	NRC-2012	PIC-2021
Feed cost ($/pig) CON	94.12	108.11	100.80
Feed cost ($/pig) DFM	92.09	105.54	98.53
Feed cost ($/pig) RED	2.04	2.58	2.27

Abbreviations: CON = Phase Feeding Model; DFM = Daily Fit Model; RED = Reduction.

7 DISCUSSION

7.1 Nutrient Reduction

The evident cost reduction among the selected scenarios can be primarily attributed to the reduced excess nutrients in the diet. Conventional phase-fed pigs often receive more nutrients than their requirements during the growing-finishing phase. Typically, these requirements are formulated based on average pig values (NRC, 2012), overlooking individual variations within the phase. Such variations are influenced by age, sex, and genetic potential (Möhn *et al*., 2000; Noblet & Quiniou, 1999). Strategies for precision feeding have emerged as a promising approach to mitigate this issue by tailoring diets to align more closely with individual animal requirements (Brossard *et al*., 2009; Ferket *et al*., 2002; Pomar *et al*., 2014).

Conventional phase feeding systems typically involve formulating three to five diets, and while increasing feeding phases can help reduce nutrient excess, it also complicates feed management (Pomar & Remus, 2019). On the other hand, implementing and managing precision feeding systems are associated with costs and structural modifications. Moreover, utilizing automated feeding systems may only be economically viable for some pig farmers, with site-specific economic profitability (Griffin *et al*., 2018). Nevertheless, these nutrient adjustments have the potential to increase nutrient efficiency (Ferket *et al*., 2002; Pomar *et al*., 2014), reduce lysine intake (Andretta *et al*., 2016), and ultimately lower overall costs (Pomar *et al*., 2011).

The reduction in CP intake, as depicted in Figures 2 and 3, exemplifies the efficacy of the Daily Fit Model (DFM). The model anticipates the subsequent diet and blends it with the current one, resulting in a reduction of nutrients and, consequently, a cost reduction in feeding. Notably, the most relevant CP decreases are observed in phases 3 to 5, where pigs exhibit higher feed intake. Failure to balance these diets during this period can lead to environmental concerns. In addition to applying the proposed DFM, low-CP diets are worth considering, particularly in the finishing phase. Studies have indicated that low CP diets supplemented with appropriate AA do not compromise pig growth performance, nutrient digestibility, or meat quality (Han *et al*., 2023).

While the AA requirements of pigs naturally decrease during the growth phase, the diet's concentration needs to be adjusted (NRC, 2012). Nevertheless, excess AA persists in conventional feeding systems. Notably, the NRC-2012 and BT-2017 models can estimate SID Lys to maximize average daily gain (ADG) but cannot account for within-herd variation (Remus *et al*., 2020). In the scenarios presented in this study, the maximum lysine reduction reached 7.55% for group-fed pigs. For individual precision-fed pigs, SID lysine reductions can reach up to 26% (Andretta *et al*., 2016). Nevertheless, these results still indicate the efficacy of the DFM in improving nutrient efficiency without compromising pig performance.

Excess lysine in the diet, exceeding 4%, has decreased weight gain by 16% and feed efficiency by 5%, with up to 26% of lysine excreted in urine (Edmonds *et al*., 1987). Pigs fed a high lysine diet produce more heat than those given low lysine diets (Noblet; Henry; Dubois, 1987), and more energy is diverted to thermoregulation than protein deposition. Another motive for the decrease in weight gain is the decrease in feed intake, inhibiting hunger in pigs (Müller et al., 2024). This excess needs to be more environmentally sustainable and economically viable. As observed with the DFM, reducing the excess of essential AA can also lower feeding costs. Conventional models for estimating AA requirements in growing-finishing pigs (NRC-2012 and BT-2017) tend to overestimate lysine requirements compared to the average pig (Remus *et al*., 2020).

In summary, the oversupply of nutrients beyond the pig's requirements can lead to growth depression, reduced feed intake (Edmonds *et al*., 1987), decreased ADFI and ADG (Toue *et al*., 2006), and reduced nutrient retention (Van Milgen *et al*., 2008). Once imbalances in AA can further impair growth and feed intake, to improve the efficiency of nutrient utilization in pigs, it is crucial to align nutrient supply as closely as possible with individual animal requirements, thus limiting oversupply (Gaillard *et al*., 2020).

The oversupply of AA and P in pig diets raises environmental concerns. Higher concentrations of urea in the blood plasma (Fuller *et al*., 1987), limited protein synthesis, increased deamination, increased feed costs, and N excretion of pigs result from the abovementioned excesses. Lowering CP diets can effectively reduce urea concentration in blood plasma (Remus *et al*., 2019), limit protein synthesis, increase deamination (Pasquetti *et al*., 2015), and reduce costs and N excretion by 1.5% for every percentage unit of CP reduction (Andretta *et al*., 2016; Esteves *et al*., 2021) maintaining the growth performance of pigs (Hong *et al*., 2016).

7.2 Reduction of total N and STTD P

The reduction of total N in the diet reduces N excretion. The highest reduction observed in this study was 6.77% in the BT scenario. Other studies have reported even higher reductions in N intake, ranging from 17% (Zhang *et al*., 2011) to 25% (Pomar *et al*., 2011; Zhang *et al*., 2011) in daily tailored diets compared to conventional phase feeding without compromising pig performance. This reduction is possible because pig diets are traditionally formulated with generous safety margins to ensure maximum population responses (Pomar *et al*., 2021).

This reduction in N excretion aligns with findings from other studies. Pomar *et al*. (2014) observed that pigs subjected to group precision feeding excreted 12% less N than pigs in the three-phase program. Andretta *et al*. (2016) found that N excretion could be reduced by over 30% when comparing individual precision-feeding pigs to phase-feeding pigs. In essence, precision feeding can enhance N efficiency (Ait-Sidhoum *et al*., 2021) and effectively reduce nutrient losses, given that nearly all animals tend to receive more nutrients than they require (Andretta *et al*., 2016).

Another nutrient frequently present in excess in pig diets is P. As the third most expensive nutrient in pig diets (Fan *et al*., 2001; Saraiva *et al*., 2009), often sourced from non-renewable resources, reducing digestible P content in diets can have significant implications. In this study, reductions in digestible P intake ranged from 5.28% to 10.87% in the BT-2017, NRC-2012, and AGPIC-2021 scenarios. These reductions align well with results obtained by Zhang *et al*. (2011) and Pomar *et al*. (2014), who reported reductions of 9.7% and 4.4% in P intake, respectively.

Reducing P excretion is also achieved, with decreases of 6.6% (Pomar *et al*., 2014) and 30% (Zhang *et al*., 2011) reported in other studies. It is crucial to note that P is not fully absorbed from pig diets, with approximately 45% of ingested P being absorbed, 30% retained, and the remaining 15% excreted in urine in diets based on soybean bran and cereals (Poulsen *et al*., 1999). P from swine manure can pose environmental pollution risks and contribute to waterway eutrophication (Lautrou *et al*., 2021). Hence, precise P estimation and feeding strategies can improve P utilization and enhance the sustainability of swine farming.

The N and P, considered critical nutrients, have higher environmental pollutant potential (Lautrou *et al*., 2022). The application of nutritional technologies in pig diets has been shown to reduce pig manure production and N and P nutrient levels compared to control diets (Afonso *et al*., 2020). Implementing individual daily feeding programs has the potential to decrease N excretion by 1.5% for each percentage unit of protein intake reduction (Andretta *et al*., 2016), reducing both N and P excretion (Jiang *et al*., 2023). Overall, reducing nutrient oversupply can help mitigate the environmental footprint of pig production in Brazil, resulting in reduced acidification, eutrophication, land occupation, and lower costs (Andretta *et al*., 2016; Esteves *et al*., 2021; Kebreab *et al*., 2016; Monteiro *et al*., 2016).

7.3 Cost Reduction

The proposed DFM demonstrates the potential to reduce feeding costs by nearly 2.4% in the simulations (Table 3). This reduction, although modest, is essential for advancing production, especially given the high international demand for pork (USDA, 2023). This reduction can be attributed to the dilution of the supplied feed. At the beginning of the growth phase, pigs have higher nutrient demands, which gradually decrease as they approach the finishing phase. This cost reduction is mainly influenced by lower CP and STTD P content, which are the second and third most expensive nutrients.

Feeds are conventionally formulated with ample safety margins and excess nutrients to maximize population responses, making it likely that adjusting diets closer to actual requirements will lead to reduced excess nutrient intake and, consequently, lower feeding costs (Remus *et al*., 2019). Feeding programs involving individually tailored diets and multi-phase feeding have been shown to result in a 10% reduction in feeding costs compared to conventional feeding programs (Andretta *et al*., 2016; Dubeau *et al*., 2011; Monteiro *et al*., 2017; Pomar *et al*., 2014). Furthermore, along with reduced feed costs, implementing adjusted nutritional levels and novel formulation methods aimed at improving nutrient utilization efficiency and reducing nutrient excretion by pigs is highly recommended due to their cost-effectiveness and applicability (Monteiro *et al*., 2017).

8 CONCLUSIONS

In summary, the proposed DFM demonstrates its potential not only in cost reduction but also in reducing nutrient intake among pigs during the crucial growing-finishing phase. The economic advantage of reducing feed expenses is a compelling incentive for swine farmers to adopt precision feeding techniques. Moreover, the reduction in nutrient intake holds promise from an environmental perspective, as it can mitigate the impact of swine manure on the environment. While more developed models may be available, this simplified approach of anticipating subsequent diets can be applied through a user-friendly spreadsheet. This approach incentivizes integrating advanced precision feeding technologies in the expanding global pig farming industry and aligns with the principles of productivity and sustainability.

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CAPÍTULO II: A LIFE CYCLE ASSESSMENT OF A DAILY FEED ADJUSTMENT IN GROWING-FINISHING PIGS DIETS

RESUMO

A alimentação, junto do manejo de dejetos e a produção de suínos são os fatores que que mais influenciam no impacto ambiental na suinocultura. Estratégias que possam mitigar esses efeitos como alimentação de precisão e uso de alimentos alternativos na dieta dos suínos podem ser empregados. Propostas mais simples como um ajuste nutricional diário também é uma opção. Este estudo explorou as implicações ambientais de duas estratégias alimentares na suinocultura, com foco em três cenários de formulação de dietas: tabelas brasileiras (BT-2017), NRC (NRC-2012) e AGPIC (AGPIC-2021). A comparação envolve modelos convencionais de alimentação em fases (CON) e modelos de ajuste diário (DFM). Empregando uma abordagem do berço à porteira, este estudo avaliou o impacto do ciclo de vida considerando fatores como acidificação, mudanças climáticas, ecotoxicidade, eutrofização, toxicidade humana, uso da terra, uso de terra, água, uso de recursos minerais, metais e fósseis. A análise foi conduzida usando o software OpenLCA e o método de avaliação de impacto Environmental Footprint (EF) 3.0. As comparações entre diferentes cenários de alimentação, abrangendo as abordagens CON e DFM em várias categorias de impacto, resultaram em diferenças que variam de 0,1 a 12% de redução do impacto ambiental nos modelos DFM. Demonstrando consistentemente suas vantagens ambientais em áreas como mudanças climáticas, eutrofização, acidificação, ecotoxicidade, uso de recursos e toxicidade humana. Notavelmente, o impacto das variações na formulação de alimentos entre os cenários (BT-2017, NRC-2012, AGPIC-2021) destaca a necessidade de tomada de decisão cuidadosa em relação aos requisitos de nutrientes, sem que uma solução única seja evidente. Técnicas de alimentação de precisão, juntamente com estratégias como a redução dos níveis de proteína bruta e a suplementação com aminoácidos sintéticos na dieta, emergem como meios eficazes de reduzir as pegadas ambientais, oferecendo caminhos práticos e acessíveis rumo à sustentabilidade na produção de suínos. No impacto de mudança climática por uso da terra a redução alcançou 12,55% ao empregar o DFM. Outras categorias de impacto como ecotoxicidade de água doce, toxicidade humana cancerígena e uso de recursos minerais e metais obtiveram reduções nas faixas de 5,05%, 3,84%, 6,12% respectivamente ao empregar o DFM. Os resultados destacam o papel crítico da produção de alimentos na condução dos impactos ambientais, enfatizando assim a importância da adoção de técnicas de alimentação de precisão e estratégias alternativas para mitigar esses efeitos de forma eficaz. O estudo contribui para o avanço da compreensão das práticas sustentáveis na produção de suínos, abrindo caminho para a adoção de abordagens mais sustentáveis que promovam o gerenciamento ambiental e a viabilidade de longo prazo na indústria.

Palavras-chave: Meio ambiente; Nutrição de suínos; Suinocultura; Sustentabilidade

ABSTRACT

Feeding, waste management, and pig production are the factors that most influence the environmental impact of swine farming. Strategies that can mitigate these effects, such as precision feeding and using alternative feeds in pig diets, can be employed. More straightforward proposals, such as daily nutritional adjustment, are also an option. This study explored the environmental implications of two feeding strategies in swine farming, focusing on three diet formulation scenarios: Brazilian tables (BT-2017), NRC (NRC-2012), and AGPIC (AGPIC-2021). The comparison involves conventional phase feeding models (CON) and daily adjustment models (DFM). Employing a cradle-to-gate approach, this study evaluated the life cycle impact considering factors such as acidification, climate change, ecotoxicity, eutrophication, human toxicity, land use, water use, and the use of mineral, metal, and fossil resources. The analysis was conducted using OpenLCA software and the Environmental Footprint (EF) 3.0 impact assessment method. Comparisons between different feeding scenarios, covering CON and DFM approaches in various impact categories, resulted in differences ranging from 0.1 to 12% reduction in environmental impact in DFM models and demonstrating consistently their environmental advantages in areas such as climate change, eutrophication, acidification, ecotoxicity, resource use, and human toxicity. Notably, the impact of variations in food formulation among scenarios (BT-2017, NRC-2012, AGPIC-2021) highlights the need for careful decision-making regarding nutrient requirements without a single solution is evident. Precision feeding techniques and strategies such as reducing crude protein levels and supplementing with synthetic amino acids in the diet emerge as effective means to reduce environmental footprints, offering practical and accessible pathways towards sustainability in pig production. Regarding climate change impact from land use, the reduction reached 12.55% when employing DFM. Other impact categories, such as freshwater ecotoxicity, carcinogenic human toxicity, and using mineral and metal resources, achieved reductions of 5.05%, 3.84%, and 6.12%, respectively, when employing DFM. The results highlight the critical role of food production in driving environmental impacts, emphasizing the importance of adopting precision feeding techniques and alternative strategies to mitigate these effects effectively. The study contributes to advancing the understanding of sustainable practices in pig production, paving the way for adopting more sustainable approaches that promote environmental management and long-term viability in the industry.

Keywords: Environment; Sustainability; Swine farming; Swine nutrition.

10 INTRODUCTION

Developing pig production worldwide has raised concerns regarding its environmental impact. Sustainable practices, particularly in waste management and feed production, are imperative to reduce the industry's ecological footprint (Spies, 2003). Among the economic and social significance of swine farming, measures must be taken to maximize positive outcomes and minimize negative impacts. Thus, the development of the pig industry can assist in meeting sustainable development goals (Mores *et al*., 2023).

Despite its economic importance, swine farming is associated with substantial environmental impact, ranking among the most polluting agricultural activities. This includes detrimental effects on air, water, and soil quality. Air quality is compromised through elevated emissions of ammonia, nitrous oxide, methane, and noxious odors (Kunz *et al*., 2009; Paolo *et al*., 2013). High water consumption (Samarin *et al*., 2021) and diminished water quality (Kunz *et al*., 2009) further contribute to environmental strain. Excessive waste production (De Brito *et al*., 2022) and inadequate treatment result in water eutrophication, altering aquatic biodiversity and fostering harmful organisms (Castro, 2017). Proper waste treatment techniques, such as biodigesters, can alleviate this impact (Mores *et al*., 2023)

Feedstuff production primarily contributes to environmental impacts, such as climate change, acidification, and eutrophication. Thus, reducing the environmental impact of pig farming necessitates a focus on feed production. Growth performance, feed formulas, and feeding plans significantly determine pig production systems' environmental and economic aspects (Dourmad & Jondreville, 2007; Dubeau *et al*., 2011). Feeding strategies like use of household waste and agro-industrial byproducts as feed ingredients (Gerber *et al*., 2007), reduction of crude protein (CP) (Esteves *et al*., 2021; Monteiro *et al*., 2016), supplementation with synthetic amino acids (Esteves *et al*., 2021; Toledo *et al*., 2014), alternative multiobjective formulation techniques (Garcia-Launay *et al*., 2018), and precision feeding (Andretta *et al*., 2018, 2016; Pomar *et al*., 2011; Pomar & Remus, 2019) can reduce environmental impacts and are suitable approaches to address the current challenges of pig production (Garcia-Launay *et al*., 2018).

This study compares two feeding strategies for growing-finishing pigs, the conventional Phase Feeding Model (CON) and Daily Fit Model (DFM), across three feeding formulation scenarios: Brazilian tables (BT-2017), NRC (NRC-2012), and AGPIC (AGPIC-2021). Employing a Life Cycle Analysis (LCA), it was assessed whether DFM can effectively reduce the environmental impact of a pig farm system. The overarching goal is pinpointing the reduction of environmental impact with the DFM in the proposed scenarios.

11 MATERIAL AND METHODS

11.1 Simulation study

This simulation employed three distinct scenarios based on the barrow requirements specified in the Brazilian tables for poultry and swine (Rostagno, 2017), the National Research Council (NRC, 2012), and the commercial lineage AGPIC (PIC, 2021). The assessment compared two feeding models: the CON and the DFM. The CON provided the same diet to all pigs within a group during each proposed phase. In contrast, the DFM adjusted the diet based on the nutritional requirements of aging pigs, anticipating subsequent diets through daily adjustments.

In the simulation, two models are employed, each with distinct considerations. The first model (CM), known as the CON, takes into account the phase duration (DP), feed price (FP) within each phase, and feed intake (FI) during the respective phase (P). The total cost is derived by summing the costs of all phases, depending on the number of feeding phases employed.

$$CM = \sum^{N} i{=}P\ (DP_i \times FP_i \times FI_i) \qquad (1)$$

On the other hand, the second model, DFM, computes daily feed costs (DA) by considering the price of the feed used (TCf) and daily feed intake (DFI) (Equation 2). The TCf requires information about the amount of feed intake (AFI) and the corresponding feed prices (FP), as indicated in Equation (3). A summary of these models is provided in Table 1.

$$DA = \sum^{N} i{=}P\ (TCf \times DFI) \qquad (2)$$

Where:

$$TCf = (AFI_1 \times FP_1) + (AFI_2 \times FP_2) \qquad (3)$$

After the model construction, results were tabulated in a Microsoft Excel® automated spreadsheet to enhance the practical application of these models.

Table 1. Description of the models used in the simulation study

Equation	Description
DP	Phase duration in days
FP	Feed price
FI	Feed intake
P	Phase
DFI	Daily feed intake
FP1 e FP2	The price of feed 1 and 2 used
AF 1 =100-PD	Amount of feed 1
PD = (100/d) x (D-1)	Phase duration
d	Phase day
D	Production day
AFI2 = 100 – AFI1	Amount of feed 2

11.2 Goal and scope definition

This study aimed to compare the environmental impact of three feeding scenarios for growing-finishing pigs: Brazilian tables (BT-2017), NRC (NRC-2012), and PIC (PIC-2021), utilizing both the CON and DFM. The primary objective was to identify the reduction of environmental impact by applying the DFM in the proposed scenarios.

11.3 System boundary

This study adopts a cradle-to-gate approach, covering the stages of crop production to pig production until the farm gate. The functional unit is defined as one barrow with an initial weight of 20.61 ± 0.85 kg, reaching a final weight of 138.94 ± 0.90 kg over a 120-day growing-finishing period. The system includes inputs such as feeds, electric energy, transportation, and infrastructure components such as pig buildings, slurry pits, and water consumption. The only variable between the systems was the feeding scenario. The system boundaries encompass all processes on the pig farm, excluding veterinary products and care, artificial insemination, small cleaning materials, and processes beyond the farm gate, such as slaughtering and meat processing. The only difference between the two systems was the feeding strategy applied.

11.4 Dataset information

The LCA dataset utilized in this study, compiled in May 2020 using AGRIBALYSE V1.4, encompasses the entire life cycle of pig production, from the growing-finishing phase to departure from the farm. The inventory spans 2005-2009, focusing on the technological aspects of the conventional output in standard pig breeding/fattening farms. This study used net energy values and adopted a conventional production mode. The dataset includes comprehensive details of all activities on a pig farm, including inputs, infrastructure, emissions, and related buildings and barns.

11.5 Scenario development

Three scenarios, BT-2017, NRC-2012, and PIC-2021, were evaluated in the LCA, each comprising CON and DFM simulations. Diets were formulated using solver procedures in Excel following the nutritional requirements of Rostagno (2017), NRC (2012), and AGPIC (2021). The scenarios were equivalent in all aspects except feed composition and quantity. Diet composition and formulation are detailed in supplementary tables 1-2 and amounts in supplementary table 3.

11.6 Data collection

For each scenario, six diets were formulated using the solver procedure in Microsoft Excel and aligned with Barrow's nutrient requirements. Before the LCA, a modeling analysis assessed DFM's cost reduction and nutrient excess compared to CON across all scenarios. The LCA aims to evaluate the environmental impact of these feeding strategies, considering the varying quantities used in each scenario based on a simulation study.

11.7 Inventory analysis and impact assessment method

OpenLCA software inventory analysis utilized the environmental footprint (EF) 3.0 impact assessment method. Environmental Footprint 3.0 quantifies environmental impacts in various categories, offering a comprehensive view of environmental aspects throughout the life cycle. Adaptations were made in impact categories to tailor EF 3.0 to the context of swine production, considering factors such as feed type, waste management, agricultural practices, and locality.

11.8 System modelling

The dataset creation employed the MEANS-InOut software, incorporating methodologies like N2O - IPCC 2006 (tier 2), N - RMT 2016, NO - EMEP/EEA 2016 (Tier 1), CH4 - IPCC 2006b, NO3 - Basset-Mens 2007, NH3 - EMEP 2009 (tier 2). Technological and geographical representativeness, precision, and methodological appropriateness were maintained throughout the modeling process.

11.9 Sensitivity analysis

The LCA in this study analyzed parameters such as acidification, climate change, ecotoxicity, eutrophication, human toxicity, land use, resource use, and water use in each proposed scenario. See Table 2 for a description of each analyzed parameter.

Table 2. Summary of the environmental impacts measured and their functional units.

Environmental impact measure	Reference unit	Description
Acidification	mol H+ eq	This is an indicator of the potential acidification of soil and water due to the release of nitrogen oxide and sulfur oxide gases.
Climate change	kg CO2 eq	Indicator of potential global warming due to emissions of greenhouse gases to the air, using carbon dioxide as a standard, with or without a change in land use.
Freshwater ecotoxicity	CTUe	Impact of toxic substances emitted to the environment on freshwater organisms using Comparative Toxic Unit for ecosystems (CTUe) as a standard.
Freshwater eutrophication	kg P eq	Indicator of the potential for increased phosphorus emission to freshwater
Marine eutrophication	kg N eq	Indicator of the potential for increased nitrogen emission to freshwater.
Human carcinogenic toxicity	CTUh	Impact of carcinogenic toxic substances on the environment using the Comparative Toxic Unit for humans (CTUh) as a standard.
Human noncarcinogenic toxicity	CTUh	Impact of noncarcinogenic toxic substances on the environment using the Comparative Toxic Unit for humans (CTUh) as a standard.
Land use	Point	Impact of converting nonagricultural land into agricultural use.
Mineral and metal resource use	kg Sb eq	Indicator of depletion of natural inorganic mineral and metal resources
Fossil resources use	MJ	Indicator of natural fossil fuel resource depletion in megajoules (MJ).
Water use	m3 depriv.	Indicator of the amount of water (cubic meters) used.

*Data extracted from (Koch and Salou, 2015)

11.10 Compliance with standards

This LCA study adhered to ISO 14040/44 standards, ensuring methodological rigor, comparability, and transparency in assessing the environmental impacts associated with swine feed production. The study followed the guidelines of ISO 14040/44: Environmental Management – Life Cycle Assessment, emphasizing principles, framework, and requirements for data quality, impact assessment, interpretation, and reporting.

12 RESULTS

12.1 Comparison of scenarios

This study considered the CON and DFM for three proposed scenarios: BT-2017, NRC-2012, and AGPIC-2021. Overall, the DFM consistently reduced environmental impact across all scenarios compared to the CON. For a detailed overview of the results, please refer to Supplementary Table 4. Additionally, Figure 1 illustrates in a circular bar plot the percentual difference in reduced environmental impact when employing the DFM.

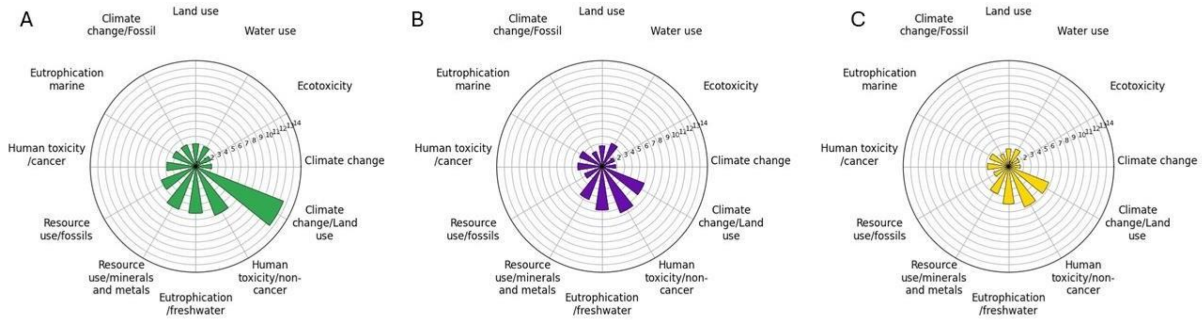

Figure 1. Percentage reduction of environmental impact using the DFM in BT-2017(A), AGPIC-2021 (B), and NRC-2012 (C) recommendations.

12.2 Reduction of environmental impact in the impact categories

In the climate change (CC) impact category, the evaluation focused on the global warming potential measured in radiative forcing over a 100-year horizon (kg CO2 equivalent). The climate change–fossil category evaluates greenhouse gas emissions from burning fossil fuels. Climate change land use and land use change evaluate the emissions and environmental impacts associated with changes in land use, mainly related to greenhouse gas emissions and their contribution to climate change (Koch and Salou, 2015).

Notably, the BT-2017 scenario exhibited higher reduction values than the AGPIC-2021 and NRC-2012 scenarios, with respective values of 2.09%, 1.59%, and 1.41%. The higher reduction in the BT-2017 scenario is due to the higher presence of maize grain in the diets, significantly contributing to the CC impact category.

Eutrophication categories assess phosphorus (P) and nitrogen (N) enrichment in marine and freshwater environments due to human activities (Khan & Mohammad, 2014). Across all simulations, the values of eutrophication were lower in the DFM than in the CON. Specifically, reductions of 6.21%, 5.79%, and 4.95% in freshwater eutrophication were observed in the BT-2017, AGPIC-2021, and NRC-2012 scenarios. Similarly, marine eutrophication reductions were noted at 3.28, 3.26, and 2.70% for the exact scenarios. These findings suggest that the

DFM effectively reduces nutrient levels such as P and N, thereby mitigating eutrophication impacts. Furthermore, the acidification impact category showed reductions of less than 1% reduction for all the scenarios, indicating that the chosen system produces minimal amounts of acidifying substances.

The ecotoxicity of the freshwater impact category showed reductions of 2.15%, 1.83%, and 1.57% in the respective BT-2017, AGPIC-2021, and NRC-2012 scenarios. These reductions signify a decrease in the potential adverse effects of products or processes on freshwater ecosystems and non-human organisms throughout their life cycle.

Regarding resource use, minerals, metals, and fossils throughout the LCA were measured. The resource use is measured in antimony equivalents, the use of minerals and metals, and RUF is measured in megajoules to quantify fossil resource consumption. Regarding resource use of minerals and metals, 6.11%, 4.72%, and 3.89% reductions were achieved for the BT-2017, AGPIC-2021, and NRC-2012 scenarios, respectively. Similarly, reductions of 4.88%, 2.53%, and 2.13% for resource use of fossils were observed for the exact scenarios.

Water use evaluates the depletion of freshwater. Reductions of 3.32, 2.89, and 2,51% were found in the AGPIC-2021, BT-2017, and NRC-2012 scenarios. Land Use assesses the impact of agriculture, settlements, and resource extraction on land. Reductions of 3.00, 2.75, and 2.33% were found in the BT-2017, AGPIC-2021, and NRC-2012 scenarios.

Human Toxicity assesses chemical effects on humans, measured in Comparative Toxic Units (CTU). It is subdivided into carcinogenic (chemical factors that can cause cancer) and noncarcinogenic (chemical factors that don’t cause cancer). Applying the CON, the impact of human toxicity was reduced in all scenarios. Reductions in human toxicity cancer were noted, with percentages ranging from 3.84% (BT-2017), 3.26% (AGPIC-2021), to 2.81% (NRC-2012 scenarios). Likewise, reductions in noncarcinogenic human toxicity ranged from 6.95% (BT-2017), 6.61% (AGPIC-2021), to 5.77% (NRC-2012 scenarios).

13 DISCUSSION

13.1 Comparison of scenarios

In evaluating the environmental impacts across scenarios, the DFM strategy emerged as a compelling avenue for reducing ecological burdens compared to the CON approach. By isolating the feed system as the sole variable, the study provided a nuanced understanding of how feed management influences environmental outcomes throughout the pig production cycle. Notably, the growing-finishing phase, constituting over 72% of the entire production cycle, emerged as a pivotal juncture where strategic feed interventions could effectively mitigate environmental impacts. This was related to the weight of the pigs in this phase, which was higher than that of the others. With higher weight, the nutritional requirements and amount of feed and manure increase (Noya *et al.*, 2017; Reckmann *et al*., 2013). Different feed and manure treatment strategies could be a great alternative to mitigate these effects.

Feed production is the major contributor to environmental impact, accounting for 60% of all emissions from the pig production supply chain (MacLeod *et al*., 2013). The processing of crop-based products, mainly maize, and soybean (McAuliffe *et al*., 2016), exerts a significant toll on various environmental categories like global warming, climate change, terrestrial acidification, marine eutrophication, biodiversity damage, and acidification (Cherubini *et al*., 2015; Strid Eriksson *et al*., 2005). In this context, precision feeding emerges, aiming to mitigate these impacts by reducing the excess nutrients in the pig's diet by adjusting to match its nutritional requirements more closely to its actual needs (Andretta *et al*., 2018; Soleimani *et al*., 2021). Other strategies, such as reducing CP levels and supplementing with synthetic amino acids, have positive effects (Esteves *et al*., 2021; Monteiro *et al*., 2016). Other potential benefits are reducing feed costs and N and P excretion (Andretta, 2014). They are critical minerals, with a significant portion excreted in pig feces and urine. This minimizes environmental impacts without affecting the growth rate or feed efficiency of the pigs (Jongbloed, 2008; Yang *et al*., 2023).

13.2 Reduction of environmental impact in the impact categories

Similarly, with founds in other LCAs, the pig production system and feed production are the major contributors to CC. Specifically, pig housing accounts for approximately 30%, while the feeding stage constitutes 63% of the overall value, with the latter being the primary influencer of CO_2 emissions (Reckmann, 2013). Notably, manure management further amplifies the pig production's CC contribution due to emissions of pollutants like nitrate and nitrous oxide associated with feed production and slurry excretion (Dalgaard, 2007).

Precision feeding techniques have reduced CC impact compared to conventional phase feeding, as seen in studies by Monteiro *et al*. (2016). Moreover, decreasing CP in the diet, achieved by adding synthetic amino acids, has proven effective in diminishing CC impact, mainly when soybean meal linked to deforestation is used (Monteiro *et al*., 2016). For instance, a 10g/kg reduction in CP can translate to a 101 kg CO2eq decrease in the CC impact per ton of feed (Grandmaison *et al*., 2020).

In a study by Alba-Reyes et al. (2023), the land transformation needed for maize and soybean cultivation accounts for 71% of CO_2 emissions. Additionally, the transportation of feed ingredients, agricultural inputs, and animals contributes to the impact of CC by consuming fossil resources, elevating CO_2 and CH4 emissions (Alba-Reyes *et al*., 2023). These findings underscore the importance of maize and soy in pig feed, emphasizing their considerable environmental footprint encompassing cultivation, plantation, and fertilizer use (McAuliffe *et al*., 2017).

Feed-related processes dominate freshwater eutrophication in pork production, ranging from 32% to 90% (Alba-Reyes *et al*., 2023; Guinée, 2002; Stone *et al*., 2012), while approximately 88% of acidifying substances originate from the pig housing, particularly ammonia emissions (Strid Eriksson *et al*., 2005). The impact of eutrophication and acidification can be modulated through feed production, ingredient use, manure treatment, and feeding systems. The reduction of the excess nutrient in the DFM contributes to the lesser values of eutrophication and acidification, primarily because of the decrease in N and P. Reducing CP in the diet is also related to being able to reduce acidification and eutrophication potential in 5% and 3% respectively, for each percentage unit of CP content (Garcia-Launay *et al*., 2014), 10% for both impact categories (Mosnier *et al*., 2011), and 11 and 13% decrease compared to diets without syntenic amino acid supplementation (Monteiro *et al*., 2016). A precision feeding strategy like individual precision feeding in a pig system in Brazil also shows benefits in obtaining the lowest eutrophication impact (mean of 16.3 g PO4–eq per kg of BWG) when compared with the conventional two-phase feeding system (mean of 18.2 g PO4–eq per kg of BWG) (Monteiro *et al*., 2021).

Besides feed production, chemicals like copper and zinc in pig diets, fertilizers, and pig manure significantly impact ecotoxicity (Alba-Reyes *et al*., 2023; Liu *et al*., 2021; González-García *et al*., 2015). The oversupply of these elements, leading to high concentrations in pig manure, can adversely affect freshwater organism populations through dose–response factors. With the reduction of nutrients in the DFM, the impact of ecotoxicity is also reduced. Pig manure significantly impacts ecotoxicity. An alternative approach involves substituting mineral fertilizers with digestate derived from pig manure, resulting in favorable environmental outcomes regarding terrestrial ecotoxicity, freshwater aquatic ecotoxicity, and marine aquatic ecotoxicity (Venslauskas *et al.* 2022).

Using mineral, metal, and fossil resources has notable negative environmental impacts. Fertilizer production (Herrera *et al*., 2023) and chemical methods to extract some composts, such as phosphoric acid, commonly used in swine diets (Jacela *et al*., 2009), and zinc (Monteiro *et al*., 2018), are integral to this impact category. Strategies to alleviate this impact include utilizing local feed ingredients, enhancing feed use, and improving manure management practices (Nguyen *et al*., 2010). Precision feeding adjustments have demonstrated reductions in these impacts compared to conventional feeding systems.

Water use is mainly associated with grains like maize and soybeans in the pig's feed since they have a higher water footprint. The fraction of water used for drinking or washing is negligible compared to water used for feed production (Chimainski *et al*., 2019). Reducing maize grain when the DFM is applied mitigates this impact. Using by-products as alternative feed ingredients to maize grain is recommended due to their lower impact on water use (Zhuo *et al*., 2019). The implementation of individual precision feeding practices and reduction of CP in the diet is also recommended to mitigate the land use impact (Andretta *et al*., 2018; Kebreab *et al*., 2016; Monteiro *et al*., 2016; Esteves *et al*., 2021), with the possibility of reaching a 5%

decrease in land use values (Monteiro et al., 2016).

Feed and pig production systems can contribute up to 98% to human carcinogenic and noncarcinogenic impacts (Dorca-Preda *et al*., 2022). The DFM shows a higher presence of maize than soybean, which reduces human toxicity, especially because crop production involves pesticide use that poses health risks to individuals coming into contact with them (Zheng *et al*., 2021)—with soybean meal having a more significant toxicity factor than wheat (Rusman *et al*., 2023). The reduction of nutrients in pig feed, like vitamins and minerals caused by the DFM, diminishes this impact (Alba-Reyes *et al*., 2023; Dorca-Preda *et al*., 2022).

14 CONCLUSION

In conclusion, the simulations reveal consistent environmental benefits associated with the DFM strategy. Precision and alternative feeding techniques emerge as practical approaches to mitigate environmental impacts. Differences were found among the proposed scenarios (BT-2017, NRC-2012, AGPIC-2021), primarily due to the modeling approach to determine the nutrient requirements. There is not one perfect recommendation, but there are suggestions to mitigate these impacts. Adjustments to feed formulation to reduce environmental impact can be made, especially with alternative ingredients to maize and soybean.

Overall, the study provides valuable insights into the environmental implications of different feeding models and scenarios, offering guidance for developing more sustainable and eco-friendly practices in the pig production industry. The results underscore the importance of considering alternative feeding strategies and optimizing feed composition to minimize the environmental footprint of pig production.

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16 CONCLUSÕES GERAIS

Com base nas conclusões apresentadas nos estudos analisados, observa-se claramente o potencial da aplicação de um simples modelo para ajuste na alimentação dos suínos. Os benefícios não são apenas para reduzir os custos associados à alimentação e o consumo de nutrientes durante a fase crucial de crescimento e acabamento, mas também para mitigar o impacto ambiental do dejeto suíno. A vantagem econômica de reduzir os gastos com alimentação representa um incentivo significativo para os produtores de suínos adotarem essas práticas mais simples, e futuramente evoluir para algo mais complexo. Além disso, a redução no consumo de nutrientes promete benefícios ambientais substanciais, alinhando-se com os princípios de produtividade e sustentabilidade na produção animal.

A avaliação do ciclo de vida (ACV) dos modelos propostos revela consistentemente benefícios ambientais associados à estratégia de ajuste diário na alimentação. Os resultados obtidos destacam a importância crítica de considerar estratégias alternativas de alimentação e otimizar a composição da ração para minimizar a pegada ambiental da produção de suínos. A escolha dos ingredientes de ração e das referências de exigências nutricionais emerge como um aspecto crucial, requerendo uma ponderação cuidadosa e detalhada para garantir a eficácia das práticas de alimentação sustentável na produção animal.

Em síntese, os estudos analisados fornecem insights valiosos sobre as implicações ambientais de diferentes modelos e cenários de alimentação em suínos. Essas descobertas contribuem para a compreensão da interação entre práticas de alimentação, eficiência produtiva e sustentabilidade ambiental na indústria de produção animal. Ao considerar estratégias de alimentação alternativas e a otimização da composição da ração, os produtores têm a oportunidade não apenas de melhorar a eficiência econômica de suas operações, mas também de desempenhar um papel fundamental na conservação e preservação do meio ambiente.

17 ANEXOS

Capitulo I

Supplementary Table 1. Nutrient requirements for barrows used in the simulations

Scenario	Brazilian Tables[1]						NRC[2]						AGPIC[3]					
Feed	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Nutrients																		
ME	3350.000	3350.000	3350.000	3350.000	3350.000	3350.000	3400.000	3400.000	3400.000	3400.000	3400.000	3400.000	3400.000	3400.000	3400.000	3400.000	3400.000	3400.000
STTD P	0.421	0.346	0.279	0.241	0.215	0.183	0.330	0.300	0.260	0.240	0.210	0.200	0.420	0.360	0.300	0.270	0.250	0.220
SID Lysine	2.134	1.326	0.980	0.716	0.704	0.582	1.070	0.960	0.810	0.700	0.590	0.530	1.220	1.030	0.830	0.730	0.670	0.582
SID Methionine	0.363	0.321	0.278	0.242	0.209	0.196	0.310	0.280	0.230	0.200	0.170	0.150	-	-	-	-	-	-
SID Methionine + Cysteine	0.713	0.631	0.547	0.483	0.418	0.391	0.600	0.540	0.460	0.400	0.350	0.320	0.708	0.597	0.481	0.423	0.389	0.337
SID Threonine	0.813	0.695	0.603	0.523	0.453	0.419	0.600	0.580	0.500	0.450	0.390	0.360	0.793	0.670	0.540	0.482	0.442	0.384
SID Thyptophan	0.238	0.214	0.185	0.161	0.139	0.131	0.180	0.160	0.140	0.120	0.110	0.100	0.232	0.185	0.149	0.131	0.121	0.105
SID Valine	0.863	0.738	0.640	0.555	0.481	0.443	0.690	0.620	0.530	0.460	0.400	0.360	0.708	0.700	0.556	0.496	0.456	0.396
SID Isoleucine	0.688	0.588	0.510	0.443	0.383	0.353	0.560	0.500	0.430	0.370	0.320	0.290	0.683	0.577	0.465	0.409	0.375	0.326
SID Leucine	1.251	1.069	0.927	0.805	0.697	0.641	1.070	0.960	0.820	0.710	0.600	0.540	1.232	1.040	0.838	0.745	0.683	0.593
SID Histidine	0.413	0.353	0.306	0.266	0.230	0.210	0.370	0.330	0.280	0.240	0.200	0.180	0.403	0.350	0.282	0.248	0.228	0.198
SID Phenylalanine	0.626	0.535	0.464	0.403	0.349	0.323	0.640	0.570	0.490	0.420	0.360	0.330	-	-	-	-	-	-
SID Phenylalanine + Tyrosine	1.251	1.069	0.927	0.805	0.697	0.641	1.000	0.900	0.760	0.660	0.570	0.510	1.135	0.968	0.789	0.701	0.643	0.558

Abbreviations: ME = Metabolized Energy; SID = Standardized ileal digestibility.

Units: ME= kcal/kg; Other nutrients= %

[1]All requirements were obtained from (Rostagno, 2017)).

[2] All requirements were obtained from NRC (2012).

[3] All requirements were obtained from PIC (2021).

Supplementary Table 2. Formulated diets used in the simulations

Diets																		
Scenario	Brazilian Tables						NRC						AGPIC					
Feed	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Price of Feed*	$ 0.65	$ 0.64	$ 0.46	$ 0.45	$ 0.42	$ 0.40	$ 0.47	$ 0.46	$ 0.43	$ 0.41	$ 0.39	$ 0.38	$ 0.45	$ 0.42	$ 0.40	$ 0.38	$ 0.37	$ 0.35
Nutrients																		
ME	3297.305	3251.765	3241.603	3246.508	3209.390	3163.792	3400.000	3400.000	3400.000	3400.000	3400.000	3400.000	3400.000	3400.000	3400.000	3400.000	3400.000	3400.000
CP	19.120	19.539	15.960	13.964	11.676	8.938	17.883	16.486	14.998	13.596	12.539	11.650	18.375	16.919	16.393	13.932	11.308	10.168
Total Calcium	0.904	0.907	0.524	0.454	0.406	0.335	0.700	0.650	0.570	0.510	0.450	0.420	0.831	0.423	0.233	0.247	0.581	0.570
STTD P	0.403	0.405	0.254	0.254	0.197	0.162	0.330	0.300	0.260	0.240	0.210	0.200	0.420	0.360	0.300	0.270	0.250	0.220
SID Lysine	1.423	1.446	0.835	0.726	0.630	0.571	1.070	0.960	0.810	0.700	0.590	0.530	1.220	1.030	0.830	0.730	0.670	0.582
SID Methionine	0.442	0.448	0.251	0.218	0.189	0.198	0.343	0.296	0.230	0.212	0.200	0.190	0.440	0.346	0.232	0.205	0.203	0.168
SID Methionine + Cysteine	0.701	0.711	0.493	0.436	0.378	0.352	0.600	0.540	0.462	0.430	0.410	0.391	0.708	0.597	0.481	0.424	0.389	0.341
SID Threonine	0.891	0.905	0.543	0.472	0.410	0.263	0.600	0.580	0.500	0.450	0.390	0.360	1.339	0.787	0.540	0.482	0.817	0.770
SID Thyptophan	0.297	0.302	0.167	0.145	0.126	0.118	0.180	0.160	0.140	0.120	0.110	0.100	0.232	0.185	0.168	0.135	0.121	0.105
SID Valine	0.762	0.780	0.663	0.575	0.473	0.347	0.702	0.647	0.592	0.537	0.497	0.461	0.761	0.700	0.687	0.577	0.460	0.412
SID Isoleucine	0.695	0.713	0.584	0.495	0.391	0.264	0.648	0.587	0.527	0.466	0.422	0.383	0.683	0.621	0.607	0.494	0.375	0.326
SID Leucine	1.395	1.424	1.317	1.195	1.045	0.863	1.442	1.364	1.289	1.211	1.156	1.106	1.440	1.361	1.346	1.194	1.029	0.963
SID Histidine	0.438	0.448	0.393	0.346	0.290	0.222	0.434	0.403	0.372	0.341	0.319	0.299	0.443	0.412	0.406	0.347	0.282	0.257
SID Phenylalanine	0.807	0.826	0.702	0.607	0.496	0.361	0.773	0.710	0.647	0.584	0.538	0.497	0.804	0.742	0.729	0.609	0.479	0.426

Abbreviations: ME = Metabolized Energy; CP = Crude Protein; STTD P = Standardized Total Tract Digestible Phosphorus; SID = Standardized Ileal Digestibility.

Units: ME= kcal/kg; Other nutrients= %.

* The conversion from Brazilian reais to US dollars was performed using an exchange rate of 5.05 reais per dollar.

Capítulo II

Supplementary Table 1. Feed composition for the diets used in the simulations.

Scenario	Brazilian Tables[1]						NRC[2]						AGPIC[3]					
Feed	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Ingredients (%)																		
Maize grain, 7.86% (CP)	57.961	64.575	71.394	76.802	83.347	87.046	67.779	72.245	77.195	81.664	87.706	91.713	58.023	67.946	75.855	79.802	83.479	89.837
Soybean meal, 45% (CP)	36.670	31.879	26.193	21.509	15.198	11.959	25.633	21.733	17.790	13.889	8.431	4.658	35.577	26.566	19.557	16.052	12.630	6.626
Soybean oil	2.124	1.718	1.286	1.002	0.690	0.450	3.454	3.156	2.741	2.451	2.074	1.866	3.597	3.048	2.608	2.388	2.196	1.874
Calcitic Limestone	-	-	-	-	-	-	1.205	1.090	0.897	0.756	0.621	0.557	0.648	0.599	0.601	0.602	0.602	0.604
Sodium Chloride	-	-	-	-	-	-	0.222	0.248	0.223	0.224	0.251	0.252	0.127	0.093	0.035	0.006	-	-
DL-Methionine	0.120	0.074	0.036	0.011	0.011	0.020	0.107	0.079	0.030	0.008	0.018	-	-	-	-	-	0.007	0.022
L-Tryptophan	-	-	-	-	-	-	-	-	-	-	-	0.028	-	-	-	-	-	-
L-Lysine HCl	1.379	0.507	0.239	0.045	0.213	0.154	0.377	0.352	0.278	0.253	0.274	0.309	0.273	0.297	0.250	0.227	0.251	0.315
L-Threonine	0.110	0.049	0.028	0.007	0.019	0.026	0.043	0.072	0.041	0.040	0.050	0.068	0.106	0.098	0.057	0.043	0.048	0.067
Dicalcium phosphate	1.636	1.197	0.822	0.624	0.521	0.346	1.180	1.026	0.805	0.714	0.575	0.548	1.648	1.353	1.038	0.880	0.786	0.655

Abbreviations: ME = Metabolized Energy; SID = Standardized ileal digestibility. Units: ME= kcal/kg; Other nutrients= %

[1]All requirements were obtained from Rostagno (2017); [2] All requirements were obtained from NRC (2012); [3] All requirements were obtained from PIC (2021).

Supplementary Table 2. Formulated diets used in the simulations.

Diets																		
Scenario	Brazilian Tables						NRC						AGPIC					
Feed	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Price of Feed*	$ 0.65	$ 0.64	$ 0.46	$ 0.45	$ 0.42	$ 0.40	$ 0.47	$ 0.46	$ 0.43	$ 0.41	$ 0.39	$ 0.38	$ 0.45	$ 0.42	$ 0.40	$ 0.38	$ 0.37	$ 0.35
Nutrients																		
ME	3297.305	3251.765	3241.603	3246.508	3209.390	3163.792	3400.000	3400.000	3400.000	3400.000	3400.000	3400.000	3400.000	3400.000	3400.000	3400.000	3400.000	3400.000
CP	19.120	19.539	15.960	13.964	11.676	8.938	17.883	16.486	14.998	13.596	12.539	11.650	18.375	16.919	16.393	13.932	11.308	10.168
Total Calcium	0.904	0.907	0.524	0.454	0.406	0.335	0.700	0.650	0.570	0.510	0.450	0.420	0.831	0.423	0.233	0.247	0.581	0.570
STTD P	0.403	0.405	0.254	0.254	0.197	0.162	0.330	0.300	0.260	0.240	0.210	0.200	0.420	0.360	0.300	0.270	0.250	0.220
SID Lysine	1.423	1.446	0.835	0.726	0.630	0.571	1.070	0.960	0.810	0.700	0.590	0.530	1.220	1.030	0.830	0.730	0.670	0.582
SID Methionine	0.442	0.448	0.251	0.218	0.189	0.198	0.343	0.296	0.230	0.212	0.200	0.190	0.440	0.346	0.232	0.205	0.203	0.168
SID Methionine + Cysteine	0.701	0.711	0.493	0.436	0.378	0.352	0.600	0.540	0.462	0.430	0.410	0.391	0.708	0.597	0.481	0.424	0.389	0.341
SID Threonine	0.891	0.905	0.543	0.472	0.410	0.263	0.600	0.580	0.500	0.450	0.390	0.360	1.339	0.787	0.540	0.482	0.817	0.770
SID Tryptophan	0.297	0.302	0.167	0.145	0.126	0.118	0.180	0.160	0.140	0.120	0.110	0.100	0.232	0.185	0.168	0.135	0.121	0.105
SID Valine	0.762	0.780	0.663	0.575	0.473	0.347	0.702	0.647	0.592	0.537	0.497	0.461	0.761	0.700	0.687	0.577	0.460	0.412

SID Isoleucine	0.695	0.713	0.584	0.495	0.391	0.264	0.648	0.587	0.527	0.466	0.422	0.383	0.683	0.621	0.607	0.494	0.375	0.326
SID Leucine	1.395	1.424	1.317	1.195	1.045	0.863	1.442	1.364	1.289	1.211	1.156	1.106	1.440	1.361	1.346	1.194	1.029	0.963
SID Histidine	0.438	0.448	0.393	0.346	0.290	0.222	0.434	0.403	0.372	0.341	0.319	0.299	0.443	0.412	0.406	0.347	0.282	0.257
SID Phenylalanine	0.807	0.826	0.702	0.607	0.496	0.361	0.773	0.710	0.647	0.584	0.538	0.497	0.804	0.742	0.729	0.609	0.479	0.426
SID Phenylalanine + Tyrosine	1.408	1.442	1.231	1.068	0.876	0.642	1.287	1.183	1.081	0.978	0.903	0.836	1.391	1.285	1.264	1.061	0.841	0.752
Total Nitrogen	2.655	2.716	2.232	1.939	1.605	1.204	2.861	2.638	2.400	2.175	2.006	1.864	2.739	2.463	2.293	1.934	1.570	1.384

Abbreviations: ME = Metabolized Energy; CP = Crude Protein; STTD P = Standardized Total Tract Digestible Phosphorus; SID = Standardized Ileal Digestibility.

Units: ME= kcal/kg; Other nutrients= %. * The conversion from Brazilian reais to US dollars was performed using an exchange rate of 5.05 reais per dollar.

Supplementary Table 3. Quantity of the feed used in the simulations

Quantit. of feed (kg)	BT-2017 CON	BT-2017 DFM	NRC-2012 CON	NRC-2012 DFM	AGPIC-2021 CON	AGPIC-2021 DFM
Feed 1	27.879	13.07	27.879	13.07	27.879	13.07
Feed 2	53.919	41.12	53.919	41.12	53.919	41.12
Feed 3	69.381	62.50	69.381	62.50	69.381	62.50
Feed 4	42.318	56.81	42.318	56.81	42.318	56.81
Feed 5	60.167	51.36	60.167	51.36	60.167	51.36
Feed 6	-	28.80	-	28.80	-	28.80

*BT = Brazilian tables; CON = Conventional Phase Feeding Model; DFM = Daily Fit Model.

Supplementary Table 4. Impact categories of the LCA

Impact category	Reference unit	BT DFM	BT CON	NRC DFM	NRC CON	AGPIC DFM	AGPIC CON
Acidification	mol H+ eq	2,574227328	2,571463	2,574227	2,571463	2,56402	2,559329
Climate Change	kg CO2 eq	161,9915526	166,7405	161,9916	166,7405	164,071	169,4916
Climate Change - Biogenic	kg CO2 eq	0,109639852	0,114783	0,10964	0,114783	0,112184	0,118034
Climate Change - Fossil	kg CO2 eq	126,1468064	128,7102	126,1468	128,7102	128,6558	131,8016
Climate Change - Land Use	kg CO2 eq	35,73510637	37,91548	35,73511	37,91548	35,30305	37,57201
Ecotoxicity, Freshwater	CTUe	11439,08546	11627,69	11439,09	11627,69	11563,51	11785,96
Ecotoxicity, Freshwater - Inorganics	CTUe	417,6658368	429,7768	417,6658	429,7768	428,9647	443,7065
Ecotoxicity, Freshwater - Metals	CTUe	6336,830508	6630,773	6336,831	6630,773	6608,884	6967,833
Ecotoxicity, Freshwater - Organics	CTUe	4689,207333	4572,012	4689,207	4572,012	4530,562	4379,643
Eutrophication, Freshwater	kg P eq	0,072515531	0,076396	0,072516	0,076396	0,076953	0,081804
Eutrophication, Marine	kg N eq	1,484862737	1,530972	1,484863	1,530972	1,535101	1,59275
Eutrophication, Terrestrial	mol N eq	10,66482554	10,58674	10,66483	10,58674	10,51571	10,40853
Human Toxicity, Cancer	CTUh	2,16376E-07	2,23E-07	2,16E-07	2,23E-07	2,22E-07	2,29E-07
Human Toxicity, Cancer - Metals	CTUh	1,7382E-07	1,78E-07	1,74E-07	1,78E-07	1,78E-07	1,83E-07
Human Toxicity, Cancer - Organics	CTUh	4,25556E-08	4,5E-08	4,26E-08	4,5E-08	4,35E-08	4,63E-08
Human Toxicity, Non-Cancer	CTUh	1,59805E-05	1,7E-05	1,6E-05	1,7E-05	1,69E-05	1,81E-05
Human Toxicity, Non-Cancer - Inorganics	CTUh	6,9901E-07	7,3E-07	6,99E-07	7,3E-07	7,09E-07	7,44E-07

Human Toxicity, Non-Cancer - Metals	CTUh	1,48052E-05	1,58E-05	1,48E-05	1,58E-05	1,57E-05	1,69E-05
Human Toxicity, Non-Cancer - Organics	CTUh	4,54541E-07	4,59E-07	4,55E-07	4,59E-07	4,56E-07	4,61E-07
Land Use	Pt	20143,5659	20629,2	20143,57	20629,2	20545,99	21132,77
Resource Use, Fossils	MJ	1468,452751	1506,757	1468,453	1506,757	1504,05	1550,71
Resource Use, Minerals And Metals	kg Sb eq	0,000327892	0,000342	0,000328	0,000342	0,000356	0,000375
Water Use	m3 depriv.	696,5331459	679,2064	696,5331	679,2064	675,0506	653,0025

- BT = Brazilian tables; CON = Conventional Phase Feeding Model; DFM = Daily Fit Model.