VINÍCIUS EDUARDO MOREIRA

MACAUBA (*ACROCOMIA ACULEATA*) PULP AS AN ALTERNATIVE FEEDSTUFF IN GROWING-FINISHING PIG NUTRITION

Thesis submitted to the Animal Science Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Doctor Scientiae.*

Adviser: Alysson Saraiva

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"O conhecimento é a única riqueza que não pode ser roubada."

Provérbio Árabe

ABSTRACT

MOREIRA, Vinícius Eduardo, D.Sc., Universidade Federal de Viçosa, January, 2024. **Macauba (*Acrocomia aculeata*) pulp as an alternative feedstuff in growing-finishing pig nutrition**. Adviser: Alysson Saraiva.

Traditional feed grains have historically formed the basis of pig diets. However, their limitations in terms of resource availability, cost volatility, and environmental impact have fueled a growing interest in alternative feed sources. In this pursuit, macauba pulp (*Acrocomia aculeata*), a coproduct of biodiesel production, emerges as a promising candidate that warrants thorough investigation for its potential to revolutionize pig nutrition and production. Thus, our study sought to optimize pig nutrition by strategically incorporating macauba pulp into their diets. Two studies were designed to guide our investigation. In study I, we aimed to evaluate the balance and digestibility of dry matter (DM), crude protein (CP), nitrogen (N), and energy of macauba pulp in finishing pig diets. By understanding the nutritional interaction between this feedstuff and pig digestive processes, we intend to provide valuable insights so that macauba pulp can be used as an alternative ingredient in pig diets. In study II, we investigated the effects of partially replacing corn with macauba pulp on the growth performance, carcass characteristics and pork quality of growing-finishing pigs; and whether differences in residual feed intake breeding values could influence pigs' growth responses to macauba pulp dietary inclusion. We intended to uncover whether certain genetic backgrounds may synergize more effectively with macauba pulp, potentially opening new avenues for precision feeding strategies. In study I, twenty-four finishing barrows (66.3 ± 0.7 kg BW) were individually housed in suspended metabolism crates allotted in two climatic-controlled rooms. The digestibility assay was conducted in a randomized complete block design, comprising two blocks (climatic-controlled rooms), four dietary treatments, and six replicates per treatment. The reference diet (RD) was a complete corn-soybean meal diet formulated to meet or exceed the nutritional requirements of finishing barrows with high genetic potential with regular-medium performance, while the test diets varied in proportions of RD and macauba pulp: 950 g/kg of RD and 50 g/kg (MAC50), 900 g/kg of RD and 100 g/kg (MAC100), and 850 g/kg of RD and 150 g/kg (MAC150). The 12-day experimental period consisted of a 7-day adaptation period followed by a 5-day quantitative collection period. Urine and fecal materials were collected using the marker-to-marker approach. In study II, a total of 282 (34.8 ± 4.40 kg) pigs (barrows and gilts), progeny of sires with high (HRFI) or low (LRFI) breeding value for residual feed intake, were pair-housed in a 2 × 2 × 2 factorial design based on sex, breeding value, and initial BW. Diets with 50 g/kg of macauba pulp inclusion (macauba) or without (control) were randomly assigned to experimental pens. Thus, eight treatment groups were formed: HRFI barrows fed the control diet; HRFI barrows fed the macauba diet; LRFI barrows fed the control diet; LRFI barrows fed the macauba diet; HRFI female pigs fed the control diet; HRFI female pigs fed the macauba diet; LRFI female pigs fed the control diet; and LRFI female pigs fed the macauba diet. The trial, lasting 90 days, comprised four phases: growing phase 1 (G1), growing phase 2 (G2), finishing phase 1 (F1), and finishing phase 2 (F2). In study I, pigs fed RD had lower ($p < 0.01$) fecal excretion of DM and CP compared to pigs fed MAC100 and MAC150. Fecal energy excretion was higher ($p < 0.01$) in macauba fed pigs than in pigs fed RD. Digestible and metabolizable energies in RD were higher ($p < 0.01$) than in MAC100 and MAC150. The apparent total tract digestibility (ATTD) of dry matter and gross energy was lower ($p < 0.01$) in MAC50, MAC100, and MAC150 than in RD. The ATTD of protein in pigs fed RD was higher ($p < 0.01$) than in pigs fed MAC100 and MAC150, although not differing from pigs fed MAC50. Pigs fed RD had lower ($p < 0.01$) fecal N excretion than pigs fed MAC100 and MAC150 but did not differ from MAC50. The ATTD of N in RD was higher ($p < 0.01$) than in MAC100 and MAC150 and did not differ from MAC50. The present study indicates that up to 50g/kg macauba pulp can be used in the diets of finishing pigs without affecting the energy partitioning, ATTD of protein, and N utilization. In addition, including macauba pulp in corn-soybean meal based diets lowers the urinary-to-fecal N excretion ratio. In study II, there was no interaction between sex, breeding value, and diet for performance, carcass, and pork traits. Barrows outperformed female pigs in feed intake (ADFI), daily gain (ADG), feed conversion rate (FCR), and final body weight. The breeding value had no effect on performance measurements. The inclusion of macauba pulp in pig diets did not affect any growth parameter during G1, G2 and F1 phases. However, reduced ADFI and improved FCR were observed in F2. Female pigs had lower backfat thickness (BF) and higher loin eye area (LEA) than barrows. HRFI pigs had higher hot carcass weight, LEA, and lower BF than LRFI pigs. There was no effect of macauba pulp inclusion on carcass traits. Pork from barrows presented lower Warner–Bratzler shear force and higher fat content than pork from females. There was no effect of breeding value on pork traits. Pork from pigs fed the macauba diet showed lower moisture content and water-holding capacity but tenderness and color was not affected by this substitution. In conclusion, the inclusion of 50 g/kg of macauba pulp in the pigs' diets did not affect any growth parameter during G1, G2 and F1 phases. However, reduced average daily feed intake and improved feed conversion rate were observed in F2. Regardless of sex and breeding value for RFI, pigs responded similarly to macauba pulp inclusion in their diets.

Keywords: Swine; Biofuels coproducts; Feed efficiency; Palm; Alternative feedstuff.

RESUMO

MOREIRA, Vinícius Eduardo, D.Sc., Universidade Federal de Viçosa, janeiro de 2024. **Polpa de macaúba (*Acrocomia aculeata*) como alimento alternativo na nutrição de suínos em crescimento e terminação**. Orientador: Alysson Saraiva.

Os cereais tradicionais têm servido durante muito tempo como base das dietas dos suínos, mas as suas limitações em termos de disponibilidade de recursos, volatilidade dos custos e impacto ambiental estimularam um interesse crescente em fontes alternativas de alimentação. Nesta busca, a polpa de macaúba (*Acrocomia aculeata*), um coproduto da produção de biodiesel, surge como um candidato promissor que merece uma investigação aprofundada pelo seu potencial para revolucionar a nutrição e a produção suína. Assim, o nosso estudo procurou otimizar a nutrição dos suínos através da integração estratégica da inclusão de polpa de macaúba nas dietas dos suínos. Dessa forma, propusemos dois estudos para nortear nossa investigação. No estudo I, objetivou-se avaliar o equilíbrio e a digestibilidade da matéria seca (MS), proteína bruta (PB), nitrogênio (N) e energia da polpa de macaúba em dietas de suínos em terminação. Ao compreender a interação nutricional entre este alimento e os processos digestivos de suínos, pretendemos fornecer informações valiosas para que a polpa de macaúba possa ser utilizada como ingrediente alternativo nas dietas suínas. No estudo II, investigamos os efeitos da substituição parcial do milho pela polpa de macaúba sobre o desempenho zootécnico, as características da carcaça e a qualidade da carne de suínos em crescimento e terminação; e se diferenças nos valores genéticos para consumo alimentar residual (CAR) poderiam influenciar as respostas dos animais à inclusão dietética da polpa de macaúba. Pretendíamos, assim, descobrir se certas origens genéticas podem sinergizar de forma mais eficaz com este coproduto, abrindo potencialmente novos caminhos para estratégias de alimentação de precisão. No estudo I, vinte e quatro suínos machos castrados em terminação (66,3 ± 0,7 kg PC) foram alojados individualmente em gaiolas metabólicas suspensas distribuídas em duas salas climatizadas. O ensaio de digestibilidade foi conduzido em um delineamento em blocos completos casualizados, compreendendo dois blocos (salas climatizadas), quatro tratamentos dietéticos e seis repetições por tratamento. A dieta referência (DR) foi uma dieta completa a base de milho e farelo de soja formulada para atender ou superar as exigências nutricionais de suínos machos castrados em terminação com alto potencial genético e desempenho regular-médio. As dietas testadas continham proporções variadas da DR e polpa de macaúba: 950 g/kg de DR e 50 g/kg (MAC50), 900 g/kg de DR e 100 g/kg (MAC100) e 850 g/kg de DR e 150 g/kg (MAC150). O período experimental de 12 dias consistiu em um período de adaptação de

7 dias seguido por um período de coleta quantitativa de 5 dias. Urina e materiais fecais foram coletados usando a abordagem marcador a marcador. No estudo II, um total de 282 (34,8 ± 4,40 kg) suínos (machos castrados e marrãs), descendentes de varrões com alto (aCAR) ou baixo (bCAR) valor genético para CAR, foram alojados aos pares em um planejamento fatorial 2 × 2. × 2 com base em seu sexo, valor genético e peso corporal. Dietas com 50 g/kg de inclusão de polpa de macaúba (macaúba) ou sem (controle) foram distribuídas aleatoriamente às baias experimentais, formando-se oito tratamentos: machos castrados de aCAR alimentados com dieta controle; machos castrados aCAR alimentados com a dieta macaúba; machos castrados bCAR alimentados com a dieta controle; machos castrados bCAR alimentados com a dieta macaúba; marrãs aCAR alimentadas com a dieta controle; marrãs aCAR alimentadas com a dieta macaúba; marrãs bCAR alimentadas com a dieta controle; e marrãs bCAR alimentadas com a dieta macaúba. O período experimentou durou 90 dias e foi dividido em crescimento 1 (C1) e 2 (C2), e terminação 1 (T1) e 2 (T2). No estudo I, os animais alimentados com DR tiveram menor excreção fecal de MS e PB em comparação com os animais alimentados com MAC100 e MAC150. A excreção de energia fecal foi maior nos suínos alimentados com macaúba do que nos suínos alimentados com DR. As energias digestível e metabolizável na DR foram maiores ($p < 0,01$) que na MAC100 e MAC150. A digestibilidade aparente total do trato (ATTD) da MS e da energia bruta foi menor na MAC50, MAC100 e MAC150 do que no DR. A ATTD da proteína nos animais alimentados com DR foi maior do que naqueles alimentados com MAC100 e MAC150, embora não tenha diferido dos animais alimentados com MAC50. Os suínos alimentados com a DR tiveram menor excreção fecal de N do que aqueles alimentados com MAC100 e MAC150, mas não diferiram da MAC50. O ATTD de N na DR foi maior que na MAC100 e MAC150, e não diferiu da MAC50. O presente estudo indica que até 50g/kg de polpa de macaúba pode ser utilizada em dietas de suínos em terminação, sem afetar a partição energética, a ATTD da proteína e o aproveitamento de N. Além disso, a inclusão da polpa de macaúba em dietas à base de milho e farelo de soja reduz a proporção de excreção urinária-fecal de N. No estudo II não houve interação entre sexo, valor genético e dieta para os parâmetros de desempenho, características da carcaça e qualidade da carne suína. Os suínos castrados apresentaram maior consumo de ração (CMD), ganho diário (GMD), taxa de conversão alimentar (CA) e peso corporal final do que as fêmeas. O valor genético não afetou nos parâmetros de desempenho avaliados. A inclusão de polpa de macaúba nas dietas dos suínos não afetou nenhum parâmetro de desempenho durante as fases C1, C2 e T1. No entanto, foram observadas redução do CMD e melhora da CA em T2. As marrãs apresentaram menor espessura de toucinho (ET) e maior área de olho de lombo (AOL) do que os machos. Animais aCAR

possuíram maior peso de carcaça quente, AOL, e menor ET do que os animais bCAR. Não houve efeito da inclusão de polpa de macaúba nas características da carcaça. A carne dos machos apresentou menor força de cisalhamento e maior teor de gordura do que a carne das fêmeas. Não houve efeito do valor genético na qualidade da carne suína. A carne de suínos alimentados com dieta de macaúba apresentou menor teor de umidade e capacidade de retenção de água, porém a maciez e a cor não foram afetadas. Conclui-se que a inclusão de 50 g/kg de polpa de macaúba nas dietas dos suínos não afetou nenhum parâmetro de desempenho durante as fases C1, C2 e T1. No entanto, foram observadas redução no CMD e melhora na CA em T2. Independentemente do sexo e do valor genético para CAR, os suínos responderam de forma semelhante à inclusão de polpa de macaúba em suas dietas.

Palavras-chave: Suínos; Coprodutos de biocombustíveis; Eficiência alimentar; Palma; Alimento alternativo.

SUMMARY

CHAPTER 1

1. GENERAL INTRODUCTION

Ensuring a stable feed grains supply and meeting the demand for meat continues to pose a fundamental unsolved challenge with profound implications for global food security objectives. The primary drivers exerting the greatest impact on the worldwide food demand include population expansion, escalating calorie intake, and evolving consumption behaviors (Department for Food, Environment and Rural Affairs - Defra, 2021). Moreover, swift economic growth and urbanization led to a transformation in people's dietary habits and nutritional preferences, with an increasing demand for animal-source food, which is inherently linked to a growing demand for grains and oilseeds (Zhu, Wang, and Zhu, 2023).

To further intensify this demand, concerns about clean and renewable energy motivated the search for alternatives to fossil fuels. Biofuels, specifically bioethanol and biodiesel, represent a category of fuels derived from biomass. Currently, the primary sources for ethanol production include maize (constituting about 60%), sugarcane (around 25%), molasses (2%), wheat (3%), and the remaining percentage sourced from other grains, cassava, or sugar beets. In the case of biodiesel, the majority (approximately 75%) is produced from vegetable oils, with rapeseed oil accounting for 20%, soybean oil for 25%, palm oil for 30%, and an additional 20% sourced from used cooking oils (Organisation for Economic Co-Operation and Development – OECD, 2023).

Over the past decade, global biodiesel production has increased from 31,188 to 55,199 million liters in 2023. This growth is primarily ascribed to higher blending targets in developing countries (OECD, 2023). Notably, Brazil has witnessed a substantial demand for biodiesel, driven by the National Program of Production and Use of Biodiesel (PNPB) and associated legislation. At the present, the blending of biodiesel into diesel has increased from 10% to 12%. Forecasts indicate a continued upward trajectory, reaching 13%, 14%, and 15% in 2024, 2025, and 2026, respectively (Brazil, 2023). This positions Brazil as a significant global player in both biodiesel production and consumption.

According to National Agency for Petroleum, Natural Gas and Biofuels (ANP, 2023), the main raw material for biodiesel production in Brazil is soybean oil, constituting 72% of national production. However, soybean biodiesel has a suboptimal land-use efficiency, requiring subsidies to remain competitive, which presents opportunities for other oil crops with significant potential in biodiesel production (Popp et al., 2016).

In the pursuit of enhanced oil productivity per hectare, the macauba palm (*Acrocomia aculeata*) stands out with an impressive oil yield, reaching 5,000 kg/ha in an optimal situation (Bhering, 2009). Additionally, it is adapted to various edaphoclimatic zones, including semi-deciduous forests or savanna biomes (Evaristo et al., 2016a). Comparative studies underscore macauba's superiority over traditional oil crops, surpassing soybean with a yield of 5,000 kg/ha/year compared to 650 kg/ha/year. Furthermore, macauba demonstrates an oil yield comparable to African palm (*Elaeis guineensis*), which currently constitutes the primary source of vegetable oil, at 5,000 kg/ha/year versus 6,000 kg/ha/year (Evaristo et al., 2016b; Colombo et al., 2018). This positions macauba as a promising alternative oil crop, rendering it a fitting raw material for the production of biodiesel (Navarro-Diaz et al., 2014) and aviation biokerosene (Fávaro and Rocha, 2022).

Macauba cultivation proves to be viable for small-scale farmers. The cost of commercial crops, priced at 6.64 USD/ton in 2011, demonstrated strong competitiveness in comparison to other crops during the same period, such as jatropha (*Jatropha curcas*) at 51.02 USD/ton, castor bean (*Ricinus communis L.*) at 164.28 USD/ton, and soybean at 85.81 USD/ton (da Silva César et al., 2015; Brazilian Central Bank – BCB, 2023). Currently, the cost of macauba commercial crops in Brazil in 2022 was 115.42 USD /ton, which was smaller than soybean (312,70 USD) (National Supply Company – CONAB, 2023; BCB, 2023).

Another benefit of macauba is its ability to be integrated into anthropized areas such as deforested sites and existing pastures, creating an agroforestry system without compromising pasture yield and playing a significant ecological role in the recovery of degraded areas (Mota et al., 2011). The past two decades have starkly revealed that the true agricultural frontier in Brazil has primarily encompassed low-yield pastures (Nogueira and Capaz, 2013). Therefore, a crucial element of land utilization in biofuel production, particularly within Brazil, lies in the opportunity to rehabilitate degraded areas and revitalize such lands for economic purposes. This is particularly significant given that in Brazil, more than 100 million hectares are used for pastureland, of which 9.9 million are made up of degraded pastures (IBGE, 2006).

Similar to African palm, two types of oil are extracted from macauba fruits. From the kernel is obtained a fine oil, characterized by its richness in lauric acid (44%) and oleic acid (26%), which exhibits significant potential for high-end applications within the food, pharmaceutical, and cosmetic industries (Bhering, 2009). On the other hand, the oil extracted from the pulp holds substantial promise for biodiesel production due to its high content of monounsaturated fatty acids (> 50%), mainly the oleic acid (> 50%), highlighted by its resistance to oxidation and operability at low temperatures (Hiane et al., 2005; Coimbra and Jorge, 2011a). In addition, studies have indicated that the development of acidity in macauba pulp oil is significantly slower than in palm oil (Hiane et al., 2005; Colombo et al., 2018). This is crucial because transesterification, a critical stage in biodiesel production from vegetable oils, depends on the oil's acidity values. Higher oil acidity values are detrimental to its viability (Meher, Sagar, Naik, 2006).

The widespread adoption of macauba palm as a key biofuel source hinges on successful research outcomes in domesticating the species, cultivating high-quality seedlings, and implementing sustainable plantation models. Additionally, the development and application of personalized harvest and postharvest technologies are essential for achieving this transition (Motoike et al., 2013; Cardoso et al., 2017).

While still in its early stages and emerging, the developing macauba production chain demonstrates sustainable growth and significant potential. An essential breakthrough was achieved by overcoming the bottleneck of dormancy and seed germination, increasing the natural germination rate from 5% to over 80% within a short and uniform period (Motoike et al., 2007). This technological advancement triggered the inception of the new macauba production chain in Brazil (Fávaro and Rocha, 2022).

The current assessment indicates that macauba is entering a positive bioeconomic cycle, encompassing cultivation, agronomic stages, and industrial processing (Fávaro and Rocha, 2022). In Brazil, numerous commercial cultivation programs are underway at various developmental stages, with several hectares already planted, underscoring its viability as a strategy, although it is not yet at a competitive level with established commodities (Cabrera et al., 2022).

The Inocas Macauba Project, situated in the Cerrado biome region of Alto Paranaíba-MG, pursues three primary objectives. Firstly, it aims to plant 2,000 hectares of macauba in a silvopastoral system, revitalizing degraded pasture areas in collaboration with smallholders, potentially sequestering 600,000 tons of carbon dioxide (CO_2). Secondly, the project seeks to facilitate the extractive collection of up to 1,500 tons of fruits annually. Lastly, it endeavors to establish a model plant for fruit processing. The initiative operates on a replicable, scalable, and profitable business model, encouraging other livestock farmers to replicate its concept. By integrating pastures in the Cerrado biome with macauba, this approach enables oil production without deforestation and supports ecological restoration. Detailed information on these endeavors can be found in Franco and Zimpel (2022).

Another project by the company Soleá, which created the startup S.Oleum, a Brazilian AgTech and CleanTech dedicated to reforestation and restoration of degraded and low-productivity areas, involves three stages. The initial phase aims to plant 150 thousand hectares by 2030 in an agroforestry format, integrating macauba with other crops. Currently, a pilot area of 700 hectares is underway. The second stage aims to implement an additional 500,000 productive hectares over five years to introduce industries like green hydrogen production. The final stage, spanning another five years with an additional one million hectares, focuses on significant genetic and operational enhancements. At this juncture, the goal is to achieve large-scale production of sustainable high-value finished products, competing cost-effectively with fossil alternatives like methanol, ammonia, hydrogen, biofuels, and serving as sustainable raw materials for petrochemicals (GrowPlus, 2021).

While the potential and prospects of macauba oil as a biodiesel feedstock are clear, this industrial chain still poses a significant bottleneck for its expansion. Investing in perennial species like macauba entails a lengthy period, approximately five years before fruit production commences (Pimentel, 2012; Fávaro and Rocha, 2022). This extended timeline poses a financial challenge for farmers, requiring them to cover project implementation costs and endure an initial income-free period. This obstacle, particularly for those lacking sufficient capital and relying on credit lines, acts as a limiting factor for new entrants (Jager, 2023).

The macauba oil yield and quality is highly susceptible to factors such as soil conditions, climate, and cultivation practices. Additionally, macauba fruits ripen slowly and its fruiting is supra-annual – less than one cycle per year –, meaning its fruits are not available for harvest all year round; as a result, macauba alone cannot sustain a profitable biodiesel plant, requiring its association with other feedstocks to ensure year-round operation (Montoya et al., 2016; Bhering, 2009).

As macauba production chain is mainly extraction-based, there are no mechanized harvesting methods and the fruits are manually collected, either directly from the bunch or from the ground after naturally detaching (Cardoso et al., 2017). However, contact with the soil lowers the oil quality. According to Evaristo et al. (2016b), the degradation becomes more pronounced after fruits been in contact with the soil for seven days or longer. Beyond this period, the fruits no longer tolerate storage and are unresponsive to fungicide treatment. Consequently, they must be promptly processed upon removal from the field to ensure the production of oil with low acidity.

In brief, macauba palm fruits processing stages encompass fruit drying, husk removal, pulping, pulp pressing for oil extraction, breaking the endocarp, separating endocarp and nuts, crushing the nuts, and subsequent oil extraction through pressing and/or organic solvent methods (Cardoso et al., 2017). Effective processing methods generate valuable co-products, such as shells, pulp cake, endocarp, and seed cake, which find various applications, including use as animal feed (Evaristo et al., 2016a). According to Poetsch et al. (2012), a plantation area of one hectare yields 20 metric tons of macauba fruits, generating around 5 tons of pulp cake. Considering S.Oleum's cultivation projections, it is anticipated that, in 2030, around 700,000 tons of macauba pulp cake will be produced.

Efficient biomass utilization centers on circularity within agricultural production, as proposed in food systems research (de Boer and van Ittersum, 2018). This concept emphasizes the reduction of food losses and waste, giving precedence to biomass for human consumption and reincorporating any residue back into the system. Livestock plays a pivotal role in this cycle by converting biomass unsuitable for human consumption into food (van Zanten et al., 2016). Thus, diminishing the demand for feed grains and oilseeds in the pork chain through alternative feedstuff use, plays a pivotal role in addressing this challenge (Zijlstra and Beltranena, 2019).

To strike the equilibrium between environmental preservation and economic advancement, the bioenergetic industry must cultivate partnerships with producers for proper waste disposal. Since the macauba pulp can account for 27.16% of the total residue from macauba fruit oil extraction, notably, this co-product, once considered a waste, emerges as a distinctive resource with attributes that align with the principles of sustainable and precision nutrition (Evaristo et al., 2016a; Ali et al., 2017).

There is an emerging strategy of using alternative ingredients, particularly co-products from the bioenergy sector, to achieve an increase in feed supply at lower costs (Zijlstra and Beltranena, 2013; van Zanten et al., 2015). Standing at the intersection of agricultural waste and animal nutrition research, industrial co-products have become prominent due to their low cost, infeasibility for human consumption, and significant pollution potential (Ali et al., 2017). Beyond their nutritional merits, biofuel co-products in animal feed can help mitigate the environmental consequences of bioenergetic industry expansion (Popp et al., 2016).

This narrative is intimately tied to the economic sustainability of the biofuel sector, which depends on the efficient use of both biofuel and its co-products generated. For instance, the inclusion of dried distillers' grains with solubles (DDGS), a co-product of ethanol manufacturing, in pig diets has the potential to reduce corn and soybean meal use, thereby mitigating the land use consequences associated with biofuel production (Stein and Shurson, 2009). According to Westcott (2015), ethanol industries redirect 33% of processed corn back to animal feed, and one metric ton of DDGS can effectively replace 1.22 metric tons of feed consisting of corn and soybean meal in the United States.

Abundant in carbohydrates, bioactive compounds (pro-vitamin A carotenoids and tocopherols), and mineral matter, essentially potassium, calcium and phosphorus macauba pulp displays potential as an alternative feedstuff in pig nutrition (Ramos et al., 2008; Coimbra and Jorge, 2011b). This co-product contains no toxic elements, such as jatropha (*Jatropha curcas*) and castor bean (*Ricinus communis L.*) cakes, and exhibits a robust nutritional profile (Xavier and Costa, 2020). The primary fatty acids identified in macauba pulp include oleic acid (C18:1), palmitic acid (C16:0), and linoleic acid (C18:2) (Navarro-Díaz et al., 2014; Lescano et al., 2015).

Furthermore, its value extends beyond its nutritional aspects; the fibrous richness of macauba pulp may contribute to the homeostasis of the gastrointestinal tract's physiological function (Jha and Berrocoso, 2015). Beyond this, its potential to mitigate stomach ulcers (Noblet and Le Goff, 2001), reduce ammonia excretion (Zhao, Wang and Zhang, 2021), and promote pig well-being is reachable (Monteiro-Alfredo et al., 2020). Moreover, integrating macauba pulp into pig diets could facilitate the valorization of an often-overlooked resource, aligning with the broader concept of resource optimization (Silva Junior, 2015).

Due to its elevated energy content (5000–6300 kcal of gross energy/kg), studies underscore the potential of macauba pulp to partially replace corn in pig diets (Pereira, 2013; Dias et al., 2021). Pereira (2013) observed no significant change in energy digestibility with the inclusion of macauba pulp in the diets of growing pigs (28 kg BW). Furthermore, Dias et al. (2021) reported that the partial replacement of corn with macauba pulp, up to an inclusion level of 50 g/kg, exerted no adverse effects on the performance and body composition of growing pigs (30–65 kg BW). Additionally, Costa Júnior et al. (2015) noted that, irrespective of the corn replacement level with macauba pulp (50, 100, 150, or 200 g/kg), it had no impact on the daily weight gain and improved the feed efficiency of finishing pigs (70–100 kg BW).

As macauba pulp is still an emerging product, it has yet to establish a presence in the market. Consequently, this co-product resulting from macauba oil extraction is regarded as a waste product and assigned a price of zero at the oil processing factory level. Incurred costs encompass both processing and transportation from the macauba processing plant to the feed mill (Ali et al., 2017).

Dias et al. (2021) demonstrated that incorporating macauba pulp in pig diets at crescent levels (50, 100, and 150 g/kg) provided substantial metabolizable energy and led to significant savings of around 2.4%, 4.7%, and 7.2% savings compared to a corn-soybean meal control diet.

Ali et al. (2017) demonstrated the economic benefits of alternative diets, with the macauba kernel cake-based diet showing a 14% price drop compared to the conventional diet based on corn and soybean meal. However, increasing the replacement of macauba co-products may necessitate lipid sources, potentially raising diet costs.

Focusing on the current Brazilian scenario, the use of co-products appears promising. Although large quantities of corn and soybeans are produced within, replacing these ingredients with co-products produced locally on marginal land can potentially reduce the environmental impact of pig production in terms of global warming and land use. However, in the process of evaluating the feasibility of adopting an alternative ingredient and justifying the shift in dietary formulation, careful assessment of factors such as composition, quality, commercial availability, physical attributes, and the presence of anti-nutritional factors is essential (Bellaver and Ludke, 2004).

Given these considerations, it is crucial to elucidate the impacts of feeding pigs with macauba pulp, ranging from growth performance to nutrient utilization, carcass characteristics, and pork quality, while considering potential interactions with dietary components and genetics. Our study aims to enhance pig nutrition through the strategic integration of an alternative feed resource, paving the way for a more sustainable and resilient swine industry.

2. THESIS OBJECTIVES

Objective 1: to evaluate the effects of including macauba pulp into the diets of growing-finishing pigs. By monitoring growth performance, carcass traits, and pork quality, this research endeavors to understand the extent to which macauba pulp can influence pig. Moreover, this study investigates whether differences in residual feed intake breeding values could impact pigs' response to macauba pulp inclusion.

Objective 2: to evaluate balance and digestibility of nutrient and energy of macauba pulp in diets of finishing pigs. The study seeks to unravel the dynamics of dry matter, protein, nitrogen, and energy, showing the potential of macauba pulp as feedstuff for pigs.

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CHAPTER 2

Evaluation of macauba (*Acrocomia aculeata*) pulp as alternative raw material for finishing pigs: balance and digestibility of dry matter, nitrogen, and energy

ABSTRACT

This study aimed to evaluate the balance and digestibility of dry matter (DM), crude protein (CP), nitrogen (N), and energy of macauba pulp (*Acrocomia aculeata*) in diets of finishing pigs. Twenty-four finishing barrows (66.3 ± 0.7 kg BW) were individually housed in suspended metabolism crates allotted in two climatic-controlled rooms. The research trial was conducted in a randomized complete block design, comprising two blocks (climatic-controlled rooms), four dietary treatments, and six replicates per treatment. The reference diet (RD) was a complete corn-soybean meal diet formulated to meet or exceed the nutritional requirements of finishing barrows with high genetic potential with regular-medium performance. The test diets comprised varying proportions of RD and macauba pulp: 950 g/kg of RD and 50 g/kg (MAC50), 900 g/kg of RD and 100 g/kg (MAC100), and 850 g/kg of RD and 150 g/kg (MAC150). The 12-day experimental period consisted of a 7-day adaptation period followed by a 5-day quantitative collection period. Urine and fecal materials were collected using the marker-to-marker approach. Pigs fed RD had lower ($p < 0.01$) fecal excretion of DM and CP compared to pigs fed MAC100 and MAC150. Fecal energy excretion was higher ($p < 0.01$) in macauba fed pigs than in pigs fed RD. Digestible and metabolizable energies in RD were higher ($p < 0.01$) than in MAC100 and MAC150. The apparent total tract digestibility (ATTD) of dry matter and gross energy was lower ($p < 0.01$) in MAC50, MAC100, and MAC150 than in RD. The ATTD of CP in pigs fed RD was higher ($p < 0.01$) than in pigs fed MAC100 and MAC150, although not differing from pigs fed MAC50. Pigs fed RD had lower ($p < 0.01$) fecal N excretion than pigs fed MAC100 and MAC150 but did not differ from MAC50. The ATTD of N in RD was higher ($p < 0.01$) than in MAC100 and MAC150 and did not differ from MAC50. The present study indicates that, up to 50g/kg, macauba pulp can be used in diets of finishing pigs, without affecting the energy partitioning and N utilization. In addition, including macauba pulp in corn-soybean meal based diets lowers the urinary-to-fecal N excretion ratio.

Keywords: Swine; Nitrogen balance; Macaw palm; Pig nutrition; Nutrient digestibility.

1. INTRODUCTION

In the 1980s, the critical global energy situation prompted efforts to reduce Brazilian dependence on imported oil (Nogueira and Capaz, 2013). In this scenario, macauba (*Acrocomia aculeata*) biodiesel has been highlighted as an alternative to fossil fuels due to its ecological nature, high oil yield, exceeding 4,000 kg/ha/year in optimal conditions (Silva et al., 2016), and quality, containing approximately 73% unsaturated fatty acids (Evaristo et al., 2016a). In addition, it thrives in diverse edaphoclimatic zones, including semi-deciduous forests or savanna biomes (Ciconini et al., 2013; Henderson, Galeano and Bernal, 2019).

Comparative studies highlight macauba's superiority over traditional oil crops, exceeding soybean with an impressive yield of 5,000 kg/ha/year compared to 650 kg/ha/year. Furthermore, macauba demonstrates an oil yield comparable to African palm (*Elaeis guineensis*), the current primary source of vegetable oil, at 5,000 kg/ha/year versus 6,000 kg/ha/year (Evaristo et al., 2016a; Colombo et al., 2018). After the post-pressing oil extraction process, pulp residues constitute 27.16% of the overall residue, presenting themselves as an economically viable alternative in animal feed (Evaristo et al., 2016b; Ali et al., 2017).

Dias et al. (2021) demonstrated that macauba pulp can be considered an alternative substitute for corn in the diets of growing pigs, with up to 100 g/kg inclusion, as it does not affect pigs' daily weight gain and feed conversion rate. Moreover, Costa Júnior et al. (2015) found that macauba pulp inclusion, up to 103 g/kg, can enhance lean meat deposition without affecting backfat thickness and the performance of finishing pigs. Recently, Moreira et al. (2022) showed that incorporating macauba pulp (at 50 g/kg) into pig diets had no impact on performance during the growing phase. Additionally, the inclusion of this co-product improved feed efficiency in the finishing phase. The study also revealed no significant effects of macauba pulp inclusion on carcass traits, pork color, and tenderness. These findings suggest that pork from pigs fed with macauba pulp as a partial replacement for corn is anticipated to have a comparable level of acceptability to pork from pigs fed a conventional diet.

The utilization of alternative ingredients to replace traditional feed grains requires a comprehensive understanding of their potential benefits and limitations (Bellaver and Ludke, 2004). Although the studies mentioned above did not reveal any deleterious effects of macauba pulp on the performance, carcass traits, and pork quality, the nutritional value of macauba pulp for swine remains insufficiently documented.

For any feed ingredient in swine diets, a thorough understanding of the digestible nutrient content is essential to ensure accurate diet formulation (Widyaratne and Zijlstra, 2007). Additionally, considering the significant concern in the swine industry regarding nutrient excretion and its potential environmental impact, it is crucial to assess the effects of macauba pulp on nutrient digestibility and energy values. Thus, this study aims to evaluate the balance and digestibility of dry matter, nitrogen, and energy of macauba pulp (*Acrocomia aculeata*) in diets for finishing pigs.

2. MATERIAL AND METHODS

The Institutional Animal Care and Use Committee at the School of Agricultural and Veterinarian Sciences of São Paulo State University (protocol No. 878/19) reviewed and approved the experimental protocol.

2.1. Animals, housing and diets

The digestibility essay was conducted at the experimental facilities of the São Paulo State University (UNESP), Brazil. Twenty-four finishing barrows (Topigs Norsvin) with an average initial body weight of 66.3 ± 0.7 kg were individually housed in suspended metabolism crates (Pekas, 1968) allotted in two climatic-controlled rooms. The research trial was conducted in a randomized complete block design, comprising two blocks (climatic-controlled rooms), four dietary treatments, and six replicates per treatment. The reference diet (RD; Table 1) was a complete corn-soybean meal diet formulated to meet or exceed the nutritional requirements of finishing barrows with high genetic potential with regular-medium performance (Rostagno et al., 2017). The test diets comprised varying proportions of RD and macauba pulp: 950 g/kg of RD and 50 g/kg (MAC50), 900 g/kg of RD and 100 g/kg (MAC100), and 850 g/kg of RD and 150 g/kg (MAC150).

Table 1 - Composition and calculated nutritional values of reference diet.

Ingredients (%)	
Corn	73.40
Soybean meal	22.40
Soybean oil	1.44
Calcium carbonate	0.55
Dicalcium phosphate	0.70
Salt	0.40
L-Lysine-HCl	0.05
Choline chloride	0.05
Mineral and vitamin premix[1]	1.00
Analyzed content	
Gross energy (kcal/kg)	3939
Crude protein (%)	14.67
Ash (%)	4.93
Crude fiber (%)	3.61
Calculated nutritional composition	
Metabolizable energy (kcal/kg) [2]	3300
Net energy (kcal/kg) [2]	2516
Calcium (%)	0.46
Total phosphorus (%)	0.44

[1] Supplied per kg of diet (as-fed basis): Vit. A (5.250 UI); Vit. D3 (750 UI); Vit. E (11 UI); Vit. K3 (1.5 mg); Vit. B1 (1 mg); Vit. B2 (2,4 mg); Vit. B6 (1 mg); Niacin (30 mg); Pantothenic acid (8.1 mg); Folic acid (0.53 mg); Biotin (0.05 mg); Vit. B12 (16.5 mcg); Copper (13.5 mg); Iodine (0.19 mg); Manganese (37.5 mg); Selenium (0.15 mg); Zinc (72 mg); Iron (72 mg); and Cobalt (0.19 mg). [2] Values calculated using the EvaPig software program (version 1.3.1.4; INRA, Saint-Gilles, France).

Table 2 - Macauba pulp chemical composition.

Item	
Dry matter, %	97.13
Ash, %	5.02
Crude protein, %	5.86
Crude fiber, %	43.39
Ether extract, %	24.23
ADF, %	39.35
NDF, %	54.69
Gross energy, kcal/kg	6357

ADF = Acid detergent fiber; NDF = Neutral detergent fiber

The metabolism crates had a low-pressure nipple drinker, a stainless-steel self-feeder, a slatted floor, and were equipped with a collection tray protected with a fine-mesh net allowing separate collection of feces and urine. The room temperature was kept at 24° C by air conditioning. Both rooms used an exhaust fan with air movement capacity of 115 m^3/min to perform air renewal. Approximately 10 hours of natural lighting were provided by glass windows.

2.2. Feeding and sample collection

The experimental trial lasted 12 days, with the initial seven days dedicated to acclimating the animals to the facilities, diets, and experimenters. The subsequent five days were allocated for feces and urine collection, following the protocol outlined by Sakomura and Rostagno (2016). Individual weights of the pigs were recorded at the commencement and conclusion of both the adaptation and collection periods. The adaptation period was used to establish the level of feeding maintained throughout the collection period.

The feed was provided at 08:00h and 16:00 hours, and the daily feed allowance was established based on the metabolic weight ($BW^{0.75}$). Feed allowance was adjusted according to the lowest feed intake observed within each replicate during the adaptation period, allowing all pigs to consume equal amounts of nutrients per metabolic weight. Water was supplied *ad libitum* throughout the trial.

Urine and fecal materials were collected following the marker-to-marker approach described by Adeola (2000). On the morning of day 8, each pig received 100g of feed mixed with 3g of an indigestible marker (Fe_2O_3) to signal the start time-point of fecal collections. Fecal collections were initiated when the start marker appeared in the feces. Feces were collected twice a day, weighed, and immediately stored in a -20° C freezer to avoid samples fermentation. On day 12, pigs were fed 100g of feed mixed with 3g of marker (Fe_2O_3) to determine the end time-point of the fecal collection, which stops with the second appearance of the colored feces. Quantitative collection of urine started and finished on the morning of days 8 and 12, respectively. Urine was collected in buckets containing a preservative of 20 mL of HCl (1:1) to avoid bacterial proliferation and nitrogen losses. A glass wool was placed on the top of the collection tanks to trap any fecal material contained in the urine. Total daily urine was weighed and a 20% aliquot was stored at -20° C freezer for subsequent analysis.

2.3. Chemical analysis

After completing sample collections, fecal samples were thawed, homogenized, oven-dried at 55° C for 72 hours, and finely ground. Urine samples were prepared and lyophilized before analysis as previously described (Kim et al., 2009). Samples of macauba pulp, dietary treatments and feces were analyzed for dry (DM) and mineral matter (MM), crude protein (CP), and crude fiber (CF) according to standard methods (AOAC, 1990) (method 934.01, 942.05, 954.01, and 962.09, respectively). The gross energy (GE) of samples (macauba, diets, feces, and urine) was measured by an adiabatic bomb calorimetry (Model 6300, Parr Instruments, Moline, IL, USA). Nitrogen content (N) was analyzed using a LECO nitrogen analyzer (Leco Corporation, St. Joseph, MI).

2.4. Calculations and statistical analysis

The coefficients of apparent total tract digestibility (ATTD) were calculated for each treatment, representing the percentage of ingested components retained in the animal's body and not excreted in feces and urine (Adeola, 2000). The digestible energy content (DE) was determined by subtracting the gross energy in feces from the gross energy of the diets. Additionally, the metabolizable energy content (ME) of the diets was calculated by subtracting the energy lost in urine from the digestible energy.

Data were initially tested for normality using the Shapiro-Wilk test and submitted to analysis of variance (ANOVA) using the package “ExpDes.pt” of software R (version 3.4.4; R Core Team 2018). The treatment means were compared to the control group by Dunnett's test at an alpha level of 0.05 using the package “DescTools” of software R (version 3.4.4; R Core Team 2018). The individual pig was considered the experimental unit.

3. RESULTS

During the trial, pigs were in good health and well-adapted to the installations, diets, and experimenters. Therefore, when they existed, differences in balance and digestibility of dry matter, protein, nitrogen, and energy were associated, specifically, with an effect of macauba pulp inclusion. During the 12-day experimental period, the ambient temperature and the relative humidity averaged 24.4 ± 2.0°C and 80.9 ± 9.0% in room 1 and 24.5 ± 2.4°C and 76.5 ± 8.7% in room 2. Overall, pigs started the trial weighing 66.3 ± 0.7kg and finished at 73.8 ± 1.4kg.

Dry matter, energy, and crude protein intake did not differ among experimental treatments (Table 3). Pigs fed RD had lower ($p < 0.01$) fecal excretion of DM and CP than pigs fed MAC100 and MAC150, but RD did not differ from MAC50. Fecal energy excretion was higher ($p < 0.01$) in pigs fed MAC50, MAC100, and MAC150 than in pigs fed RD. The digestible and metabolizable energies in RD were higher ($p < 0.01$; Table 4) than in MAC100 and MAC150, but RD did not differ from MAC50. The ATTD of DM and GE was less ($p < 0.01$) in MAC50, MAC100, and MAC150. The ATTD of CP in pigs fed RD was higher ($p < 0.01$) than in pigs fed MAC100 and MAC150, but RD did not differ from pigs fed MAC50.

Table 3 - Effects of dietary levels of Macauba (*Acrocomia aculeata*) pulp on intake and excretion of dry matter, energy, and protein in 70 kg BW finishing pigs.

	Dietary treatments				RMSE[2]	Diet effect (P-value)
	RD	MAC50	MAC100	MAC150		
Initial BW, kg	67.20	66.33	66.01	65.53	3.953	0.93
Final BW, kg	73.75	74.68	75.03	71.88	3.686	0.57
DM intake, g/d	1475	1446	1513	1447	118.9	0.80
DM excretion, g/d	112	159	200*	230*	29.1	<0.01
Energy balance, kcal/d						
GE intake	5811	5782	6069	5971	477.3	0.77
GE excretion						
In feces	474	682*	882*	1056*	124.5	<0.01
In urine	166	165	191	147	27.1	0.13
Protein balance, g/d						
Intake	216	199	204	184	16.3	0.06
Protein excretion						
In feces	19	23	29*	32*	5.0	<0.01
In urine	112	96	108	88	16.4	0.14

[1] Root mean squared error; body weight (BW); RD = corn-soybean meal reference diet; MAC50 = 950 g/kg of RD + 50 g/kg of macauba pulp; MAC100 = 900 g/kg of RD + 100 g/kg of macauba pulp; MAC150 = 850 g/kg of RD + 150 g/kg of macauba pulp; *Different from the control group (Dunnett's test); DM = Dry matter, GE = Gross energy.

Table 4 - Effects of dietary levels of Macauba (*Acrocomia aculeata*) pulp on energy partition of diets and digestibility coefficients.

	Dietary treatments				RMSE[1]	Diet effect (P-value)
	RD	MAC50	MAC100	MAC150		
Diet						
GE, kcal/g**	3939	4000	4012	4126		
DE, kcal/g	3615	3528	3429*	3389*	79.5	<0.01
ME, kcal/g	3503	3414	3302*	3288*	77.9	<0.01
ATTD[2], %						
Dry matter	92.34	89.03*	86.83*	83.93*	1.860	<0.01
Digestible energy	91.76	88.19*	85.47*	82.14*	1.961	<0.01
Metabolizable energy	88.92	85.35*	82.31*	79.68*	1.918	<0.01
Crude protein	91.09	88.40	85.79*	82.44*	2.521	<0.01

[1] Root mean squared error; [2] Apparent total tract digestibility; RD = corn-soybean meal reference diet; MAC50 = 950 g/kg of RD + 50g/kg of macauba pulp; MAC100 = 900 g/kg of RD + 100 g/kg of macauba pulp; MAC150 = 850 g/kg of RD + 150 g/kg of macauba pulp; *Different from the control group (Dunnett's test); **Analyzed value; GE = Gross energy; DE = Digestible energy; ME = Metabolizable energy.

Nitrogen intake did not differ among experimental treatments (Table 5). Pigs fed RD had lower ($p < 0.01$) fecal nitrogen excretion than pigs fed MAC100 and MAC150, but it did not differ from MAC50. The nitrogen retained was not different among experimental diets. The ATTD of nitrogen in RD was higher ($p < 0.01$) than in MAC100 and MAC150 and did not differ from MAC50.

Table 5 - Effects of dietary levels of Macauba (*Acrocomia aculeata*) pulp on nitrogen utilization, net protein utilization, and biological value of feed protein.

	Dietary treatments				RMSE [1]	Diet effect (*P-value*)
	RD	MAC50	MAC100	MAC150		
Nitrogen balance						
Intake, g/d	34	32	33	29	2.6	0.06
Excretion, g/d						
In feces	3	4	5*	5*	0.8	<0.01
In urine	18	15	17	14	2.6	0.13
Retained, g/d	14	13	11	10	2.5	0.15
ATTD[2], %	91.09	88.40	85.79*	82.44*	2.522	<0.01

[1] Root mean squared error; [2] Apparent total tract digestibility; RD = corn-soybean meal reference diet; MAC50 = 950 g/kg of RD + 50g/kg of macauba pulp; MAC100 = 900 g/kg of RD + 100 g/kg of macauba pulp; MAC150 = 850 g/kg of RD + 150 g/kg of macauba pulp; *Different from the control group (Dunnett's test).

4. DISCUSSION

We hypothesize that macauba pulp could be an alternative ingredient in finishing pig diets. Therefore, this study was conducted to evaluate the balance and digestibility of nutrients and energy in macauba pulp when included in the diets of finishing pigs. The study aims to unravel the dynamics of dry matter, protein, nitrogen, and energy, highlighting macauba pulp potential as a valuable feedstuff.

This study reveals that macauba pulp exhibits high levels of neutral detergent fiber (54.69%), acid detergent fiber (39.35%), and ether extract (24.23%), along with low levels of CP (5.86%), highlighting its fibrous and energetic characteristics. Additionally, macauba, found throughout Brazil in all five regions (Ampese et al., 2021), may vary in nutritional value and chemical composition due to its widespread distribution, diverse origins, and extraction methods (Pereira, 2013).

The nutrient composition of macauba pulp varies due to its nature as a co-product of biodiesel production. In our study, the macauba pulp used had a higher dry matter (DM) value (97.13%) compared to values reported by Coimbra and Jorge (2011) (94.02%), Costa Júnior et al. (2015) (88.23%), and Pereira (2013) (95.49%). The crude protein (CP) content in the macauba pulp utilized in this study was 5.86%, differing from values reported by Coimbra and Jorge (2011) (6.72%), Costa Júnior et al. (2015) (4.11%), and Pereira (2013) (5.37%). Herein, the ash content of macauba pulp (5.02%) exceeded that reported by Coimbra and Jorge (2011) and Pereira (2013), 2.17% and 3.53%, respectively. The gross energy was also higher (6357 kcal/kg) than values reported by Pereira (2013) (5015 kcal/kg) and Moreira et al. (2022) (3974 kcal/kg). These variations are normal due to differences in origin, growing conditions, climate, and oil extraction methods (Hiane et al., 2006). Additionally, macauba palm fruits undergo processing using outdated equipment initially designed for other biomass types, resulting in an inefficient process with a variable coproduct composition (Cardoso et al., 2017). The diverse conditions in macauba pulp studies emphasize the need for standardized and high-quality information to aid in precise diet formulation.

Alternative ingredients, including co-products from the food and biofuel industries (such as sugar beet pulp, soybean hulls, macauba pulp, and distillers' dried grains with solubles - DDGS), have been integrated into pig diets to boost feed supply, offering a promising solution to the food-feed-fuel conflict (Li et al., 2021). Nevertheless, these feedstuffs are fibrous and often perceived as having lower nutritional value, which can impact their utilization in swine nutrition negatively (Zhao, Wang, and Zhang, 2021).

In the present study, dry matter (DM) excretion was higher in pigs fed MAC100 and MAC150 diets compared to those on RD and MAC50 diets. This observation suggests that including macauba pulp at these levels in the diet could lead to an increase in manure volume. The elevated DM excretion may be attributed to the high crude fiber content of macauba pulp, as the addition of a fiber source to the diet has been shown to increase fecal DM excretion in pigs (Widyaratne and Zijlstra, 2006).

While previous studies (Urriola, Shurson, and Stein, 2010; Yang et al., 2021) have reported a negative correlation between the increase in dietary fiber and digestible and metabolizable energies, the lowest level of macauba pulp inclusion (50 g/kg), which increased the fiber content by 1.15% compared to the reference diet, did not affect the energy partitioning of the diets. Different sources of fiber, depending on their specific physicochemical properties, can affect nutrient and energy digestibility in varying ways (Ndou, Kiarie, and Nyachoti, 2019; Zhao et al., 2019). Additionally, the physiological state of the animal and the environment also plays an important role in nutrient and energy utilization (Sakomura and Rostagno, 2016).

As expected, the dietary fiber content in the diets increased with the inclusion of macauba pulp, rising by 3.61%, 4.76%, 5.63%, and 7.70% for RD, MAC50, MAC100, and MAC150, respectively. Consequently, there were reductions in the digestibility coefficients of dry matter and energy from the lowest inclusion level (50 g/kg), and a significant decrease in crude protein digestibility emerged at the 100g/kg inclusion level. These declines in nutrient and energy digestibility can be attributed to an acceleration in intestinal transit rate induced by the heightened dietary fiber content. This, in turn, limits the physical and enzymatic action on digesta, as well as microbial degradation in the hindgut (Dégen et al., 2009; Ndou, Kiarie, and Nyachoti, 2019). Furthermore, as previously noted by Jha and Leterme (2012), fibrous feedstuffs might elevate endogenous N losses, consequently resulting in increased N excretion and leading to a lower apparent total tract digestibility of crude protein.

Our results clearly demonstrate the relationship between increasing macauba pulp inclusion and urinary and fecal N excretion. The inclusion of macauba pulp in corn-soybean meal based diets increased fecal N output from 3 to 5 g/d. This change resulted in a lower urinary-to-fecal N excretion ratio, decreasing from 6.0 for the reference diet to 2.8 when 150 g/kg of macauba pulp was included. It is noteworthy that nitrogen bound with feces is bacterial in nature and tends to be less volatile due to its bonding with the enzyme urease present in feces, which reduces the loss of pollutants like ammonia through volatilization (Mpendulo et al., 2018).

5. CONCLUSION

The present study indicates that, up to 50g/kg, macauba pulp can be used in diets of finishing pigs, without affecting the energy partitioning, protein digestibility and N utilization. In addition, including macauba pulp in corn-soybean meal based diets lowers the urinary-to-fecal N excretion ratio. It's worth noting that the use of macauba pulp in pig nutrition is a relatively new area of research, and more studies are needed to fully understand its nutritional value, potential benefits, and any limitations.

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CHAPTER 3

Growth performance, carcass and pork quality traits of growing-finishing pigs with high and low breeding values for residual feed intake fed diets with macauba (*Acrocomia aculeata*) pulp as alternative raw material

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ABSTRACT

This study evaluated the effects of dietary macauba (*Acrocomia aculeata*) pulp on the growth performance, carcass, and pork traits of growing-finishing pigs; and whether differences in residual feed intake breeding values could influence the pigs' growth responses to macauba pulp inclusion in the diet. A total of 282 (34.8 ± 4.40 kg) pigs (barrows and females), progeny of sires with high (HRFI) or low (LRFI) breeding value for residual feed intake, were pair-housed on the basis of sex, breeding value, and initial BW. Diets with (macauba) or without (control) of 50 g/kg of macauba pulp inclusion were randomly assigned to the experimental pens. There were eight treatment groups: HRFI barrows were fed the control diet; HRFI barrows were fed the macauba diet; LRFI barrows were fed the control diet; LRFI barrows were fed the macauba diet; HRFI female pigs were fed the control diet; HRFI female pigs were fed the macauba diet; LRFI female pigs were fed the control diet; and LRFI female pigs were fed the macauba diet. The trial lasted 90 days and was divided into four phases: growing phase 1 (G1) and 2 (G2); and finishing phases 1 (F1) and 2 (F2). There was no interaction between sex, breeding value, and diet for performance, carcass, and pork traits. Barrows had higher feed intake (ADFI), daily gain (ADG), feed conversion rate (FCR), and final body weight than female pigs. The breeding value had no effect on performance measurements. The inclusion of macauba pulp in the pigs' diets did not affect any growth parameter during G1, G2 and F1 phases. However, reduced ADFI and improved FCR were observed in F2. Female pigs had lower backfat thickness (BF) and higher loin eye area (LEA) than barrows. HRFI pigs had higher hot carcass weight and LEA, and lower BF than LRFI pigs. There was no effect of macauba pulp inclusion on carcass traits. Pork from barrows presented lower Warner–Bratzler shear force and higher fat content than pork from the females. There was no effect of breeding value on pork traits. Pork from pigs fed the macauba diet showed lower moisture content and water-holding capacity. In conclusion, macauba pulp can partially replace corn without reducing the performance of pigs. Regardless of sex and breeding value for RFI, pigs responded similarly to macauba pulp inclusion in diets.

Keywords: Swine; Biofuels coproducts; Feed efficiency; Palm; Alternative feedstuff.

1. INTRODUCTION

Approximately three-quarters of swine production costs are related to feed [1]. The food-feed-fuel conflict has increased the demand and prices of traditional feedstuffs, affecting the profitability of livestock production [2,3]. Reducing commodities dependence (e.g., corn and soybean) by introducing alternative ingredients, such as biofuels industry co-products, is vital to economically and environmentally improve pig production systems [4].

Economic, environmental, and geopolitical concerns over fossil-fuel dependency have intensified the focus on developing renewable energy sources. In this context, due to its large production (4000 L of oil per hectare per year) and high-quality oil (±73% unsaturated fatty acids), Macauba (*Acrocomia aculeata*) has emerged as a raw material for biodiesel production in Brazil [5,6]. After macauba fruit oil extraction, co-products, such as pulp and kernel cakes, are produced and have been indicated as an economically viable alternative in pig feed.

As an omnivore species, pigs are ideal for converting non-human-edible co-products into high-quality food animal protein [2]. Dias et al. [7] reported that up to 100 g/kg of macauba pulp inclusion did not affect growth performance and body composition in growing pigs. In addition, Costa Júnior et al. [8] found that up to 103 g/kg of macauba pulp inclusion improved lean meat deposition without affecting the performance of finishing pigs.

Not only the inclusion of alternative ingredients but also the improvement of the feed efficiency of pigs can contribute to improving the profitability and sustainability of the system. In general, feed efficiency is expressed as the feed conversion ratio (FCR), that is, the ratio between feed intake and weight gain [9]. In turn, selecting pigs with higher growth rates and lower fat deposition can reduce FCR [9]. However, as FCR is a ratio trait, its selection responses can be erroneous [10].

For a more accurate individual comparison of animals, Koch et al. [11] proposed an adjustment of feed intake according to weight gain and average body weight, known as residual feed intake (RFI). Traditionally, RFI is a moderately heritable trait, genetically correlated with rate of gain and backfat thickness [12]. Therefore, it is evaluated as the difference between the feed intake observed and the feed intake expected based on backfat and growth rate [9]. The higher the RFI value, the lower the feed efficiency of the animal [13].

Nevertheless, including alternative feedstuff in commercial farms may alter the predicted performance of current commercial genotypes once pig improvement programs are carried out with pigs fed traditional cereal-based diets [14,15]. Therefore, the objective of this study was to evaluate the effects of dietary macauba pulp on the growth performance, carcass traits, and pork traits of growing-finishing pigs (30–150 kg BW); and whether differences in residual feed intake breeding values could influence pig growth responses to macauba pulp inclusion in the diet.

2. MATERIAL AND METHODS

2.1. Ethic statement

The Institutional Ethics Commission on the Use of Farm Animals of the Universidade Federal de Viçosa, MG, Brazil approved all the procedures performed in this experiment (protocol 83/2019).

2.2. Animals, experimental design, and diets

Two hundred and eighty-two pigs (barrows and females) progeny of sires (Topigs-Norvisn) with high or low breeding value for residual feed intake (RFI) crossed with Topigs-Norvisn sows were randomly selected at 34.7 ± 4.40 kg BW and 76 ± 3 days old, distributed into eight groups, and pair-housed in slatted concrete floor pens (2.41 ± 1.36 m). They had free access to feed by a semi-automatic feeder and water via a nipple drinker (Pig Breeding Research Facility of the Universidade Federal de Viçosa, MG, Brazil). The study was carried out in two batches. Batch 1 consisted of 134 pigs (72 barrows and 62 females) with 33.4 ± 3.4 kg of initial BW and 73 ± 2 days old, and batch 2 consisted of 148 pigs (78 barrows and 70 females) with 35.98 ± 4.9 of initial BW and 79 ± 2 days old. It was performed as a 2 × 2 × 2 factorial design in which pigs were pair-housed in experimental pens based on sex (barrows and females), breeding value (progeny of boars with high and low RFI), and initial BW and the diets (without and with 50 g/kg of macauba pulp inclusion) were randomly assigned to them. Therefore, there were eight treatments groups: treatment 1 consisted of high residual feed intake (HRFI) barrows fed the control diet (n = 21); treatment 2 consisted of HRFI barrows fed the macauba diet (n = 21); treatment 3 consisted of low residual feed intake (LRFI) barrows fed the control diet (n = 16); treatment 4 consisted of LRFI barrows fed the macauba diet (n = 17); treatment 5 consisted of HRFI female pigs eating the control diet (n = 18); treatment 6 consisted of HRFI female pigs eating the macauba diet (n = 18); treatment 7 consisted of LRFI female pigs eating the control diet (n = 14); and treatment 8 consisted of LRFI female pigs eating the macauba diet (n = 16). The experimental period lasted 90 days (day 0 to 90) and was divided into four phases: growing phases 1 (0–20 days; G1) and 2 (21–40 days; G2); and finishing phases 1 (41–65 days; F1) and 2 (66–90 days; F2).

The macauba level was defined based on a previous study [7] which demonstrated that up to 50 g/kg of macauba pulp inclusion had no deleterious effects on the growth performance and carcass traits of growing pigs (30 to 65 kg BW). The experimental diets (Table 1) were formulated to meet or exceed the nutritional requirements of all nutrients according to Rostagno et al. [16] recommendations and to have similar levels of metabolizable energy between treatments in each growth phase.

Prior to the study, macauba pulp was analyzed for dry matter, crude protein and fiber, ash, phosphorus and calcium content (Table 2) [17]. Gross energy was assessed by an adiabatic bomb calorimeter (Parr Instrument Co., Moline, IL). Calcium and phosphorus content were measured by the ICP-OES method 2011.14 [18]. The nutritional composition of the raw materials was obtained from Rostagno et al. [16]. The metabolizable energy content of diets was calculated according to Sauvant et al. [19].

Relative humidity and ambient temperature were registered hourly by data loggers (Klimalogg Pro, TFA Dostmann® Klima Logger Professional, model 30.3015, Wertheim, Germany). Lighting was not controlled.

Table 1 - Experimental diets ingredients and composition for the corn–soybean meal diets without (control) or with 50 g/kg of macauba pulp inclusion (macauba).

Ingredients	0 – 20 days (G1)		21 – 40 days (G2)		41 – 65 days (F1)		66 – 90 days (F2)	
	Control	Macauba	Control	Macauba	Control	Macauba	Control	Macauba
Corn, %	65.91	59.00	66.53	63.43	66.08	65.77	74.34	72.69
Macauba, %	0.00	5.00	0.00	5.00	0.00	5.00	0.00	5.00
Soybean oil, %	0.70	2.20	0.35	1.36	0.15	1.10	0.00	0.75
Soybean meal, %	30.50	30.90	31.00	28.00	32.00	26.35	24.00	19.90
Limestone, %	0.61	0.61	0.62	0.61	0.58	0.59	0.58	0.58
Dicalcium phosphate, %	1.40	1.40	0.84	0.84	0.56	0.56	0.46	0.46
NaCl, %	0.50	0.50	0.40	0.40	0.37	0.37	0.36	0.36
L-Lys HCl, %	0.09	0.09	0.00	0.10	0.00	0.00	0.00	0.00
DL-Methionine, %	0.03	0.04	0.00	0.00	0.00	0.00	0.00	0.00
Vitamin-trace mineral premix[1], %	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
BHT, %	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Choline chloride, %	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Calculated content								
Metabolizable energy, kcal/kg*	3251	3251	3250	3250	3250	3250	3261	3250
CP, %	19.20	19.13	19.37	18.14	19.79	17.47	16.79	15.08
SID Lysine, %	1.076	1.071	1.021	1.010	1.048	0.889	0.843	0.724
Ca, %	19.20	19.13	19.37	18.14	19.79	17.47	16.79	15.08
Total P, %	0.64	0.66	0.53	0.52	0.45	0.45	0.41	0.41

[1] Mineral vitamin supplement (per kg of diet): Vit. A (5250 UI); Vit. D3 (750 UI); Vit. E (11 UI); Vit. K3 (1.5 mg); Vit. B1 (1 mg); Vit. B2 (2.4 mg); Vit. B6 (1 mg); Niacin (30 mg); Pantothenic acid (8.1 mg); Folic acid (0.53 mg); Biotin (0.05 mg); Vit. B12 (16.5 mcg); Copper (13.5 mg); Iodine (0.19 mg); Manganese (37.5 mg); Selenium (0.15 mg); Zinc (72 mg); Iron (72 mg); and Cobalt (0.19 mg). * Sauvant et al. [19].

Table 2 - Macauba pulp composition.

Item	
Dry matter, %	94.17
Ash, %	5.02
Crude protein, %	4.74
Crude fiber, %	43.39
Ether extract, %	24.23
Phosphorus, %	0.05
Calcium, %	0.315
Gross energy, kcal/kg	3974
Metabolizable energy, kcal/kg*	2225

Sauvant et al. [19].

2.3. Performance measurements

Pigs were individually weighed at days 0, 21, 41, 66, and 90 without fasting. The feeding amount and leftovers were recorded daily (between 08:00 and 08:30 h). These values were used to calculate average daily feed intake (ADFI; g/d), average daily gain (ADG; g/d), and feed conversion rate (FCR; g/g).

2.4. Slaughter procedure and carcass traits

All slaughtering procedures followed good animal welfare practices. At the end of the 90-day trial, one pig from each pen was subjected to 12 hours' fasting, weighed and slaughtered, following standard commercial proceedings. Hot carcass weight (HCW) of each pig was recorded to calculate the dressing percentage [20]. Carcasses were divided longitudinally, maintained at ambient temperature until approximately 45 min *postmortem* and then refrigerated at 4° C for 24 h.

At 24 h postmortem, the left-half carcass was ribbed at the 10th rib region to assess backfat thickness (BF) and loin eye area (LEA). In short, BF was quantified by a digital caliper, and the muscle area of the *Longissimus dorsi* (LM) between the 10th and 11th cervical vertebra was covered with transparent paper and contoured using a permanent fine-tipped marker to determine LEA. The area within the outline was calculated by ImageJ software (version 1.51, National Institutes of Health, Bethesda, MD, USA).

At 15 min, 45 min, 1 h, 3 h, 6 h, 9 h, 12 h, and 24 h postmortem, the decline in pH and temperature was measured in the left LM of carcasses by a handheld pH/temperature measuring instrument (Testo SE & Co., Lenzkirch, FR, Germany). Bleeding was considered the baseline (minute 0) *postmortem*.

From the left-half carcass, a sample of 20 cm of LM (between the 10th cervical and the 1st lumbar vertebra) was collected for pork quality assessment. After 24 h of freezing at -20° C, LM samples were divided into five chops (2.54 cm), individually vacuum packed and frozen for posterior analysis [21].

2.5. Pork quality

Water-holding capacity (WHC) was evaluated in fresh LM by the centrifugal method [22]. Briefly, 5 g of meat samples free from fat and connective tissue were centrifuged at 3000 rpm for 10 minutes at 4° C, and the liquid expelled was separated from the meat. WHC was expressed as the percent difference between weights measured prior to and after centrifuging. The average of two samples for each animal was considered.

Pork color was evaluated on the cranial surface of LM after 30 minutes of exposure to air by a portable spectrophotometer (HunterLab MiniScan EZ 45/0 LAV, Reston, VA, USA) adjusted to 31.8 mm port size, an illuminant D65 and a 10° angle to the observer. The L* (lightness), a* (redness), and b* (yellowness) values of each LM sample were defined according to the CIELab scale as the mean of six spectrophotometer readings at six different points on the LM surface [23,24].

Cooking loss analysis followed the methodology described by Bruce et al. [25], with adjustments described by Silva et al. [26]. After a thawed period (16 h at 4° C), vacuum packaged chops were weighed and cooked at 71° C for 40 min in a digital water bath with a stirrer (WEALAB). Then, the chops rested for 10 minutes in an ice bath to stop the cooking process. After this period, the chops were refrigerated for 16 h at 4° C and weighed. Cooking loss was expressed as the percent difference between weights measured prior to and after cooking.

After cooking loss analysis, cooked samples were used in Warner–Bratzler shear force (WBSF) measurement, as proposed by [27]. From each chop, six cylindrical subsamples (1.27 cm diameter) were removed parallel to the longitudinal orientation of muscle fibers and free from fat and connective tissue. These cylindrical samples were sheared perpendicularly to the longitudinal orientation of the muscle fibers, in the Warner–Bratzler machine (GR Electrical Manufacturing Company, Manhattan, KS, USA). The maximum force to cut the cylindrical samples was recorded and the WBSF was determined by the average of six measures.

Sarcomere length was estimated by the laser diffraction technique [28]. Eight strands of the sheared cylindrical samples were removed and distinctly placed on a microscope slide. One drop of sucrose solution (0.2 M sucrose and 0.1 M NaHPO buffer at pH 7) at 4° C was placed on each filament and a helium-neon laser (Model 05-LHR-021, MelleGriot, Carlsbad, CA, USA) was focused on those strands. The mean of eight diffraction bands was considered the sarcomere length according to the equation below:

$$\text{Sarcomere length } (\mu\text{m}) = \frac{0.6328 \text{ x } D \text{ x } \sqrt{\left(\frac{T}{D}\right)^2 + 1}}{T} \qquad (1)$$

where, D = the distance (mm) between the lamina fixation support and the collection site of the diffuse laser bands (in this work, 120 mm were used) and T = distance (mm) between the extreme bands divided by 2.

Pork moisture, protein, fat, ash, and collagen were performed by near-infrared (NIR) spectroscopy analysis [17] on 120 g of the LM ground in a tissue homogenizer (TURRAX CT-132) after trimmed visible fat and connective tissues, using the FoodScanTM device (FoodScan, FOSS NIR systems Inc., Laurel, MD, USA).

2.6. Data analysis

The experimental unit for performance analysis was the pen, while the slaughtered animal was the experimental unit for carcass and pork quality traits. Data were analyzed using the PROC GLM model of SAS (SAS®Version 9.4, SAS®Institute, Inc., Cary, NC, USA) licensed by Universidade Federal de Viçosa, considering the fixed effects of sex, breeding value, experimental diet, batch, and their interactions. For pH and temperature decline, the sampling time was introduced to the model and the comparisons were performed within each sampling time. A comparative analysis between means was performed by Tukey test. Statistical differences were considered significant at $p < 0.05$.

3. RESULTS

Because of excessive wasted feed and health problems, data from seven experimental pens from batch 1; and three from batch 2 were not considered. The remaining animals stayed healthy and performed well. The first batch was conducted from January to April (summer) and the second one from June to September (winter). During batch 1, ambient temperature was 23.7 ± 3.6° C and relative humidity was 82 ± 14 %. In batch 2, these values were 20.1 ± 2.3° C and 69 ± 6 %, respectively.

3.1. Performance

No interaction between sex, breeding value, diet, and batch was observed for performance traits ($p > 0.05$; Table 3). On average, pigs started the trial at 34.7 ± 4.40 kg BW and 76 ± 3 days old and finished the trial at 133.7 ± 9.06 kg BW and 166 ± 3 days old. Whatever the sex, breeding value, and dietary treatment pigs had similar BW ($p > 0.05$) at the beginning of the trial.

Regarding sex effects, barrows had greater ADFI ($p < 0.01$) and ADG ($p < 0.01$) than females, while FCR was similar between sexes ($p = 0.46$) in G1 phase. In G2 phase, barrows had higher ADFI ($p < 0.01$) and FCR ($p < 0.01$) than females whereas ADG did not differ between sexes ($p = 0.15$). In F1 and F2 phases barrows had greater ADFI ($p < 0.05$), ADG ($p < 0.05$), and FCR ($p < 0.05$) than females. Considering the entire fattening period, barrows had higher ADFI ($p < 0.01$), ADG ($p < 0.01$), and FCR ($p < 0.01$) than female pigs.

In respect of breeding value, it did not affect ($p > 0.05$) performance of pigs at the G1phase. In the G2 phase, both genetic groups had similar ADFI ($p = 0.11$) but LRFI pigs had greater ADG ($p = 0.02$) and lower FCR ($p < 0.01$) than high HRFI pigs. No difference was observed between LRFI and HRFI progeny pigs on performance traits in the F1 phase ($p > 0.05$). In F2 phase, LRFI progeny pigs had greater ADFI ($p = 0.03$) than HRFI pigs, while ADG ($p = 0.31$) and FCR ($p = 0.49$) were not affected by breeding value. Overall, the breeding value had no effect ($p > 0.05$) on performance measurements.

Concerning the diet effects, the inclusion of 50 g/kg of macauba pulp did not affect any performance trait in the first three experimental phases ($p > 0.05$). In F2 phase, animals receiving the macauba diet had lower ADFI ($p = 0.01$) and FCR ($p = 0.01$) while ADG did not differ from pigs fed control diet (p = 0.82). Overall, pigs fed control and macauba diets had similar ADFI (p = 0.09), ADG (p = 0.84), and FCR (p = 0.07).

Table 3 - Effect of sex, sire breeding value, and diet on performance of pigs.

Phase/Traits	Sex		BV[1]		Diet		RMSE[3]	p-value		
	Bar.	Fem.	HRFI	LRFI	Cont.	Mac.[2]		Sex	BV[1]	Diet
Experimental units	71	60	74	57	63	68				
0 – 20 days (G1)										
IBW, kg	34.9	35.1	35.5	34.4	34.8	35.1	4.26	0.72	0.13	0.65
ADFI, g/day	2223	2045	2143	2125	2144	2124	190.5	<0.01	0.61	0.55
ADG, g/day	1134	1061	1110	1085	1096	1100	98.0	<0.01	0.16	0.81
FCR, g/g	1.96	1.94	1.94	1.97	1.96	1.94	0.169	0.46	0.33	0.43
FBW, kg	57.4	56.0	57.6	55.7	56.4	56.9	5.10	0.10	0.03	0.57
21 – 40 days (G2)										
IBW, kg	57.4	56.0	57.6	55.7	56.4	56.9	5.10	0.10	0.03	0.57
ADFI, g/day	3012	2610	2847	2776	2819	2803	249.1	<0.01	0.11	0.71
ADG, g/day	1156	1130	1120	1165	1148	1138	103.1	0.15	0.02	0.57
FCR, g/g	2.61	2.33	2.55	2.39	2.47	2.47	0.240	<0.01	<0.01	0.98
FBW, kg	81.6	78.7	81.5	78.7	80.1	80.1	6.51	0.01	0.01	0.97
41 – 65 days (F1)										
IBW, kg	81.6	78.7	81.5	78.7	80.1	80.1	6.51	0.01	0.01	0.97
ADFI, g/day	3334	2869	3113	3089	3096	3106	279.7	<0.01	0.63	0.85
ADG, g/day	1164	1076	1124	1116	1106	1134	101.5	<0.01	0.64	0.12
FCR, g/g	2.87	2.66	2.77	2.76	2.79	2.73	0.255	<0.01	0.95	0.17
FBW, kg	105.1	110.0	109.0	106.0	107.4	107.7	7.52	<0.01	0.02	0.79
66 – 90 days (F2)										
IBW, kg	105.1	110.0	109.0	106.0	107.4	107.7	7.52	<0.01	0.02	0.79
ADFI, g/day	3675	3241	3401	3516	3528	3389	286.4	<0.01	0.03	0.01
ADG, g/day	1148	1061	1095	1114	1102	1107	101.0	<0.01	0.31	0.82
FCR, g/g	3.21	3.08	3.13	3.16	3.21	3.08	0.297	0.01	0.49	0.01
FBW, kg	137.6	129.4	134.5	132.5	133.3	133.7	7.84	<0.01	0.13	0.74
Entire fattening period (90 days)										
IBW, kg	34.9	35.1	35.5	34.4	34.8	35.1	4.26	0.72	0.13	0.65
ADFI, g/day	3.144	2.734	2.983	2.925	2.997	2.920	221.2	<0.01	0.21	0.09
ADG, g/day	1.157	1.067	1.124	1.106	1.118	1.114	62.3	<0.01	0.15	0.84
FCR, g/g	2.72	2.57	2.65	2.64	2.68	2.62	0.183	<0.01	0.81	0.07
FBW, kg	137.6	129.4	134.5	132.5	133.3	133.7	7.84	<0.01	0.13	0.74

[1] Progeny of sires with high (HRFI) or low (LRFI) breeding value for residual feed intake; [2] Inclusion of 50 g/kg of Macauba pulp in the diet; [3] Root Mean Square Error. IBW = Initial body weight; ADFI = Average daily feed intake; ADG = Average daily gain; FCR = Feed conversion rate; FBW = Final body weight.

3.2. Carcass traits

No interaction between sex, breeding value, diet, and batch was observed for carcass traits ($p > 0.05$; Table 4). For sex effect, female pigs had lower slaughter body weight ($p < 0.01$), HCW ($p < 0.01$), BF ($p < 0.01$) and higher LEA ($p = 0.01$) than barrows. Regarding breeding value, HRFI pigs presented higher HCW ($p = 0.03$) and LEA ($p = 0.01$), and a lower BF ($p < 0.01$) compared to progeny from LRFI pigs. There was no effect ($p > 0.05$) of macauba pulp inclusion in the carcass traits.

Table 4 - Effect of sex, sire breeding value, and diet on carcass traits of growing-finishing pigs.

Traits	Sex		BV[1]		Diet		RMSE[3]	p-value		
	Bar.	Fem.	HRFI	LRFI	Cont.	Mac.[2]		Sex	BV[1]	Diet
Slaughter BW, kg	139.3	131.2	136.7	133.8	135.4	135.1	9.49	<0.01	0.09	0.90
HCW, kg	119.6	112.4	117.5	114.5	116.2	115.8	8.03	<0.01	0.04	0.78
DP, %	85.8	85.7	86.0	85.6	85.9	85.7	1.25	0.78	0.10	0.44
BF, mm	22.2	16.2	17.7	20.7	18.8	19.6	4.35	<0.01	<0.01	0.27
LEA, cm²	53.9	56.8	57.2	53.6	56.1	54.6	6.78	0.01	<0.01	0.20

[1] Progeny of sires with high (HRFI) or low (LRFI) breeding value for residual feed intake; [2] Inclusion of 50 g/kg of Macauba pulp in the diet; [3] Root Mean Square Error, HCW = Hot carcass weight; DP = Dressing percentage; BF = Backfat thickness; LEA = Loin eye area.

3.3. Carcass pH and temperature

No interaction between sex, diet, breeding value and batch was observed for the decline of pH and temperature of carcass at all sampling times ($p > 0.05$). Barrows had greater ($p < 0.05$) carcass pH from 45 min to 6 h after slaughter than female pigs (Figure 1A). Carcasses from HRFI pigs had greater pH ($p < 0.05$) at 12 h and 24 h postmortem than LRFI pigs (Figure 1B). Despite the similar response pattern, carcasses from barrows had higher ($p < 0.05$) temperatures at 9 h and 12 h after slaughter than female pigs (Figure 2A). There was no effect ($p > 0.05$) of breeding value (Figure 2B) on the temperature decline of carcasses. Macauba pulp inclusion did not affect the pH (Figure 1C) and temperature (Figure 2C) decline of carcasses at any time.

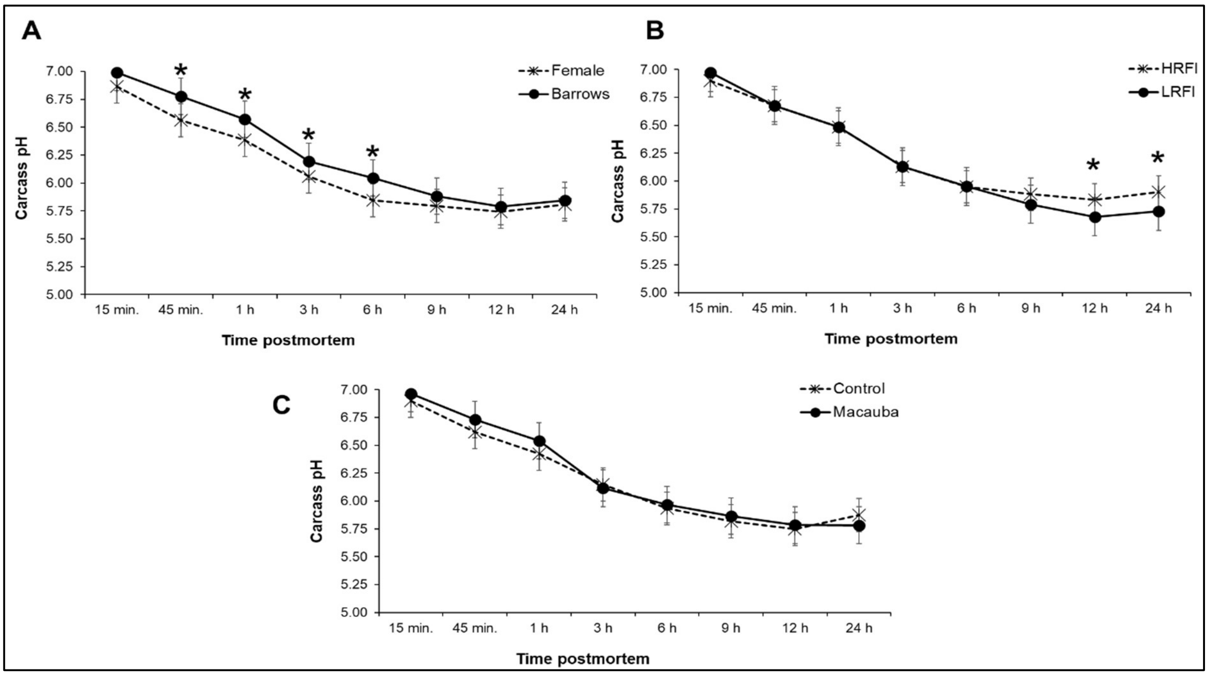

Figure 1 - Effect of sex (**A**), sire breeding value (**B**), and diet (**C**) on carcass pH decline during the first 24 h postmortem. Progeny of sires with high (HRFI) or low (LRFI) breeding value for residual feed intake. Each vertical bar is the standard error of the mean. *$p < 0.05$.

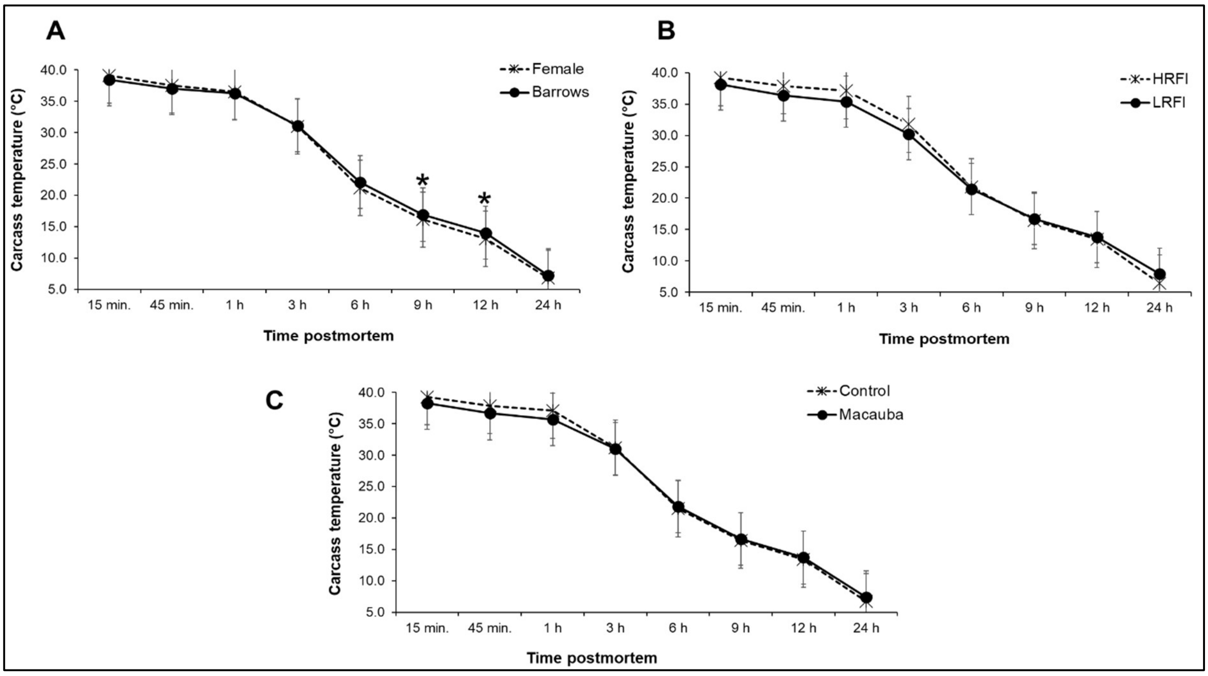

Figure 2 - Effect of sex (**A**), sire breeding value (**B**), and diet (**C**) on carcass temperature decline during the first 24 h postmortem. Progeny of sires with high (HRFI) or low (LRFI) breeding value for residual feed intake. Each vertical bar is the standard error of the mean. *$p < 0.05$.

3.4. Pork quality traits

There was no interaction between sex, breeding value, diet, and batch for pork quality traits ($p > 0.05$; Table 5). Regarding sex, pork from barrows presented lower ash content ($p < 0.01$), WBSF ($p = 0.03$), and higher fat content ($p < 0.01$) compared with pork from the females. There was no effect of breeding value on the pork traits ($p > 0.05$). Concerning diet effect, pigs fed with 50 g/kg of macauba pulp had lower ($p < 0.01$) moisture and ash contents. Pigs fed the control diet showed higher WHC ($p < 0.01$). Pork color was not affected ($p > 0.05$) by any factor (Table 5).

Table 5 - Effect of sex, sire breeding value, and diet on pork quality parameters of growing-finishing pigs.

Traits	Sex		BV[1]		Diet		RMSE[3]	p-value		
	Bar.	Fem.	HRFI	LRFI	Cont.	Mac.		Sex	BV[1]	Diet
Experimental units	71	60	74	57	63	68				
Moisture, % FM	71.2	71.5	71.4	71.3	71.5	71.2	0.91	0.08	0.76	0.02
Protein, % DM	25.2	25.4	25.4	25.3	25.3	25.3	0.78	0.09	0.33	0.87
Fat, % DM	2.7	1.9	2.2	2.4	2.2	2.4	1.09	<0.01	0.36	0.21
Ash, % DM	0.9	1.1	0.9	0.9	0.9	1.1	0.32	<0.01	0.91	0.01
Collagen, % DM	0.8	0.7	0.8	0.7	0.7	0.8	0.17	0.35	0.25	0.41
WBSF4, kgf	3.29	3.49	3.43	3.35	3.38	3.40	0.534	0.03	0.45	0.86
WHC5, %	88.0	87.8	87.5	88.3	88.6	87.2	2.52	0.55	0.09	<0.01
Cooking loss, %	21.6	21.8	22.1	21.3	21.1	22.2	3.95	0.80	0.26	0.11
Sarcomere len., µm	1.56	1.55	1.55	1.56	1.56	1.54	0.136	0.46	0.73	0.44
Color parameters										
Lightness (L*)	57.6	57.2	57.2	57.5	57.6	57.2	3.76	0.52	0.67	0.56
Redness (a*)	6.8	6.6	6.7	6.7	6.6	6.8	1.20	0.30	0.45	0.87
Yellowness (b*)	14.8	14.5	14.6	14.7	14.8	14.5	1.84	0.45	0.65	0.45

[1] Progeny of sires with high (HRFI) or low (LRFI) breeding value for residual feed intake; [2] Inclusion of 50 g/kg of Macauba pulp in the diet; [3] Root Mean Square Error; 4 WSBF = Warner Bratzler shear force; 5 WHC = Water-holding capacity.

4. DISCUSSION

This study was performed to elucidate the effects of macauba pulp inclusion in diets of growing-finishing pigs on growth performance, as well as on carcass traits and pork quality traits; and whether differences in residual feed intake breeding values could influence pig growth responses to macauba pulp inclusion in the diet.

As there was no interaction between factors, they were discussed independently. There is significant evidence for differences in growth performance between barrows and female pigs, and the present data reaffirm these findings. Generally, at the same slaughtering age, barrows are heavier, grow faster, and have greater feed and energy intake than gilts [29–34]. However, as gilts have a greater ratio of protein accretion relative to lipid accretion, they are also expected to have better feed efficiency than barrows [29,35].

The exact physiological mechanism behind the increased feed intake of barrows is not yet fully elucidated [36]. In the literature, this rise in barrows' feed intake is mostly attributed to behavioral changes resulting from the decrease of gonadal hormones, which reduce aggressive and sexual behaviors, increasing the time spent in feeders, and, thus the feed intake [33,37]. Administration of exogenous gonadal hormones to barrows reduced feed intake [38] and a higher amount of time spent at the feeder in physically castrated pigs compared to intact males and gilts have been reported by Puls et al. [39].

Furthermore, the decline in the maximum protein deposition (PDmax) with increasing live body weight tends to start at a lower live body weight in barrows than in female pigs [40]. According to de Lange et al. [40], the PDmax is lowest in barrows, intermediate in gilts, and highest in boars. In addition, these authors reported that the difference in PDmax between growing-finishing gilts and barrows is approximately 5%. In turn, the PDmax indicates the maximum amount of protein retained in the body and, together with the energy intake, the PDmax regulates the partitioning of energy towards lean and/or fat deposition [41,42]. Therefore, once this plateau is reached, the protein deposition will remain at its greatest level, and an additional rise in energy consumption will solely increase the rates of body lipid deposition, resulting in a fatter carcass and worse feed efficiency [43].

As expected, barrows do not present testosterone's anabolic effect, which has been proven to increase muscle accretion and diminish fat deposition in entire and immunocastrated male pigs before the second vaccination [43,44]. According to Bjorntorp [45], testosterone exerts inhibitory effects on lipoprotein lipase and glycerophosphate dehydrogenase, turning metabolism towards lipid mobilization and lean deposition. In accordance, our results related fat metabolism as backfat thickness and intramuscular fat are all aligned with that statement.

Overall, visual evaluation of color is driven by the decisions of consumers purchasing meat [46], and tenderness is the most important palatability trait for cooked pork [47]. Also, consumers associate higher pork marbling with a more tender, juicy, and flavorful product [48]. Previous studies have reported that pork tenderness is positively correlated with its intramuscular fat content [49–51] and negatively correlated with the rate and extent of pH decline [47].

In the present study, barrows presented higher intramuscular fat content, as well as lower WBSF and pH decline up to 6 h postmortem than female pigs. In agreement, D'Souza and Mullan [52] reported greater tenderness of pork from barrows than from gilts. Although we observed a lower fat content in female pork, the value found was higher than the minimum (1.5%) proposed by Fortin et al. [49] to ensure a satisfying eating experience.

Despite significant improvements in pig management and genetics, feeding still represents the largest cost in a pig production system, arousing great interest in optimizing the use of nutrients by animals [53]. Residual feed intake is a moderately heritable trait, genetically correlated with growth rate and backfat, and is used as a feed efficiency indicator [12]. It is the difference between the observed and predicted feed intake for determined production and maintenance levels, in which a more efficient animal has a lower RFI value [10,54]. Our results demonstrated negligible effects of breeding value on pigs' performance and efficiency. In contrast, Soleimani and Gilbert [55] observed that LRFI line had lower feed intake, daily gain, feed conversion rate, backfat thickness, and lean meat than HRFI line. These divergent responses among studies could be related to the genetic selection process of lineages. In the present study, progenies came from commercial populations ranked according to their RFI, contrasting the experimental data of Soleimani and Gilbert [55] obtained from experimentally selected lines for RFI. In addition, factors such as the methodologies used to measure feed intake, imprecise estimates of the energy content of diets, the weight range used to measure the feeding efficiency, and differences in gain composition can also affect feed efficiency measurement [11,12].

According to Hoque and Suzuki [10], selection for low residual feed intake is expected to favor animals with lower maintenance energy expenditure. Reduced RFI may come from better nutrient and energy utilization efficiency in several functions, such as digestion, intermediary metabolism, and maintenance [9]. Previous studies have reported a positive (unfavorable) genetic correlation between residual feed intake, growth rate, and backfat thickness [9,54–56]. In addition, fat deposition energetic cost is superior to that of protein accretion in muscle [57]. Therefore, it is expected that LRFI pigs would deposit less fat than HRFI pigs due to their lower energy intake [58].

As breeding value did not affect feed intake, animals had similar energy intake. Therefore, the greater backfat thickness of LRFI carcasses may be associated with a decreased maintenance requirement in association with a decreased heat production, lower basal metabolic rate and decreased physical activity [59,60]. According to Gilbert et al. [9], as feed efficiency and energy metabolism are closely related, maybe LRFI pigs muscles present a lower number of mitochondria which in turn have better energy use efficiency. Also, they suggest that reduced Cori cycle rates may play a role in limiting energy expenditure in LRFI pigs. In agreement, Dekkers and Gilbert [54] reported that LRFI pigs have diminished basal maintenance requirements and tissue turnover rates. Faure et al. [58] reported that muscle energy metabolism in HRFI relies on fatty acid and glycogen breakdown, while LRFI pigs mainly relies on glycogen storage and utilization.

Although low and high residual feed intake pigs showed a similar rate and extent of pH and temperature decline, the carcass pH of HRFI pigs stabilized above the LRFI. However, the ultimate pH values were within the range (5.3–5.8) proposed by Smulders et al. [61] for a typical final pH in pig carcasses. In agreement, Faure et al. [58] and Horodyska et al. [62] reported no differences in carcass pH rate and the extent of pigs divergently selected for RFI. In addition, our results did not evidence differences in quality traits of pork between LRFI and HRFI pigs. These findings are in agreement with those reported by Cai et al. [56] and Smith et al. [63].

The pigs showed no signs of objection to, or gastrointestinal complications from, the macauba-containing diets, and the performance and carcass traits were similar between dietary treatments. However, when evaluating by phases, it is evident that macauba pulp inclusion improved feed efficiency in finishing phase 2 and that this co-product did not affect any growth parameter during the first three growth phases. In agreement, Dias et al. [7] reported that, up to 100 g/kg of inclusion, macauba pulp did not affect the performance and body composition of growing pigs, and Costa Júnior et al. [8] reported that the inclusion of 50 g/kg of macauba pulp in finishing pigs' diet improved their feed efficiency.

Dietary fiber digestibility has been shown to ameliorate with increasing pigs' body weight [64–66]. Several causes could explain it, including a longer retention time, a decrease in feeding level relative to BW, a greater intestinal volume, and a better capacity of hindgut flora to digest fiber [67]. Thus, the reduced feed intake and better feed efficiency observed in finishing pigs fed the macauba diet may be explained by the better use of dietary fiber [68].

Pork quality and palatability are dependent on properties such as WHC, oxidative stability, and color, which are critical for processing and storage [69]. In addition, these pork attributes are primarily determined by postmortem changes, such as the rate and extent of pH decline, proteolysis, and protein oxidation [70–72]. The lower the muscle pH, the lower its ability to retain water, increasing liquid loss during cooking, which may negatively affect pork tenderness, juiciness, and color [73,74].

In the present study, macauba pulp inclusion did not influence the rate or extent of carcass pH decline, or the color, tenderness, and loss of liquid during the cooking of pork. However, pork from pigs fed the macauba diet showed lower WHC and moisture compared to pigs fed the control diet. Huff-Lonergan and Lonergan [75] reported that WHC variation at a given storage pH and temperature is supposedly due to alterations in proteolysis and consequent muscle cell shrinkage, by the expulsion of water into the extracellular space. According to Savell et al. [70] and den Hertog-Meischke et al. [73], as the pH drops, all the negatively and positively charged filaments become equal, reducing the repulsion between them. This maximal attraction diminishes the space between filaments, holding them close together, not allowing water to enter, and decreasing the WHC. However, because we did not evaluate the denaturation of muscle protein, we were unable to conclude that the inclusion of 50 g/kg of macauba pulp was responsible for the decreased stability of water in the muscles. However, these WHC and moisture values in pigs fed the macauba pulp diet are in accordance with previous studies [76–78].

5. CONCLUSION

In conclusion, macauba pulp (*Acrocomia aculeata*) showed great potential as an alternative feedstuff in pigs' diets. It was evident that feeding pigs with this co-product did not affect growth performance during growing phases 1 and 2, and finishing phase 1, resulting in improved feed efficiency in finishing phase 2. In addition, it did not influence the carcass traits, fat and protein content, tenderness, color, and cooking loss of pork, indicating that pork from macauba-fed pigs will have a similar acceptability as pork from pigs fed a conventional corn and soybean meal-based diet. The results of this study suggest that regardless of sex and breeding value for RFI, pigs respond similarly to macauba pulp inclusion in their diets.

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GENERAL CONCLUSION

Employing 50 g/kg of macauba pulp as a partial substitute for corn in pig diets presents a promising and economically strategic approach. Our comprehensive study demonstrates that incorporating up to 50 g/kg of macauba pulp not only sustains overall pig growth performance but also enhances feed efficiency in the latter stage of the pig production cycle (105 to 140 kg BW), regardless of sex and breeding value for residual feed intake. Furthermore, at this substitution level, we observed that macauba pulp does not adversely affect crucial factors such as carcass traits, pork quality, energy partitioning, and protein digestibility. This suggests that macauba pulp, while significantly influencing feed efficiency, achieves this without introducing any unwanted alterations in these key parameters. These findings underscore the potential of macauba pulp as a valuable and versatile component in swine diets.

The achieved results so far demonstrate the potential use of macauba pulp in pig feed as a partial substitute for corn, particularly in regions close to industries producing biodiesel from macauba. Currently, there is no market for macauba pulp, and it is assumed that being waste, its value is solely linked to the cost of processing and transportation. In our study, to reach a similar slaughter body weight, pigs fed macauba pulp consumed 3 kg less feed than those fed the conventional diet, showcasing its cost-effectiveness. Moreover, the economic impact analysis reveals substantial savings, with a significant decrease in feed production costs by US$1.37 per finished pig compared to the conventional diet. It's worth noting that integrating macauba pulp into pig diets to enhance feed supply presents a promising solution to the food-feed-fuel conflict, as using 50 g/kg of macauba pulp in growing-finishing pig diets could save up to 8.4 kg of corn per finished pig. As we navigate the complexities of modern pig farming, the integration of macauba pulp into swine diets presents a win-win scenario. The financial benefits, combined with sustained pig performance, make it a viable alternative, opening avenues for further exploration and optimization in pursuit of economically and environmentally sustainable swine production practices.

Macauba pulp shows promise in pig diets, but its potential impact on biofuel and co-product value chains is hindered by small-scale production and a non-structured supply chain. As the macauba biodiesel chain is in its early stages, some bottlenecks impair its progress. Firstly, macauba fruits are not available for harvest year-round, disrupting production stability. Relying solely on macauba cannot sustain a profitable biodiesel plant, necessitating its association with other feedstocks for year-round operation. Additionally, variations in soil and climate characteristics significantly affect fruit yield and quality, leading to inconsistencies in coproduct nutritional composition. Furthermore, the non-domesticated nature of the macauba palm and the extraction-based production chain without established pre- and post-harvest protocols compromise fruit yield and quality. Finally, the current infrastructure and logistics in the macauba value chain lack customization and adjustments, hindering the achievement of greater productivity.

Addressing these challenges is imperative for unlocking the full potential of macauba as a valuable resource in both the biodiesel and animal feed industry. By fostering a more consistent and sustainable supply chain, transitioning away from extractive practices, and embracing advanced oil extraction technologies, the macauba biodiesel chain can evolve into a more efficient, environmentally friendly, and economically viable industry. Such improvements will not only benefit the biodiesel sector but also enhance the availability and quality of co-products like macauba pulp for applications in animal nutrition, further contributing to the overall sustainability and success of the macauba industry.