UNIVERSIDADE FEDERAL DE SÃO CARLOS
CENTRO DE CIÊNCIAS EXATAS E DE TECNOLOGIA
DEPARTAMENTO DE ENGENHARIA DE PRODUÇÃO

PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA DE PRODUÇÃO

Leticia Caroline da Silva David

ASSESSING THE ADOPTION OF DIGITAL TECHNOLOGIES BY BRAZILIAN BEEF CATTLE FARMERS

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Dissertação de Mestrado apresentada como um dos requisitos para a obtenção do título de Mestra no Programa de Pós-Graduação em Engenharia de Produção da Universidade Federal de São Carlos.
Orientador: Prof Dr. Marcelo José Carrer
Coorientadora: Dra. Marcela de Mello Brandão Vinholis
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UNIVERSIDADE FEDERAL DE SÃO CARLOS

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Comissão Julgadora:

Prof. Dr. Marcelo José Carrer (UFSCar)

Profa. Dra. Marcela de Mello Brandão Vinholis (EMBRAPA)

Prof. Dr. Sergio Raposo de Medeiros (EMBRAPA)

Prof. Dr. Humberto Francisco Silva Spolador (ESALQ/USP)

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RESUMO

A produção de bovinos desempenha papel estratégico no cenário nacional e internacional, tanto pela relevância econômica quanto pela contribuição para a segurança alimentar. A incorporação de tecnologias digitais tem potencial para aprimorar diversos aspectos dessa produção, atuando como ferramenta de gestão operacional, automatização de processos e redução do uso de insumos. Essa dissertação possui dois objetivos complementares: (i) identificar os principais fatores associados à adoção de tecnologias digitais por bovinocultores de corte em confinamentos; e (ii) investigar como e em que medida a digitalização, as capacidades humanas, as capacidades de marketing e a integração da cadeia de suprimentos estão associadas à eficiência técnica desses confinamentos brasileiros. O estado da arte foi explorado por meio de uma revisão sistemática de literatura, conduzida para mapear as tecnologias adotadas mundialmente por produtores de gado de corte e de leite e os possíveis determinantes dessa adoção. Empiricamente, utilizaram-se Modelos de Análise de Correspondência Múltipla e Modelos de Fronteira Estocástica para traçar o perfil dos produtores e mensurar o impacto da adoção tecnológica. As análises basearam-se em dados coletados entre 2020 e 2023, envolvendo 238 confinadores de gado de corte bovino e 359 observações. Os resultados indicam que pecuaristas de leite apresentam maior adoção de tecnologias voltadas à aquisição e comunicação de dados, bem como de automação, controle e robótica. Já na pecuária de corte, além das tecnologias de aquisição e comunicação de dados, destaca-se também a adoção de sistemas de informação. Adicionalmente, constatou-se que os fatores determinantes da adoção tecnológica estão relacionados tanto às características do produtor (idade, nível educacional, acesso a consultoria), as características da produção (escala de produção, quantidade de trabalhadores, uso de ferramentas de proteção de risco, realização de serviço de boitel e recebimento de bonificação de frigoríficos no momento da venda). Por fim, verificou-se que a adoção de softwares de gestão, sensores para automação da distribuição de ração e contratos formais apresenta associação positiva com aumentos na eficiência técnica produtiva. Esses achados podem subsidiar políticas públicas e fomentar a difusão de tecnologias digitais na pecuária.

Palavras-chave: adoção de tecnologia; bovinocultura; fronteira de produção; pecuária de precisão; tecnologias digitais.

ABSTRACT

Beef cattle production plays a pivotal role in global food systems and national economies. Digital technologies offer substantial opportunities to enhance operational management, automate processes, and optimize input use. This dissertation pursues two complementary objectives: (i) to identify the main factors associated with the adoption of digital technologies by feedlot beef cattle producers; and (ii) to examine how, and to what extent, digitalization, human capabilities, marketing capabilities, and supply chain integration are linked to the technical efficiency of Brazilian feedlots. A systematic literature review was conducted to map the global landscape of digital technology adoption in beef and dairy cattle production and to identify potential determinants. Empirically, Multiple Correspondence Analysis and Stochastic Frontier Models were applied to data collected from 238 Brazilian feedlot producers (359 observations) between 2020 and 2023. Results show that dairy producers exhibit higher adoption rates of data acquisition and communication technologies as well as automation, control, and robotics systems, whereas beef producers complement these with information system technologies. Technology adoption is associated with producer characteristics (age, education, access to consultancy) and production features (scale, labor, risk management practices, custom feeding services, and slaughterhouse bonuses). Adoption of digital management software, automated feed distribution sensors, and formal contracting is positively linked to higher technical efficiency. These findings provide empirical evidence to guide policy design and support the diffusion of digital technologies in livestock systems.

Keyword: beef cattle; digital technologies; precision livestock; production frontier; technology adoption.

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Summary

1. Introduction

The livestock sector plays a fundamental role in the Brazilian economy, contributing to food production, income generation, and employment while also driving beef and dairy exports. Brazil has the world's largest commercial cattle herd, with 194 million head and a production of around 10 million tons of beef, approximately 30% of which is exported to dozens of countries around the world (ABIEC, 2025). These figures place Brazil as the world's largest beef exporter, with an export value of US$ 12.8 billion in 2024 (ABIEC, 2025). Pasture systems, which are predominant in Brazilian beef cattle farming, occupied an estimated area of 164 million hectares in 2024 (MAPBIOMAS, 2024). However, the number of beef cattle fattened in feedlots, a land-saving production system, increased from 5.2 million heads in 2015 to 8.84 million heads in 2024, with the proportion of animals finished in feedlots reaching approximately 19,86% of the total animals slaughtered (ABIEC, 2025). The share of feedlot-finished cattle in total slaughters increased steadily from 2015 to 2021, Figure 1, reaching its peak in 2021, followed by a relative decline in subsequent years. Nevertheless, its participation remains consistently above the levels observed at the beginning of the period, highlighting the growing relevance of feedlots in Brazilian beef production (ABIEC (2025) and IBGE (2015 - 2025)).

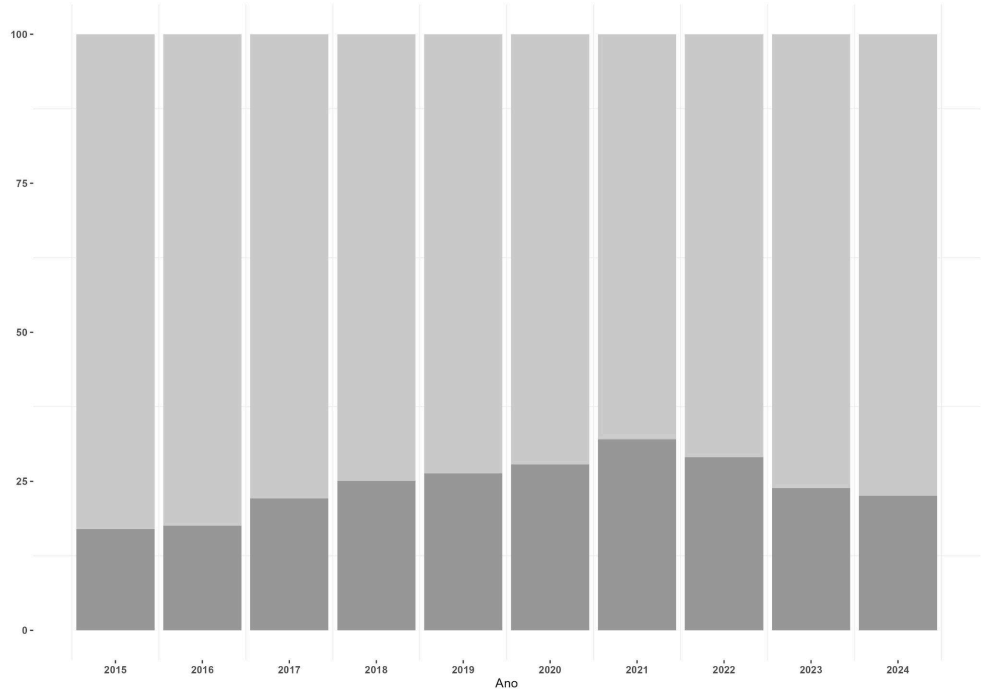

Figure 1. Evolution of feedlot cattle relative to total slaughters in Brazil (2015–2024). Source: ABIEC (2025) and IBGE (2015 - 2025).

Brazilian beef cattle farming is characterized by considerable heterogeneities. While some farmers have adopted capital-intensive production systems with high rates of inputs and productivity, others have adopted extensive systems with low efficiency in inputs use and higher environmental externalities (LATAWIEC *et al*., 2014; TELLES *et al*., 2024). Social concern regarding sustainability in the Brazilian beef supply chain has been increasing considerably worldwide. The sustainability of beef industry requires high on-farm technical efficiency and productivity, which might be positively affected by the adoption of production technologies and management practices (GREENWOOD, 2021; VINHOLIS *et al*., 2021).

The adoption of digital technologies has emerged as a strategic approach to improving livestock production management by enabling more precise resource control and increasing operational efficiency. Precision livestock farming relies on the integration of sensors, automation, data analytics, and information systems to try optimize management and production performance, ultimately contributing to animal welfare and sustainable production (MORRONE *et al*., 2022). Collected data are stored in cloud computing platforms and analyzed using management software that integrates information to optimize resource utilization (BERCKMANS, 2017; GARCÍA *et al*., 2020). Sensors and digital platforms facilitate real-time monitoring and integrated management, leading to more accurate decision-making (GUNASEKARAN *et al*., 2018; LIU; CHEN; LIANG, 2023).

The decision to adopt these technologies can be influenced by multiple factors, including characteristics of the producer, farm, production system, institutional environment, and the technology itself (GEROSKI, 2000; SOUZA FILHO *et al*., 2011). Empirical studies have shown that socioeconomic aspects, the availability of skilled labor, access to credit, and rural extension services can significantly affect adoption decisions (BARNES *et al*., 2019; BIANCHI *et al*., 2022; CARRER; SOUZA FILHO; BATALHA, 2017; DREWRY *et al*., 2019; MOZAMBANI *et al*., 2023). Additionally, producers adopt technologies to varying degrees, allowing for classification into categories based on adoption intensity (BARNES *et al*., 2019; ISGIN *et al*., 2008; KOLADY *et al*., 2021; PAXTON *et al*., 2011).

Some empirical studies have analyzed the adoption and impacts of digital technologies across different farming production systems (ZHU *et al*., 2021; ZHENG *et al*., 2021; DELAY *et al*., 2022; CARRER *et al*., 2022; MCFADDEN; ROSBURG; NJUKI, 2022; MENDES *et al*., 2023). In beef cattle farming, sensors help monitoring animal health, feed requirements and water intake; software integrates real-time data for livestock management, nutrition management, and economic analysis; radio frequency identification (RFID) ear tags enable animal tracking and can store additional individual data (GARCÍA *et al*., 2020; MORRONE *et al*., 2022). Most of these technologies have been embedded into processes, shaping a digital operational capability to increase operations management efficiency. Furthermore, these technologies have been employed to enhance the integration of beef cattle farmers with input suppliers and the slaughterhouse industry, for example through RFID systems that improve traceability, blockchain platforms that ensure transparency and trust in transactions, and IoT-based solutions that enable real-time data sharing across the value chain (GRANDE; VIEIRA, 2013; PIÑA *et al*., 2023). The investigation about whether and to what extent digital technologies adoption are associated to beef cattle feedlot efficiency is quite important for strategies of developers of technologies, transfer technologies agents and other beef cattle stakeholders. Despite the advancements in digital technologies and their potential benefits for livestock production efficiency, a gap remains in the literature regarding empirical investigation of technology adoption and its impacts in Brazilian beef cattle farming.

1.1. Objectives

The main objectives of this thesis are: (i) to identify the main factors associated with the adoption of digital technologies by beef cattle farmers; and (ii) to empirically investigate how and to which extent digitalization, human capabilities, marketing capabilities, and supply chain integration are associated with the technical efficiency of beef cattle feedlots in Brazil.

The specifics objectives are:

(i) to conduct a systematic literature review that highlights the digital technologies adopted by beef and dairy cattle farmers worldwide and the main determinants factors for the adoption;

(ii) to develop an analytical model with hypothesis regarding the adoption of digital technologies;

(iii) to analyze the characteristics of adopters and non-adopters of digital farming technology based on micro data obtained from a sample of beef cattle feedlots;

(iv) to investigate the association of digital technology adoption and technical efficiency of Brazilian feedlots applying stochastic production frontier econometric models.

This research utilizes a unique micro dataset obtained through a collaborative research project involving the Scot Consultoria Company, the Brazilian Agricultural Research Corporation (Embrapa), and the Federal University of São Carlos (UFSCar). The data collection was performed by the Company Scot Consultoria. This company conducted annual in-person visits to approximately 150 feedlots across all regions of Brazil in the years 2020, 2021, 2022 and 2023. During these field visits, there are three main objectives: (i) to collect primary data applying a structured questionnaire; (ii) to introduce feedlot managers to the project sponsors (e.g., sales managers from companies that produce livestock feed), which aims to initiate or strengthen commercial partnerships; and (iii) to produce videos and photos that present a new and improved perspective of beef cattle production to Brazilian society. Embrapa and UFSCar have assisted the company in the elaboration of structured questionnaires, team training for questionnaire application, data tabulation, data organization, and empirical analyses. The empirical findings presented in chapters 3 and 4 of this thesis were obtained by using this dataset.

1.2. Justification

The increasing complexity of livestock management and the demands of consumer markets, such as quality, traceability, and sustainability, underscore the need to modernize management practices. Digital technologies provide solutions to address these challenges by enabling real-time monitoring, task automation, and data integration for more accurate decision-making. Moreover, they foster greater integration with the supply chain, facilitating compliance with the requirements of both domestic and international markets (CARRER; SOUZA FILHO; VINHOLIS, 2014; MITHAS and RUST, 2016).

Although the literature has extensively explored the adoption of digital technologies in agricultural systems, specific studies on their application in cattle farming, particularly in feedlots, remain scarce (MOZAMBANI *et al.*, 2023; MORRONE *et al.*, 2022). This knowledge gap limits the development of public policies and private sector strategies to promote the adoption of these innovations.

Understanding the factors associated with the adoption of digital technologies and to which extent digitalization is associated with feedlots performance are relevant for proposing targeted actions to increase the technical and economic efficiency of beef cattle production in this production system. This study is justified by the economic relevance of cattle farming to Brazil, the need for more sustainable production, and the opportunity to advance management practices through digitalization and supply chain integration. The empirical analysis, based on data from Brazilian feedlots, contributes to advancing knowledge about the adoption and associations of digitalization and the technical performance of beef cattle production in the country.

1.3. Thesis structure

The present thesis is structured into three interrelated articles. While the articles can be read independently, their complementary nature makes it advisable to read them together.

Chapter 2 presents the first paper, a systematic literature review with two main objectives: (i) to identify the digital technologies adopted by beef and dairy cattle producers; (ii) to map the determinants factors to the adoption of these technologies. The review was conducted using the Web of Science and Scopus databases. A preliminary version of this paper was presented in the following conferences: 62º Congresso da Sociedade Brasileira de Economia, Administração e Sociologia Rural (SOBER, 2024) and Congresso Brasileiro de Agricultura de Precisão e Digital 2024.

Chapter 3 contains the second paper, which features a multivariate analysis aimed at characterizing the profile of beef cattle farmers in Brazil who adopted digital technologies in 2021. A preliminary version of this paper was presented at the 61º Congresso da Sociedade Brasileira de Economia, Administração e Sociologia Rural (SOBER, 2023).

Chapter 4 presents the third paper, which provides an empirical analysis using stochastic production frontier models to examine the association between digitalization and the technical efficiency of beef cattle farmers in Brazil using a panel micro data set from 2020 to 2023.

Finally, Chapter 5 offers the final considerations, discussing the implications of the results obtained in the articles included in this thesis.

2. Paper 1: What drives digital technology adoption in cattle farming? A systematic literature review

ABSTRACT: This article aims to identify the digital technologies adopted by cattle farmers worldwide and to analyze the main factors influencing their adoption. To achieve these objectives, a systematic literature review (SLR) was conducted. The findings reveal that the adoption of Data Acquisition and Communication Technologies is predominant in both dairy and beef production systems. Next, the adoption varies according to the production system. Beef cattle farmers tend to adopt Information Systems technologies, while dairy farmers are more likely to implement Automation, Control and Robotics technologies. Automation technologies, such as robotic milking systems and automated feeders, play a central role in dairy farming by improving labor efficiency and productivity. However, their adoption is often constrained by high investment costs and structural limitations, particularly among smallholders. Furthermore, the key factors influencing adoption include characteristics of the production system and farm, as well as the socioeconomic profile of the farmer. The results can contribute to the development of public policies and support decision-making processes among cattle producers. Additionally, this review highlights a notable research gap regarding the determinants of digital technology adoption in cattle farming, particularly in beef production.

KEYWORDS: cattle farming, dairy farming, precision agriculture, SLR.

2.1. Introduction

The livestock sector plays a crucial role in Brazil, serving as a source of food, income, and employment for the domestic market while also contributing significantly to global food exports and foreign exchange earnings. Brazil rank as the world's third-largest milk producer and the leading commercial exporter of beef (ABIEC, 2023; IBGE, 2021). The scale of the national livestock industry presents the challenge of achieving more sustainable production systems with reduced environmental impact. The adoption of precision and digital technologies has the potential to increase efficiency and add value, promoting more sustainable production.

Precision livestock farming refers to the strategic and integrated application of advanced technologies, such as sensors, automation, data analytics, and information systems, to optimize the management and performance of livestock operations. This approach enhances productivity and animal welfare while enabling more accurate, data-driven decision-making (MORRONE *et al.*, 2022).

The decision to adopt agricultural technologies can be influenced by a combination of socioeconomic, production related, technological, and systemic factors. These include producer characteristics, farm attributes, the perceived benefits and complexity of the technology, and broader environmental or institutional elements (GEROSKI, 2000). Both empirical and literature review studies have examined various factors that impact the adoption of digital technologies in agriculture (BARNES *et al.*, 2019; CARRER; SOUZA FILHO; BATALHA, 2017; GIUA; MATERIA; CAMANZI, 2021; MOZAMBANI *et al.*, 2023; TEY; BRINDAL, 2012; 2022; VINHOLIS; CARRER; SOUZA FILHO, 2017). However, no comprehensive literature review has focused specifically on digital technology adoption in the cattle farming sector.

Understanding the current landscape of digital technology adoption in cattle production, along with the determinants of this process, is essential for the formulation of targeted strategies and public policies to encourage adoption. This study aims to identify the main digital technologies adopted by cattle producers worldwide and to analyze the key factors influencing their adoption.

Following the technology classification proposed by Moreno *et al.* (2024), this review focuses on technologies grouped into one of the four following categories: (I) Automation, Control, and Robotics (technologies related with automatic control, automation, robotics and autonomous systems); (II) Data Acquisition and Communication (technologies related with data integration, data pre-processing, data storage and image acquisition and remote sensing technologies); (III) Data Science and Artificial Intelligence (technologies related with Artificial Intelligence (AI), Big Data and Blockchain); and (IV) Information Systems (technologies related with Softwares, Geo-informatics, Information and Communication Technologies (ICTs)).

The paper is structured into three additional sections beyond this introduction. The next section describes the systematic review protocol and data collection methods. Section three presents and discusses the main findings. The final section offers concluding remarks and implications.

2.2. Materials and methods

This study employed a Systematic Literature Review (SLR) methodology, which aims to identify, evaluate, and synthesize all available evidence related to a specific research question in a rigorous, unbiased, and comprehensive manner. The review followed the PRISMA protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) as proposed by Moher *et al*. (2010).

Based on the insights gained from an initial scoping review, two research questions were formulated to guide the study as shown in Table 1. The data sources selected for this review were the Scopus and Web of Science (WoS) databases, chosen for their global relevance and academic credibility. Searches were conducted across article titles, abstracts, and keywords, using search strings designed for each construct. Inclusion criteria were limited to peer-reviewed journal articles written in English. Book chapters, conference proceedings, and other non-peer-reviewed materials were excluded. The search covered all available publication dates up to December 31, 2024, without restrictions regarding journal impact factor or open access status.

Table 1 . Systematic review protocol

Question	**Constructs**	**String**
What digital technologies are adopted by cattle farmers?	Digital technology	((Digit* OR Precision OR Smart OR Intelligent OR Automat* OR "4.0") w/0 (Agri* OR Livestock OR Farm* OR Rural))
What are the determinants of digital technology adoption in cattle farming?	Adoption	(Adopt* OR Diffus* OR Transf* OR Dissemin*)
	Cattle farming	(Beef OR Dairy OR Cattle OR Livestock OR Ruminant* OR (Animal W/0 Husbandry) OR Breed*)

Source: Authors' own elaboration

The initial search returned 1,035 documents from Scopus database and 702 from WoS. After removing non-peer-reviewed publications, 561 and 492 articles remained, respectively. Filtering for English-only publications yielded 510 articles from Scopus and 483 from WoS. Duplicate entries (n = 380) were eliminated, resulting in 613 unique records for initial screening.

Based on title and abstract screening, 556 articles were excluded for lacking relevance to the research theme. The remaining 57 studies underwent full-text analysis, where introductions, methodologies, and conclusions were reviewed to determine alignment with the research questions. Ultimately, 21 articles met all inclusion criteria.

To increase the sample size and capture additional relevant works, a snowball sampling technique was applied, yielding four additional articles. Thus, the final sample consisted of 25 peer-reviewed studies. Descriptive statistics and graphical representations were generated using the R statistical software (R CORE TEAM, 2024).

2.3. Results and discussion

2.3.1. Descriptive analysis

The final set of 25 articles selected for this review was identified as highly relevant to the research topic and is summarized in Table 2. To ensure that the analysis was specific to cattle production systems, 76% of the selected studies focused exclusively on cattle farming, offering targeted insights for dairy and/or beef producers. The remaining 24% included broader samples on the agricultural sector but still provided disaggregated data relevant to cattle farming. Among the 25 articles, the majority (60%) focused on dairy cattle producers, while 12% analyzed data exclusively from beef cattle producers. Other portion of the sample (28%) included samples from both dairy and beef cattle farmers.

This distribution reveals a strong research emphasis on the dairy sector, with relatively limited attention to beef production systems. One possible explanation for this imbalance is that dairy farming typically requires more frequent and detailed monitoring of production parameters, such as daily milk yield, feed intake, and animal health, which creates a stronger demand for technological solutions (RUTTEN *et al.*, 2013; CAJA; CASTRO-COSTA; KNIGHT, 2016). In contrast, although beef systems also benefit from data-driven management, their lower frequency of measurable outputs may reduce the immediate adoption of such technologies and, consequently, the research focus (BANHAZI *et al.*, 2012; WOLFERT *et al.*, 2017).

In terms of geographic distribution, the country with the highest number of studies was the United States of America with five studies followed by Italy and New Zealand, each represented by three articles. The Italian studies were conducted primarily in the Cremona and Lombardy regions, while the U.S. studies focused on states such as Oklahoma, New Mexico, Tennessee, Texas, and Wisconsin. Other countries with two studies each include Brazil, Australia, Canada, and Germany. The remaining studies were conducted in a variety of countries, each represented by a single empirical investigation. Figure 2 illustrates the global distribution of study locations.

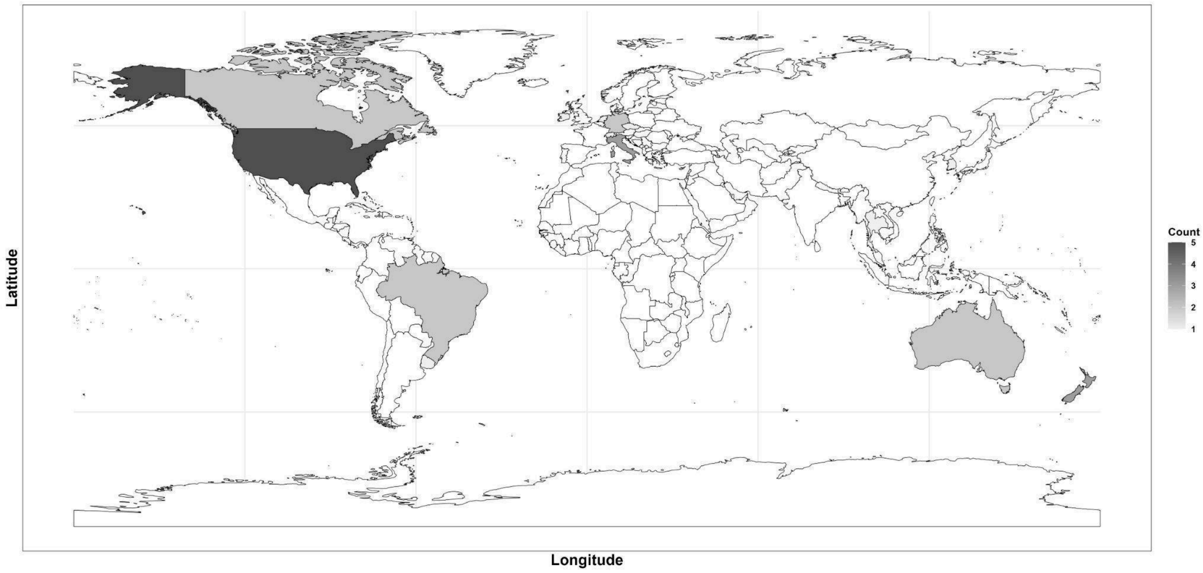

Figure 2. Distribution of study locations. Source: Authors' own work.

The predominant methodology across the reviewed studies was quantitative analysis, with logistic or probit regression being the most frequently employed approach, appearing in 40% of the articles. Most studies were based on primary data collected through survey or case studies. Only three articles utilized secondary data (JELINSKI *et al*., 2020; GILLESPIE; NEHRING; SITIENEI, 2014; LEE *et al*., 2024). In nearly all studies, the respondents were producers themselves. Exceptions include Makinde *et al*. (2022), which also involved veterinarians, and Gargiulo *et al.* (2018), which included service providers. A notable outlier is Vrchota, Pech, Švepešová (2022), where the respondents were company managers, rather than producers.

Table 3 presents the journals in which the selected studies were published, along with their respective impact factors for the year 2022, as reported by the Journal Citation Reports (JCR) provided by Clarivate. The journal with the highest number of publications was Computers and Electronics in Agriculture, accounting 25% of studies. This journal also holds the highest JCR impact factor among the analyzed outlets, highlighting its prominence in disseminating research on digital technologies in agriculture.

Table 2. Description of the studies resulting from the systematic literature review.

Year	Author(s)	Cattle	Analysis method	Sample size	Citation
2019	Abeni, Petrera, Galli	Dairy	Logistic regression	490	42
2006	Alvarez and Nuthall	Dairy	Structural equation model	100	83
2005	Batte	Both	Probit regression	1001	65
2022	Bianchi *et al.*	Dairy	Generalized linear model, Principal components, Multiple correspondence	52	18
2024	Boyer *et al.*	Beef	Logistic regression	201	6
2020	Dela Rue *et al.*	Dairy	Descriptive	500	38
2019	Drewry *et al.*	Both	Logistic regression	1021	5
2014	Edwards, Dela Rue, Jago	Dairy	Chi-square, Anova, Cluster analysis	278	40
2023	Gabriel and Gandorfer	Both	Bootstrap	2390	86
2018	Gargiulo *et al.*	Dairy	Generalized linear model	301	149
2014	Gillespie, Nehring, Sitienei	Dairy	Logistic regression	3729	7
2020	Groher, Heitkämper, Umstätter	Both	Logistic regression	1497	122
2020	Jelinski *et al.*	Dairy	Logistic regression	26935	14
2024	Lee *et al.*	Dairy	Logistic regression with propensity score matching	177	0
2022	Makinde *et al.*	Beef	Descriptive/Qualitative	52	28
2021	Marescotti *et al.*	Dairy	Cluster analysis	63	42
2023	Mendes et al.	Both	Poisson regression and Hurdle	175	11
2020	Newton; Nettle; Pryce	Dairy	Case study	7	71
2023	Palma-Molina *et al.*	Dairy	Logistic regression multinomial	274	19
2023	Piña *et al.*	Beef	Probit regression	84	11
2023	Rajchamaha and Makararpong	Dairy	Multiple linear regression	461	2
2021	Schukat and Heise	Both	Factor analysis	422	20
2021	Silvi *et al.*	Dairy	Cluster analysis	378	24
2015	Steeneveld and Hogeveen	Dairy	Linear discriminant analysis	512	71
2022	Vrchota, Pech, Švepešová	Both	Chi-square	131	4

Source: Authors' own work.

The most cited publication among the reviewed articles is titled "Dairy farmers with larger herd sizes adopt more precision dairy technologies" (GARGIULO *et al.*, 2018), with a total of 149 citations (see Table 2). Notably, research on this topic is relatively recent. While the earliest studies date back to 2005 and 2006, there was a publication gap of nearly a decade that followed. A marked increase in publication activity began after 2014, with the years 2020, 2022, and 2023 each producing the highest number of articles (four in each year). A clear upward trend in scientific output related to digital technology adoption in cattle farming has emerged since 2018. No eligible publications were identified for the years 2016 and 2017.

Table 3. Journals where the studies were published.

Journal	Publications	JCR
Computers And Electronics In Agriculture	5	7.7
Animals	3	2.7
Journal Of Dairy Science	3	3.7
Animal	2	4.0
Animal Production Science	2	1.3
Others journal with only 1 publication*	10	
Total	25	

*Journals: Sustainability; Agricultural and Food Economics; Agricultural Systems; Agriculture; Canadian Veterinary Journal; International Journal Of Interactive Mobile Technologies; Journal Of Agribusiness In Developing And Emerging Economies; Journal Of Rural Studies; Precision Agriculture; Smart Agricultural Technology.

Source: Authors' own work.

2.3.2. Adopted Technologies

Figure 3 displays the categories of digital technologies analyzed in the selected studies, along with their frequency of appearance across the 25 articles. The classification is based on the primary functionality of each technology, meaning that while a single technology could potentially fit into multiple categories, it is assigned to the one most closely aligned with its core function. This categorization is adapted from the framework proposed by Moreno *et al*. (2024). The types of technologies adopted vary according to the production system. In studies focused on beef cattle, the most frequently adopted technologies were related to Data Acquisition and Communication Technologies (43.8%), (e.g., radio frequency animal identification, sensors integrated into automatic weighing scales, image use through drones for herd counting and inventory or cameras for body condition scoring). In addition, the adoption of Information Systems (28.1%) (e.g., software or cloud-based digital platforms for operational and economic management of production), was also noted. In the field of Data Science and AI, the probability of adopting big data tools increases when producers have previously implemented sensor-based technologies, indicating complementarity between systems (PIÑA *et al*., 2023). The use of smartphones was primarily linked to weather forecasting, followed by internet browsing and communication with other producers

(DREWRY *et al*., 2019; GABRIEL; GANDORFER, 2023; MARESCOTTI *et al*., 2021; MENDES *et al*., 2023; RAJCHAMAHA; MAKARARPONG, 2023).

Studies focused on dairy farming predominantly addressed technologies classified under Data Acquisition and Communication Technologies (47.8%), as well as Automation, Control, and Robotics (36.9%). Altogether, 84.7% of the technologies analyzed in these studies fell within these two categories. Dela Rue *et al*. (2020) observed greater investments in automation compared to data acquisition, with most funds allocated to rotary (carousel) milking parlors. Regardless of herd size, the most widely adopted technologies in both herringbone and rotary systems included automatic milking cup removers, management software, and automated cleaning systems (GARGIULO *et al*., 2018). Milking-related automation tools, particularly those improving labor efficiency and hygiene, were perceived as offering a favorable cost-benefit ratio and were regarded as desirable even by non-adopters (EDWARDS; DELA RUE; JAGO, 2014). Despite the prevalence of automation in milking routines, the adoption of robotic milking systems (RMS) remains limited due to their high initial cost (GARGIULO *et al*., 2018; SILVI *et al*., 2021; VRCHOTA; PECH; ŠVEPEŠOVÁ, 2022). Within the Data Acquisition category, the most frequently adopted tools were activity meters for lactating cows and milk yield monitoring systems (ABENI; PETRERA; GALLI, 2019; BIANCHI *et al*., 2022; GARGIULO *et al*., 2018; SILVI *et al*., 2021).

Although most studies focused on individual technologies, it is important to note that many of these solutions are complementary, and some farms adopt multiple technologies across categories. Palma-Molina *et al*. (2023) emphasized that encouraging the adoption of technology bundles, rather than isolated tools, may be an effective strategy for expanding adoption in dairy systems.

Beyond their technical functions, digital technologies in dairy farming also have significant implications for labor management. Automation tools such as robotic milking systems, automated calf feeders, sorting gates, and cleaning systems reduce manual workload by streamlining repetitive and time-consuming tasks. This labor optimization allows producers to reallocate time from operational to strategic decision-making roles, which would be particularly beneficial for family-run and small-scale operations (DELA RUE *et al*., 2020; LEE *et al*., 2024).

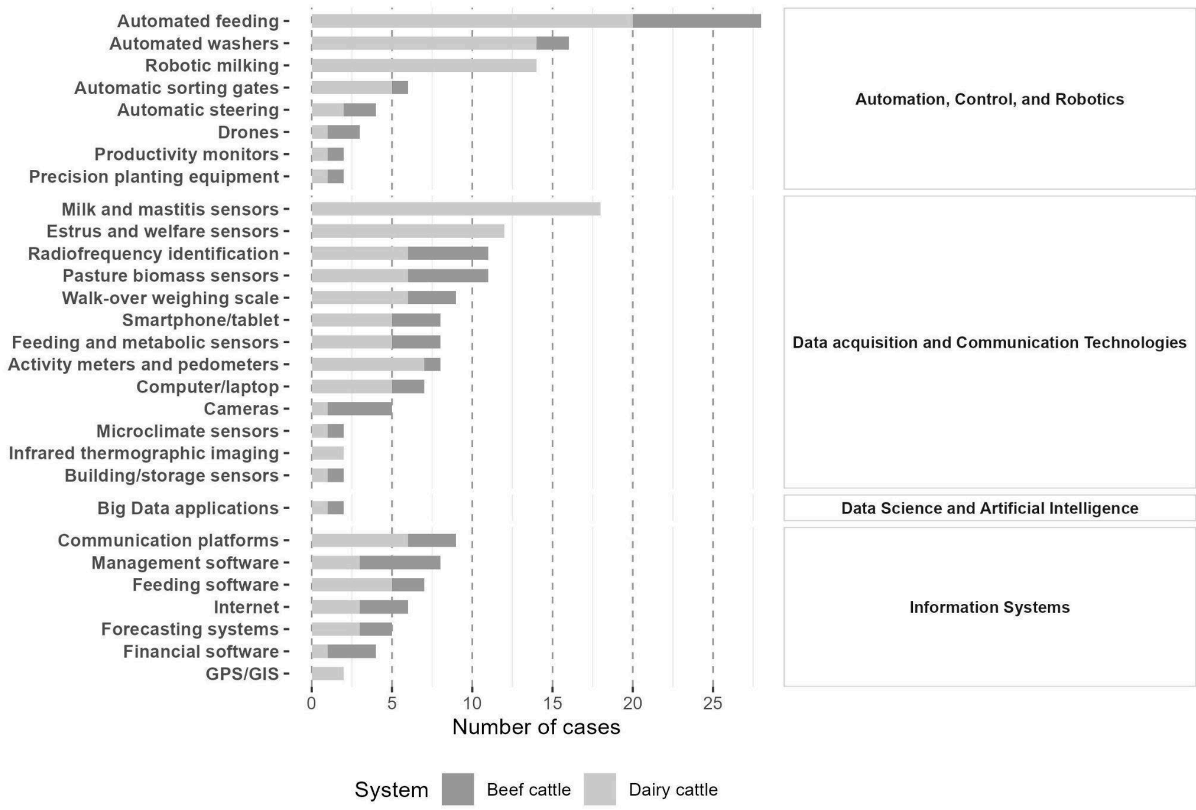

Figure 3. Adopted technologies in dairy or beef cattle farming. Source: Authors' own work.

However, the adoption of labor-saving technologies is not without barriers, especially among smallholders. High capital costs and the need for facility upgrades, especially in farms with traditional herringbone systems, pose considerable challenges (EDWARDS; DELA RUE; JAGO, 2014). Additionally, technological complexity and lack of digital literacy may discourage adoption among producers with limited access to training or technical support (MARESCOTTI *et al*., 2021; BOYER *et al*. 2024). Lee *et al*. (2024) further highlighted that, despite improved labor efficiency observed in small farms, some producers remain hesitant to fully rely on automation technologies due to unfamiliarity and lack of trust in their operation.

2.3.3. Facilitating Factors for Incorporation or Barriers to the Adoption of Digital Technologies

This study not only examined whether specific factors were statistically significant but also assessed their relevance in explaining technology adoption. Figure 4 presents the frequency with which each factor was identified as significant in the selected studies. These factors were considered significant if they were statistically relevant at a 10% threshold in quantitative analyses, such as generalized linear models, multivariate analyses, or descriptive statistics, or if they were highlighted as important through qualitative methods, including case studies and interviews. The maximum frequency observed corresponds to the total number of reviewed studies (n = 25).

The factors influencing adoption were organized into eight thematic categories: (1) Producer Characteristics (sociodemographic profile, training and skills, decision-making, and behavior); (2) Farm and Herd Characteristics (farm structure, herd size and management, type of production); (3) Farm Management and Structure (team structure and management, labor use, work schedule, and time dedicated); (4) Technology, Innovation, and Information (technology adoption and adaptation, access and use of technology, digital infrastructure, data use and information); (5) Support and Relationship Networks (external support, participation in networks); (6) Economic and Financial Factors (farm revenue and costs, efficiency, and productivity); (7) Benefits and Impacts of Smart Products (perception of smart products); (8) Infrastructure and Production Quality (milking infrastructure, sanitary issues).

The adoption of digital technologies in cattle farming is driven by both economic motivations and regulatory requirements. On one hand, producers are incentivized to adopt technologies that improve production processes such as heat detection, labor management, animal health, and welfare (BIANCHI *et al*., 2022; SCHUKAT; HEISE, 2021), or those that increase profitability and are complementary to existing tools (ABENI; PETRERA; GALLI, 2019, NEWTON; NETTLE; PRYCE, 2020; STEENEVELD; HOGEVEEN, 2015; PALMA-MOLINA *et al*., 2023). On the other hand, adoption may also be stimulated by government mandates, such as the compulsory use of RFID systems in New Zealand (EDWARDS; DELA RUE; JAGO, 2014; MARESCOTTI *et al*., 2021). Similar policy-driven incentives can be observed in other countries as well, such as Brazil, where the adoption of RFID technologies is promoted through the National Program for Individual Identification of Cattle and Buffaloes (PNIB) (BRASIL, 2024).

Some technologies, especially activity sensors, have lower adoption rates due to the complexity of data interpretation (PALMA-MOLINA *et al*., 2023). Conversely, Gabriel and Gandorfer (2023) suggest that the availability of low-cost and easy-to-use digital tools may help stimulate the adoption of more advanced systems.

Social influence can also play a role in the adoption decision. For example, Lee *et al*. (2024) and Schukat and Heise (2021) found that neighbor complaints about manure management were a significant factor motivating the adoption of automated cleaning systems.

Among all factors, perceived usefulness and ease of use were consistently associated with adoption decisions (SILVI *et al*., 2021). However, producers with limited prior experience or familiarity with technology tend to perceive lower utility, often requiring external support to operate these systems effectively.

Farm size and production scale, usually measured by herd size, emerged as the most robust and frequently significant variable across studies, with positive effects on digital technology adoption reported in 90% of the quantitative analyses (ALVAREZ; NUTHALL, 2006; BOYER *et al*. 2024; DELA RUE *et al*., 2020; EDWARDS; DELA RUE; JAGO, 2014; GABRIEL; GANDORFER, 2023; GARGIULO *et al*., 2018; GILLESPIE; NEHRING; SITIENEI, 2014; GROHER; HEITKÄMPER; UMSTÄTTER, 2020; LEE *et al*., 2024; MARESCOTTI *et al*., 2021; PALMA-MOLINA *et al*., 2023; PIÑA *et al*., 2023; SILVI *et al*., 2021; STEENEVELD; HOGEVEEN, 2015). Larger producers demonstrated lower levels of technological aversion (MARESCOTTI *et al*., 2021) and a greater propensity to adopt digital technologies (GROHER; HEITKÄMPER; UMSTÄTTER, 2020). In beef production systems, these technologies included animal activity sensors (BIANCHI *et al*., 2022; GARGIULO *et al*., 2018), radio-frequency identification (RFID) devices for monitoring and tracking (BOYER *et al*. 2024), and big data tools for data storage and analysis (PIÑA *et al*., 2023). In dairy farming, the most frequently adopted technologies by larger producers were automated milking parlor cleaning systems and robotic calf feeders (GARGIULO *et al*., 2018).

The age of the decision-maker was also one of the most commonly tested variables, appearing in 19 of the 23 quantitative studies. Younger farmers were consistently found to be more inclined toward adoption, whereas older producers, often described as technophobic (MARESCOTTI *et al*., 2021), were less likely to implement digital solutions (ALVAREZ; NUTHALL, 2006; BATTE, 2005; DREWRY *et al*., 2019; GROHER; HEITKÄMPER; UMSTÄTTER, 2020; LEE *et al*., 2024; MARESCOTTI *et al*., 2021; PALMA-MOLINA *et al*., 2023). Younger age was particularly associated with the adoption of cameras, big data platforms, feeding behavior sensors, milk quality sensors, and mastitis detection systems (BIANCHI *et al*., 2022; BOYER *et al*. 2024; PIÑA *et al*., 2023).

As for gender, Drewry *et al*. (2019) found that female decision-makers were more likely to use the internet and agricultural laptops or tablets. However, this result was not confirmed by other studies (JELINSKI *et al*., 2020; GROHER; HEITKÄMPER; UMSTÄTTER, 2020).

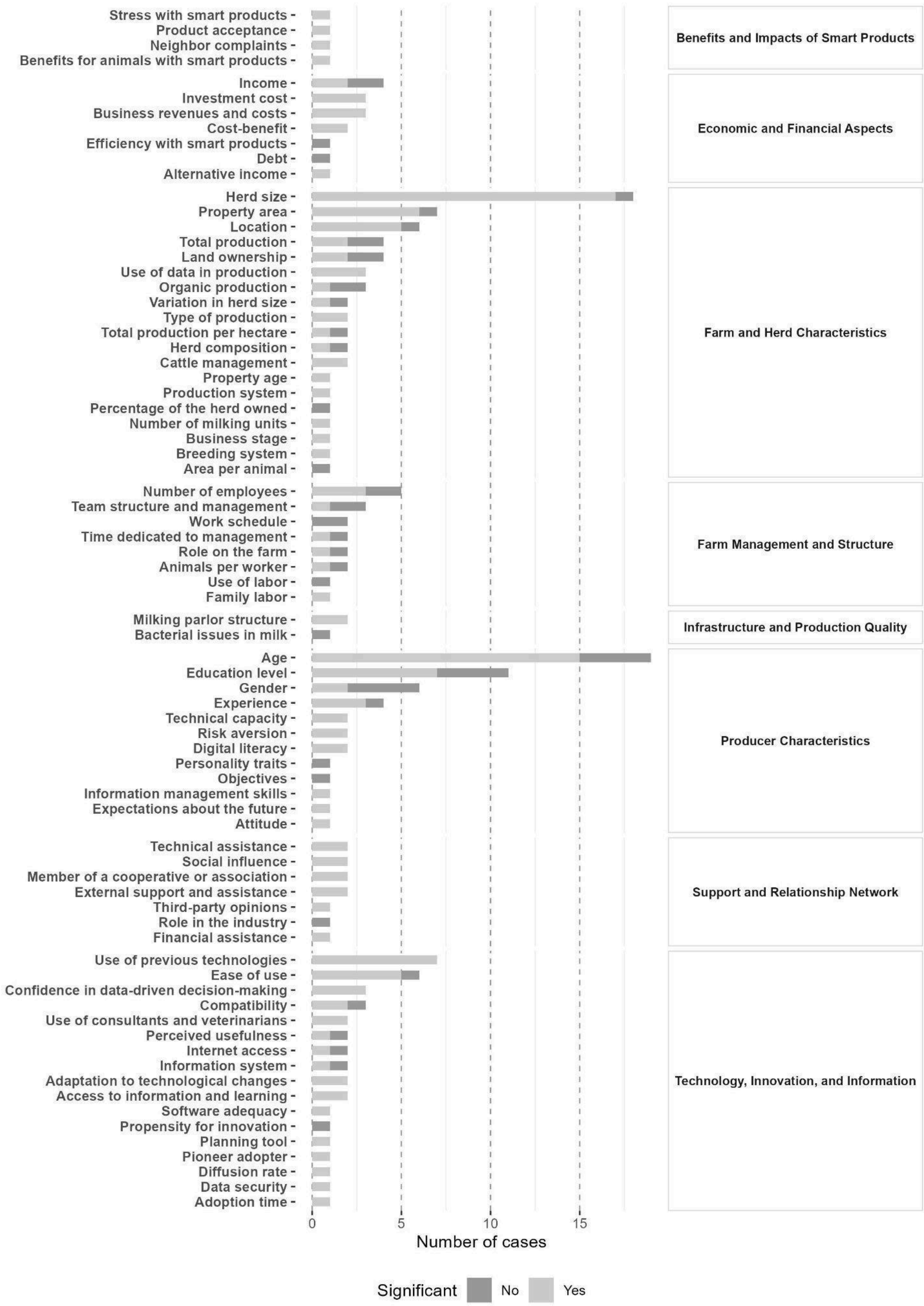

Figure 4. Frequency with which each factor was identified as significant in the selected studies. Source: Authors' own work.

The educational level of the decision-maker was widely tested (ALVAREZ; NUTHALL, 2006; BATTE, 2005; BOYER *et al*. 2024; DREWRY *et al*., 2019; GABRIEL; GANDORFER, 2023; GILLESPIE; NEHRING; SITIENEI, 2014; MARESCOTTI *et al*., 2021; MENDES *et al*., 2023; PALMA-MOLINA *et al*., 2023; PIÑA *et al*., 2023; RAJCHAMAHA; MAKARARPONG, 2023). However, only about half of these studies identified a significant and positive correlation between higher education and digital technology adoption (ALVAREZ; NUTHALL, 2006; BATTE, 2005; DREWRY *et al*., 2019; MARESCOTTI *et al*., 2021; MENDES *et al*., 2023).

In dairy farming, the type and condition of milking facilities played an important role in technology adoption. Newer installations, particularly those equipped with rotary milking systems, facilitated the use of automation (DELA RUE *et al*., 2020; EDWARDS; DELA RUE; JAGO, 2014; GARGIULO *et al*., 2018). Automation provided efficiency gains compared to the herringbone milking system (DELA RUE *et al*., 2020).

Batte (2005) noted that farmers who had off-farm employment were more likely to adopt computers for farm management. Palma-Molina *et al*. (2023) pointed out that high labor costs were a strong driver of automation-related technology adoption. Lee *et al*. (2024) found that implementing milking automation significantly improved labor efficiency in small-scale or family-run farms, although this effect was less evident in large farms, possibly small farms can be relatively more flexible in integrating new technologies into their existing routines.

In terms of barriers, the most frequently cited obstacles were high upfront investment costs, especially for technologies requiring facility upgrades, and uncertainty regarding return on investment (ABENI; PETRERA; GALLI, , 2019; BIANCHI *et al*., 2022; BOYER *et al*. 2024; STEENEVELD; HOGEVEEN, 2015; MARESCOTTI *et al*., 2021; MAKINDE *et al*., 2022).

Some producers expressed concerns that the time lag between data collection and the generation of actionable information could limit the benefits of digital technologies for production management (ABENI; PETRERA; GALLI, 2019; BIANCHI *et al*., 2022; DELA RUE *et al*., 2020). In addition, several studies reported a lack of clarity regarding how to interpret and apply the collected data (BIANCHI *et al*., 2022; DELA RUE *et al*., 2020). This issue was often linked to limited technical knowledge and the perceived complexity of certain digital tools (BOYER *et al*. 2024; LEE *et al*., 2024; MAKINDE *et al*., 2022), which represented a significant barrier to adoption. Boyer *et al*. (2024) further noted that many producers considered seeing the technology in operation on another farm a crucial step before making an adoption decision.

Another relevant concern was data privacy, particularly in relation to cloud-based or local data storage systems. This was especially pronounced among older producers, who demonstrated greater resistance to big data technologies (DREWRY *et al*., 2019; PIÑA *et al*., 2023).

Additionally, uncertainty regarding the compatibility of new technologies with existing farm software and platforms was identified as a major limiting factor in some studies (DREWRY *et al*., 2019; RAJCHAMAHA; MAKARARPONG, 2023).

Finally, internet access and connectivity issues were reported inconsistently. While Boyer *et al*. (2024) did not consider them a major barrier in the United States, Marescotti *et al*. (2021) identified poor connectivity as a key constraint in mountainous regions of Italy. Groher, Heitkämper, Umstätter (2020) also found that topographic conditions significantly influenced adoption rates, with lower adoption observed in mountain areas compared to valleys. These findings underscore the importance of regional context when evaluating structural barriers to adoption.

2.4. Conclusion and implications

This study revealed that the adoption of digital technologies by cattle farmers can varies according to the production system. Dairy producers are more inclined to adopt technologies related to Automation, Control, and Robotics, particularly in the milking process, as well as Data Acquisition and Communication Technologies aimed at improving animal welfare, reproduction, and health monitoring. These technologies play a key role in optimizing labor use, reducing operational workloads, and enhancing overall productivity. However, their effective implementation is contingent on producers' access to financial resources, technical training, and adequate infrastructure, especially among smallholders. In contrast, beef producers are more likely to adopt data acquisition and communication technologies, and information systems that support herd monitoring and production management. In both production systems, the primary motivation for adoption is the potential to increase efficiency and productivity.

Several factors were identified as influencing the adoption of digital technologies in cattle farming. These include socioeconomic characteristics of decision-makers, such as age, education level, and gender, as well as farm-level attributes, including herd size, infrastructure conditions, and milking system type. The evidence suggests that larger and better-structured farms, managed by younger and more educated producers, tend to be more open to adopting digital innovations. On the other hand, significant barriers to adoption persist. These include high initial investment costs, uncertainty regarding cost-benefit ratios, concerns about data privacy, and a general lack of technical knowledge related to the use of complex digital tools. In some cases, limited internet connectivity, software incompatibility, and the need for structural adaptations further hinder the adoption process.

The findings of this review contribute to a more comprehensive understanding of the digital transformation process in cattle farming. They offer valuable insights for the formulation of targeted public policies, training programs, and technological support strategies aimed at promoting more widespread and equitable adoption of precision livestock technologies. Moreover, the study highlights a persistent research gap, particularly in the context of beef production systems, where empirical evidence remains scarce. Future research should address this imbalance by exploring adoption dynamics in diverse geographic and structural contexts.

3. Paper 2: Characterization of the adoption of digital technologies in beef cattle feedlots in Brazil

ABSTRACT

This study identifies the main digital technologies adopted by beef cattle feedlots in Brazil, as also the factors that differentiate farmers with different levels of technological intensity. Primary data from 184 feedlots collected through a structured questionnaire in 2021 were analyzed by descriptive statistics, hypothesis, tests, and multiple correspondence analysis. We identified the adoption of the following technologies: (I) electronic animal identification; (II) management software; (III) automatic meteorological station; (IV) automatic food dispensing in troughs; (V) automatic weighing scales; (VI) infrared thermography; and (VII) feeding/drinking troughs, with automatic intake verification. The adoption of these innovations is associated with several key characteristics: Younger farmers with higher levels of education, reliance on specialized consulting firms, feedlot operationswith more head of cattle, increased workforce size, use of price risk management tools, provision of Cattle-fattening services to other farmers, and bonuses received upon the sale of animals to slaughterhouses. These findings support the diffusion of precision livestock farming technologies in Brazil, contributing positively to technical efficiency, environmental sustainability, and animal welfare.

Keywords: beef cattle; diffusion of innovations; digital technologies; precision livestock farming.

3.1. Introduction

Feedlot is a capital-intensive production system with high yields, both per area and per animal (VINHOLIS *et al.*, 2016). The technical and economic viability of this production system requires production planning and strict control of production factors, which increases the management complexity (VINHOLIS; CARRER; SOUZA FILHO, 2017). In addition, there is the challenge to cause a lower environmental impact. Precision livestock farming aims to "develop a management system based on integrated and automatic production management and control of the environmental impact and animal health and welfare in real time" (MORRONE *et al.*, 2022), which results in the improvement in management and greater efficiency in the use of resources (BANHAZI; BLACK, 2009; WATHES, 2009).

In the field of precision livestock farming, systems for identifying individual animals were among the first digital technologies to be introduced in cattle management (MORRONE *et al*., 2022; TZANIDAKIS *et al*., 2023). Radio Frequency Identification (RFID) ear tagging was widely used in intensive beef cattle systems. Combined with sensors, it allowed automated data collection and real-time monitoring at lower costs. The synergistic approach was demonstrated by the integration of RFID technology and automated weighing scales, enabling precise monitoring of weight gain and body growth (DICKINSON *et al*., 2013; TZANIDAKIS *et al*., 2023). Additionally, RFID has been adopted alongside automated feeding troughs to accurately measure individual animal feed intake (CHAPINAL *et al*. 2007; MORRONE *et al*., 2022; OLIVEIRA JUNIOR *et al*., 2018; TZANIDAKIS *et al*., 2023; ZANETTI *et al*., 2019). RFID technology automates precise feed dispensation to animal batches, ensuring optimal nutrient provision (PEZZUOLO *et al*., 2020).

Images from drones are used to automate herd inventory, monitor food in troughs, and analyze cattle feeding behavior (BOYER *et al*. 2024). Animal temperature verification through infrared thermography is used to assess animal health and welfare (MORRONE *et al*., 2022; TZANIDAKIS *et al*., 2023). Automatic meteorological stations gather data on temperature, humidity, and rainfall. This information is utilized to make informed decisions regarding the provision of shade, the deployment of sprinklers, and other devices aimed at enhancing animal welfare (NIENABER; HAHN, 2007).

Furthermore, input and environmental data are stored in cloud platforms, analyzed by algorithms and management software, which issue alerts for early deviations and useful information for management (BERCKMANS, 2017; GARCÍA *et al*. 2020). Market data can be aggregated to enhance decision-making (BANHAZI; BLACK, 2009; WATHES, 2009). These software tools manage herds, finances, and diet optimization. They can enhance production efficiency, animal welfare, product quality, and reduce environmental impacts (TULLO; FINZI; GUARINO, 2019). However, even though the benefits of digital technologies have been verified in the literature, their diffusion is still in the incipient stage (ROSA, 2021).

Factors related to the characteristics of technologies, such as, decision-making, farming, production systems, and institutional environments could both encourage and hinder the adoption of innovations in agriculture (GEROSKI, 2000). Empirical studies have indicated that factors such as farmers' socioeconomic status, behavioral characteristics, access to information, production scale, workforce availability, and access to farm credit and agricultural extension services, might influence their decision to adopt agricultural innovations (BARNES *et al*., 2019; BIANCHI *et al*., 2022; CARRER; SOUZA FILHO; BATALHA, 2017; CARRER *et al*., 2022; DREWRY *et al*., 2019; GARGIULO *et al*., 2018;

GIUA; MATERIA; CAMANZI, 2021; GROHER; HEITKÄMPER; UMSTÄTTER, 2020; JELINSKI *et al*., 2020; MENDES *et al*., 2023; MOZAMBANI *et al*., 2023; ROJO-GIMENO *et al*., 2019; SOOD; BHARDWAJ; SHARMA, 2022; TEY; BRINDAL, 2022; VINHOLIS; CARRER; SOUZA FILHO, 2017). Furthermore, we confirmed that some farmers adopt a single digital technology, while others implement comprehensive technology sets. Different categories of digital technology adopters can be identified according to the number and type of digital technologies they adopt (BARNES *et al*., 2019). Such categorization establishes groups of farmers that could be differentiated from each other based on their intensity of digital technology adoption. This approach allows for the assessment of factors that characterize groups with different levels of adoption intensity (GIUA; MATERIA; CAMANZI, 2022; ISGIN *et al*., 2008; KOLADY *et al*., 2021; PAXTON *et al*., 2011; MOZAMBANI *et al*., 2023).

This study aims to identify the main digital technologies used in beef cattle feedlots in Brazil, as well as the factors that distinguish groups with varying levels of technological intensity in the use of these technologies.

3.2. Materials and methods

3.2.1. Sampling

A review of empirical studies on the factors influencing the adoption of digital technologies in agriculture helped guide the development of a structured questionnaire for data collection: (i) The decision-maker's behavioral and socioeconomic characteristics; (ii) the farm and the production system; and (iii) the digital technologies that are used in the feedlot. The questions used for analysis are described in the Appendix A.

Primary data were collected through a technical cooperative agreement between Embrapa, a public research company, and Scot Consultoria, a private consulting firm for beef cattle farmers in Brazil. A structured questionnaire was applied by the private company through face-to-face interviews with 184 feedlot beef cattle farmers, between June and October 2021. Each interview lasted an average of two hours. The interviewers were professionals in Agrarian Sciences, such as Agronomy and Veterinary. Before data collection, there were meetings between the public and private companies, to improve the questionnaire and to train the interviewers on application. The researchers of the public company accompanied the private company on the first visits to the feedlots.

The sample was derived from a comprehensive list of feedlot beef cattle farmers, which was compiled through collaboration with associations, input companies, and beef cattle technical events. The sample included 134 municipalities across 14 states in all five regions of Brazil. The team visited 184 farms dedicated to beef cattle farming in feedlots (Table 4 and Figure 5).

Table 4. Farms and confined livestock sampled in 2021, by state.

States	Number of farms (n, %)	Total animals (n, %)	Mean animals per farm
Mato Grosso	29 (15.8%)	338,096 (16.3%)	11,658.48
Paraná	20 (10.9%)	74,177 (3.6%)	3,708.85
Rio Grande do Sul	19 (10.3%)	100,596 (4.9%)	5,294.53
Rondônia	16 (8.7%)	187,718 (9.1%)	11,732.38
São Paulo	16 (8.7%)	244,100 (11.8%)	15,256.25
Mato Grosso do Sul	13 (7.1%)	78,099 (3.8%)	6,007.62
Pará	13 (7.1%)	76,408 (3.7%)	5,877.54
Tocantins	13 (7.1%)	136,836 (6.7%)	10,525.85
Goiás	12 (6.5%)	494,643 (23.9%)	41,220.25
Santa Catarina	11 (6.0%)	25,350 (1.2%)	2,304.55
Bahia	8 (4.3%)	99,500 (4.8%)	12,437.50
Minas Gerais	8 (4.3%)	185,031 (8.9%)	23,128.88
Espírito Santo	3 (1.6%)	26,448 (1.3%)	8,816.00
Rio de Janeiro	3 (1.6%)	2,660 (0.1%)	886.67

Source: Authors' own work.

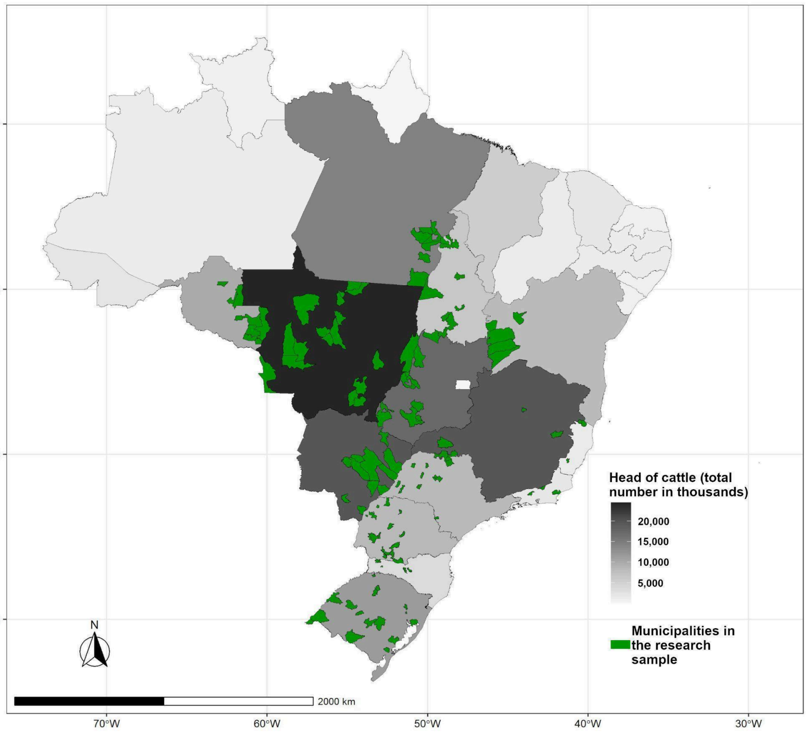

Figure 5. Geographical distribution of municipalities that were visited for data collection. Source: IBGE (2017) and research data.

3.2.2. Method

The data analysis was divided into three stages: 1) Identification of the digital technologies adopted and their diffusion level in the sample; 2) construction of technological groups at different levels of intensity of adoption through Multiple Correspondence Analysis (MCA); 3) identification of farmers' and the production characteristics that differentiate the technological groups, through descriptive statistics, hypothesis tests, and MCA.

The diffusion of digital technologies is presented according to the frequency of adoption of the following technologies: Electronic animal identification (ID), automatic weighing scale (AW), infrared thermography (IT), automatic food dispensing in troughs (AD), feeding/drinking troughs with automatic intake verification (AV), automatic meteorological station (MS), operational management software (OS), financial management software (FS), and diet formulation software (DS). We applied MCA to obtain a bi-dimensional map that could reveal the technological groups. The groups established an adoption intensity gradient. Dummy variables were used to identify the adoption or non-adoption of each digital technology (1 = adopts the technology, 0 = does not adopt it).

The farmers' and production characteristics that statistically differentiate the technological groups were assessed. Table 5 presents the description of the variables used in this analysis. Descriptive statistics were calculated for each technological group and hypothesis tests were performed to identify the differences. Pearson's chi-square test was used to verify whether or not there was an association between the groups and the qualitative variables, (PEARSON, 1900). The number of observations (N) for some variables was smaller than the sample size, due to missing answers. Yates' continuity correction was adopted to assure that the value of the chi-square statistics would not be overestimated in such circumstances (YATES, 1934).

The variables that statistically differentiated the technological groups at the 10% significance level in the hypothesis tests were selected for the MCA. The MCA map visually shows the global relationship between the matrix's columns and rows, covering the farmers' production characteristics and technological groups, by reducing the data dimensionality (JOHNSON; WICHERN, 2007). The statistical software R was used for data analysis (R CORE TEAM, 2024). The specifications used for analysis are described in the Appendix B.

Table 5. Description of variables related to farmers' and production characteristics.

Abbr.	Variable	Description
Farmer's characteristics		
Human capital		
AGE	Age	1, if up to 40 years old; 2, if between 41 and 54 years old; 3, if 55 years old or older*.
EDU	Education	1, if the farmer has university degree; 0, otherwise**
GEN	Gender	1, if the farmer is the female gender; 0, if the farmer is the male gender
Behavior		
INC	Innovation capacity	Farmer's innovation capacity based on their response (Likert scale) (1, I disagree; 2; indifferent; 3, I agree) to the statement: "I like to try new technologies on my farm".
AVR	Aversion to risk	Farmer's level of aversion to risk based on their response (Likert scale) (1, I disagree; 2; indifferent; 3, I agree) to the statement: "When it comes to business, I prefer the safest option, even if I know that I could make less money".
Financial resources		
FCR	Farm credit	1, if the farmer took farm credit for investment in the past 3 years; 0, otherwise.
Information source		
CON	Private consulting	1, if a private consultant is an important information source for decision-making related to farm management; 0, otherwise.
Production characteristics		
Production scale		
HSZ	Herd size	1, if the farmer has up to 2,000 head in feedlot per year; 2, for between 2,001 and 8,000 head; 3, for 8,001 head or more.
SC	Static capacity	1, if the farm has the capacity to hold up to 1,000 head in feedlot per cycle; 2, if the capacity is between 1,001 and 4,999 head; 3, for 5,000 head or more.
FCY	Fattening cycles	1, for 1 feedlot cycle per year; 2, performs up to 1.9 cycles; 3, for 2 or more cycles.
Diversification of production		
CRO	Crop cultivation	1, if there is crop cultivation on the farm in addition to beef cattle farming; 0, otherwise.
Human resources		
WOR	Workers	1, up to 3 full-time employees dedicated to the feedlot; 2, between 4 and 8 employees; 3, if there are 9 or more employees.
Commerce		
FAT	Cattle-fattening services	1, if the farmer provides Cattle-fattening services to other farmers; 0, otherwise.
BON	Bonus	1, if the farmer receives a bonus when selling cattle for slaughter; 0, otherwise.
PRI	Price risk	1, if the farmer uses a price protection tool such as a forward contract and hedge; 0, otherwise.

Note: * The age categorization considered the length of career horizon, the balance of the number of observations in each category, and the correspondence fit with the categories of other factors. The age limit of 55 years was also utilized by Drewry *et al.* (2019). ** The schooling categorization considered undergraduate education as significantly enhancing the decision-maker's capacity for analytical requirements of digital technology. This categorization was also adopted by Carrer *et al.* (2017, 2022), Isgin *et al.* (2008), Kolady *et al.* (2021), Mendes *et al.* (2023), and Mozambani *et al.* (2023).

Source: Authors' own work.

3.3. Results and discussion

3.3.1. Diffusion of digital technologies and technological groups

Table 6 shows the frequency of adoption of ten digital technologies. Out of 184 feedlots, 145 adopted at least one of the technologies (79%). Electronic identification (ID) and operational software to manage the herd (OS) were adopted by 57% of the feedlots. and 72% of those, adopted at least one technology. Financial management software (FS) and diet formulation software followed, with adoption rates of 50% and 46% of the feedlots, respectively.

Table 6. Frequency of adoption of the digital technologies in the sample.

Digital technology	n	Adoption in the adopters' group (%) (n = 145)	Adoption in the total sample (%) (n = 184)
(ID) Individual animal identification	105	72,41	57,06
(OS) Operational management software	105	72,41	57,06
(FS) Financial management software	93	64,14	50,54
(DS) Diet formulation software	84	57,93	45,65
(MS) Automatic meteorological station	21	14,48	11,41
(AD) Automatic food dispensing in troughs	19	13,10	10,33
(AW) Automatic weighing device	15	10,34	8,15
(IT) Infrared Thermography	8	5,52	4,35
(AV) Feeding / drinking troughs with automatic intake verification	5	3,45	2,72
(OT) Other technologies	3	2,07	1,63

Source: Authors' own work.

The adoption of electronic animal identification began to grow in 2006, when SISBOV (Brazilian Bovine and Buffalo Individual Identification System) was established, to ensure meat traceability for export to the European Union. The RFID technology in ear tags is complementary to the adoption of more recent digital technologies, such as, automatic weighing scales (AW) or feeding/drinking troughs with automatic intake verification (AV). These technologies have lower adoption rates (Table 6) because they are at their early stage of diffusion.

Figure 6 shows the bidimensional map generated through the MCA, based on variables related to the adoption of each digital technology presented in Table 6. Each technology is represented by two categories in the map, one for adopters of the technology, with the suffix “1” after their abbreviation, and one for non-adopters, with the suffix “0”.

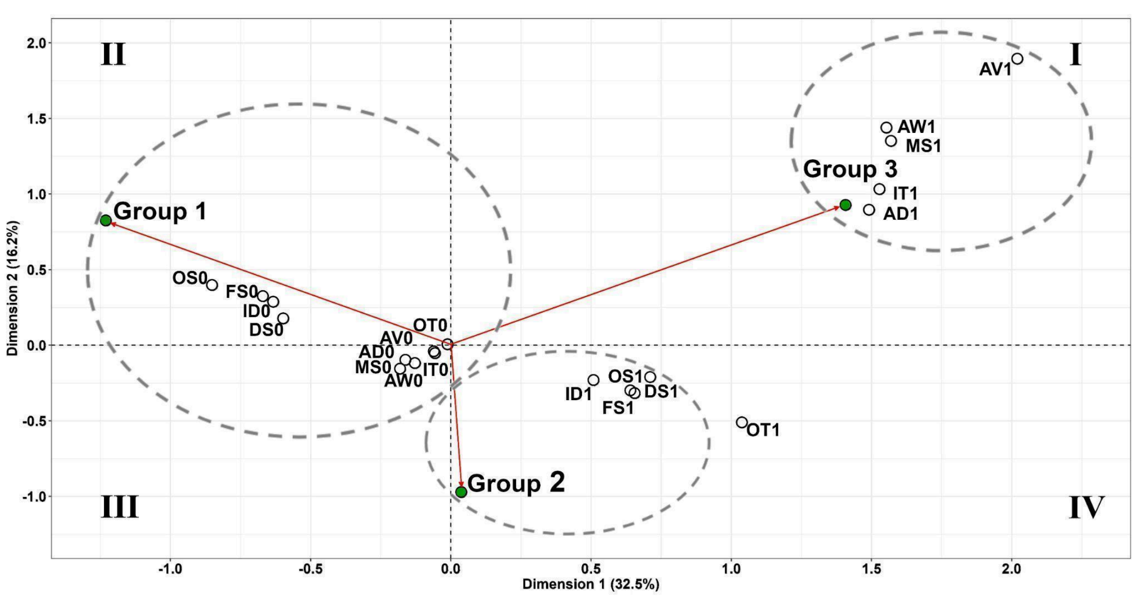

Figure 6. Bidimensional map of the MCA carried out to define three technological groups (n = 184). Source: Authors' own work.

The results allowed us to identify three technological groups that could be differentiated from each other based on their intensity of adoption of digital technologies:

- ✔ Group 1: Non-adopters of digital technologies, encompassing 53 feedlots (quadrants II and III);
- ✔ Group 2: Adopters of electronic identification (ID) and at least one management software (FS; OS; DS), totaling 87 feedlots (quadrant IV);
- ✔ Group 3: Adopters of electronic identification, management software and at least one extra digital technology (AW; IT; AD; AV; MS; OT), totaling 44 feedlots (quadrant I, except for OT).

The ID technology was included in both adopting groups, because it facilitated the adoption of other digital technologies.

3.3.2. Farmers' and production characteristics that differentiate the technological groups

Table 7 presents the descriptive statistics of the characteristics of decision-makers.

Table 7. Frequencies and hypothesis tests of the variables related to decision-makers' characteristics.

Variable	Category	Group 1	Group 2	Group 3	n	p-value
Human capital						
Age (AGE) (N1=52, N2=84, N3=43)	≤ 40 years old	28,80%	47,60%	44,20%	74	0,050
	≥ 41 and ≤ 54 years old	28,80%	33,30,%	30,20%	56	
	≥ 55 years old	42,30%	19,00%	25,60%	49	
Education (EDU) (N1=44, N2=,80 N3=43)	Has a higher education degree	61,40%	76,20%	90,70%	127	0,006
	Does not have a higher education degree	38,60%	23,80%	9,30%	40	
Gender (GEN) (N1=53, N2=86, N3=44)	Female	1,89%	13,95%	2,27%	14	0,010
	Male	98,11%	86,05%	97,73%	169	
Behavior						
Innovation capacity (INC) (N1=45, N2=63, N3=20)	Agrees	93,33%	95,24%	100%	122	0,585
	Indifferent	4,45%	4,76%	0,00%	5	
	Disagrees	2,22%	0,00%	0,00%	1	
Aversion to risk (AVR) (N1=45, N2=63, N3=20)	Agrees	82,20%	74,60%	70,00%	98	0,412
	Indifferent	4,50%	11,10%	20,00%	17	
	Disagrees	13,30%	14,30%	10,00%	13	
Financial resources						
Farm credit (FCR) (N1=53, N2=87, N3=44)	Obtains credit	69,80%	66,70%	72,70%	127	0,770
	Does not obtain credit	30,20%	33,30%	27,30%	57	
Information source						
Private consulting (CON) (N1=53, N2=87, N3=44)	Yes	22,60%	35,60%	52,30%	66	0,010
	No	77,40%	64,40%	47,70%	118	

Note. * Ni= number of observations in group i (i=1,2,3).

Source: Authors' own work.

Education (EDU) statistically differentiates the groups containing adopters of digital technologies (Groups 2 and 3) from the non-adopting farmers (Group 1) at the significance level of at least 10%. In the two groups of adopters, there is a strong presence of farmers with a higher education degree in contrast to the group formed by non-adopters. In fact, the positive impact of education on the adoption of digital technologies is strongly emphasized by other empirical studies (BIANCHI *et al*., 2022; CARRER; SOUZA FILHO; BATALHA, 2017; CARRER *et al*., 2022; DREWRY *et al*., 2019; GIUA; MATERIA; CAMANZI, 2021; ISGIN *et al*., 2008; MENDES *et al*., 2023; MTHETHWA *et al*., 2022; ROJO-GIMENO *et al*., 2019; and VINHOLIS; CARRER; SOUZA FILHO, 2017). Individuals with a higher educational level may have an easier time processing and interpreting sensor information and selecting vital data for decision-making (ROJO-GIMENO *et al*. 2019). Individuals with less education often struggle to understand information and recognize the benefits of technology (MTHETHWA *et al*., 2022). Additionally, some digital technologies have systems that are non-intuitive and complex, featuring a challenging interface and numerous resources. This necessitates acquiring new skills for effective adoption (GIUA; MATERIA; CAMANZI, 2021).

Gender (GEN) statistically discriminates the group formed by adopters of management technologies (Group 2) from both non-adopters (Group 1) and adopters of a greater number of technologies (Group 3), at a significance level of at least 5%. This result aligns with Drewry *et al*. (2019), who found that women were more likely to adopt information management systems. However, the robustness of this finding may be limited by the underrepresentation of female decision-makers in the sample. This reflects a broader structural imbalance in rural contexts, where decision-making positions are predominantly held by men (GALIÈ *et al*., 2015; QUISUMBING; DOSS, 2021). Such gender skewness in managerial roles may dilute the statistical impact of female-driven adoption behaviors in empirical analyses.

Age (AGE) statistically discriminates the group formed by adopters of management technologies (Group 2) from the group of non-adopters (Group 1). The average age in Group 1 (50 years old) is more advanced than in the other groups. This result supports the findings of Boyer *et al*. (2024), Groher, Heitkämper and Umstätter, (2020), and Mendes *et al*. (2023), confirming that younger farmers prefer digital technologies and embrace innovations.

Both groups of adopters have high percentages of farmers who consider consultants (CON) to be important information sources. Access to information on digital technologies through consulting is highlighted in other empirical studies (CARRER *et al*., 2022; MENDES *et al*., 2023; MOZAMBANI *et al*., 2023; VINHOLIS; CARRER; SOUZA FILHO, 2017). Farmers make decisions based on the information they receive, which influences the timing of adopting innovations (early or late) (SOOD; BHARDWAJ; SHARMA, 2022). Information reduces uncertainty about the effectiveness of the technology, helping farmers make more objective decisions (DHRAIEF *et al*., 2018). TRAN *et al.* (2020) argue that besides having access to consulting services, it is important to consider the quality of the technicians and the information provided by them. In general, private consultants provide a customized service tailored to the needs and characteristics of farmers and their production. In many cases, consultants encourage the adoption of digital technologies because interpreting the collected data is one of their most important tasks. Digital technologies and consulting services are commonly sold as a bundle. According to ROJO-GIMENO *et al*. (2019), information provided by digital technology becomes valuable only when it is used in decisions that yield improved outcomes.

Aversion to risk (AVR), a decision-makers' innovation capacity (INC), and access to farm credit (FCR), do not statistically differentiate the three technological groups.

Table 8 presents the results of the descriptive statistics of the variables related to production. The variables related to production scale — feedlot static capacity (SC), number of feedlot cycles per year (FCY), and herd size in the feedlot (HSZ) — statistically discriminated the three technological groups. On an average, the adopters in Group 3 have a larger static capacity (10,432 head), a higher number of feedlot cycles per year (2.46), and consequently, larger number of animals in the feedlot per year (26,031 head). The average number of workers per feedlot (WOR) is also statistically higher in Group 3 (23.45 workers) when compared to the averages presented by Groups 2 and 1 (9.22 and 4.47, respectively). These findings corroborate that the adoption of digital technologies is positively associated with the size of the feedlot. The positive effect of the production scale on the adoption of digital technologies was also observed by other empirical studies (BIANCHI *et al*. 2022; BOYER *et al*. 2024; GROHER; HEITKÄMPER; UMSTÄTTER, 2020; JELINSKI *et al*. 2020; ROJO-GIMENO *et al*. 2019; VINHOLIS; CARRER; SOUZA FILHO, 2017). Precise control and management of inputs are crucial in intensive livestock farming, particularly with large production volumes, which heighten the complexity of the production processes and the amount of information to be handled. The significant volume of information produced and processed by digital technologies in real time is useful to managers. It is also important to consider that large-scale farmers have a greater capacity to try new technologies and manage the associated risks and learning time.

Cattle-fattening services for animals with the third-party farmers (FAT) is related to Groups 2 and 3 (p-value=0.004). This service involves a partnership where a feedlot offers fattening services for animals owned by other farmers, providing the necessary facilities and food until the animals are prepared for slaughter. This system adds to the managerial complexity of the feedlot, due to the increased scale of production and the diversity of the animals, in terms of breed, age, weight, and nutritional requirements. The need for precise control and monitoring encourages the use of digital technologies in these feedlots.

The use of tools for price risk management, such as forward and future contracts (PRI), is related to a higher intensity of adoption of digital technologies (p-value < .001). Digital technologies enhance input management to meet production goals and fulfill commitments, particularly with forward contracts signed with slaughterhouses.

Table 8. Frequencies and hypothesis tests of the variables related to the characteristics of production.

Variable	Category	Group 1	Group 2	Group 3	n	p-value
Production scale						
Herd size (HSZ) (N1=53, N2=87, N3=44)	≤ 2000	58,50%	26,40%	13,60%	60	<,001
	≥ 2001 and ≤ 8000	26,40%	44,80%	22,70%	63	
	≥ 8001	15,10%	28,70%	63,60%	61	
Static capacity (SC) (N1=51, N2=85, N3=41)	≤ 1000	56,85%	24,70%	14,60%	55	<,001
	≥ 1001 and ≤ 4999	27,45%	47,06%	22,00%	63	
	≥ 5000	15,70%	28,24%	63,40%	58	
Fattening cycles (FCY) (N1=51, N2=85, N3=41)	1 cycle	39,20%	25,90%	22,00%	51	0,008
	2 cycles	23,50%	40,00%	17,00%	53	
	≥ 2 cycles	37,30%	34,10%	61,00%	73	
Diversification of production						
Crop cultivation (CRO) (N1=52, N2=78, N3=41)	Diversifies	90,40%	79,50%	80,50%	142	0,237
	Does not diversify	9,60%	20,50%	19,50%	29	
Human resources						
Workers (WOR) (N1=53, N2=86, N3=42)	≤ 3 workers	56,60%	26,70%	19,00%	61	<,001
	≥ 4 and ≤ 8 workers	32,10%	40,70%	21,40%	61	
	≥ 9 workers	11,30%	32,60%	59,50%	59	
Commerce						
Cattle-fattening services (FAT) (N1=52, N2=86, N3=44)	Offers fattening services	9,60%	26,70%	38,60%	45	0,004
	Does not offer the service	90,40%	73,30%	61,40%	137	
Bonus (BON) (N1=50, N2=79, N3=40)	Receives a bonus	26,00%	29,10%	47,50%	55	0,065
	Does not receive a bonus	74,00%	70,90%	52,50%	114	
Price risk (PRI) (N1=49, N2=81, N3=42)	Uses it	10,20%	22,20%	45,20%	42	<,001
	Does not use it	89,80%	77,80%	54,80%	130	

Note. *Ni= number of observations in group i (i=1,2,3).

Source: Authors' own work.

Groups 2 and 3 have more farmers receiving bonuses when cattle are sold, indicated by the variable BON. These bonuses are usually paid when technological and quality requirements are imposed. Compliance with them demands efficient management, which is improved with the use of digital technologies.

Figure 7 summarizes the characteristics of farmers and production that represent each technological group. The MCA was applied to the variables that statistically differentiated the technological groups in the hypothesis test (Tables 4 and 5). The bidimensional map presents 32.60% of the total inertia of the observations. The non-adopters' characteristics (Group 1) are on the left of the map (quadrants II and part of quadrant III). The characteristics of adopters in Group 2 are in the lower half of the map, between quadrants III and IV, whereas, the characteristics of adopters in Group 3 are in quadrant I and in part of quadrant IV.

Non-adopters (Group 1) are characterized by a higher percentage of farmers who are 55 years old or older (IDD3) and who do not have a higher education degree (EDU2) as compared to the groups of adopters. Production scales of feedlots in this group tend to be smaller: 56.8% of them have a static capacity to hold 1,000 head of cattle or less (SC1) and 39.2% perform only one feedlot cycle per year (FCY1). Therefore, they have a smaller number of animals in their feedlot per year than Groups 2 and 3; 58.5% have 2,000 head of cattle or less per year (HSZ1). The number of workers is also relatively smaller: 56.6% employ up to three workers (WOR1). Most farmers do not provide Cattle-fattening services (FAT2), do not use tools for price risk management (PRI2), do not hire management consulting (CON2), and do not receive bonuses (BON2).

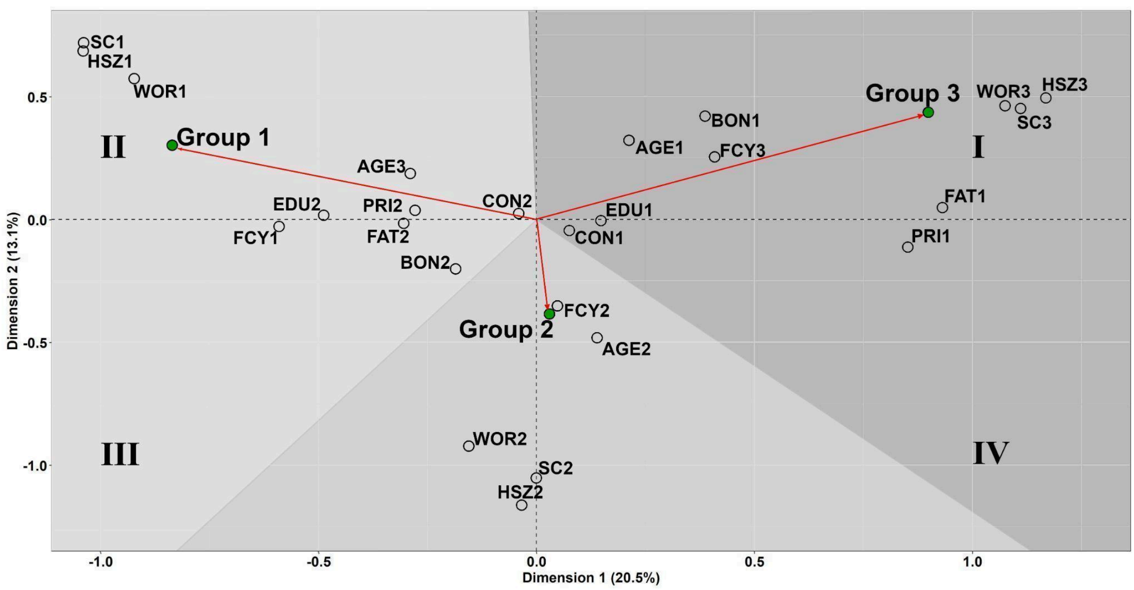

Figure 7. Bidimensional map of the MCA for the socioeconomic characterization of the technological groups (N=142). Source: Authors' own work.

Group 2 (adopters of electronic identification and management software) is characterized by a high percentage of younger farmers: 47.6% are 40 years old or younger (AGE1). Most feedlots in this group are larger than those in Group 1, but smaller than those in Group 3. Specifically, 47% have a static capacity of 1,001 to 4,999 cattle, 74.1% conduct two or more cycles per year, 44.8% maintain between 2,000 and 8,000 cattle, and 40.7% employ three to eight workers.

Group 3 (adopters of electronic identification, management software and at least one more digital technology) is characterized by many younger farmers (44.2% are 40 years old or younger, AGE1) with high education level (90.7% have a university degree, EDU1). The size of feedlots here is significantly larger than in the other two groups: 63.4% have a static capacity to hold at least 5,000 head of cattle (SC3), 61% perform two or more fattening cycles per year (FCY3), 63.6% have more than 8,000 head of cattle (HSZ3), and 59.5% employ nine or more workers on their farms (WOR3). Moreover, Group 3 stands out from the other groups because 38.6% of the farmers provide Cattle-fattening services (FAT1), 52.3% hire management consulting (CON1), 45.2% use price risk management tools (PRI1), and 47.5% receive bonuses from slaughterhouses (BON1).

3.4. Conclusion and implications

The beef cattle Brazilian feedlots analyzed in this study present three digital technological levels. The adoption of a more complete set of digital technologies, such as feedlot management software, devices for data collection, and operational automation, is associated with the following characteristics of farmers and feedlots: (i) younger farmers; (ii) a higher education level; (iii) hiring specialized consulting; (iv) a larger number of head of cattle in feedlots that have a large static capacity; (v) a larger number of workers; (vi) the use of price risk management tools; (vii) providing Cattle-fattening services to other beef cattle farmers; and (viii) receiving some type of bonus when cattle are sold to slaughterhouses.

The results bring new knowledge on the adoption of innovations in beef cattle farming in Brazil, which have the potential to increase its competitiveness and sustainability. Technology diffusion is desirable so that Brazil can increase its beef production with a lower environmental impact, while taking animal welfare into consideration. The educational and extension programs should provide practical training and demonstration of the benefits of digital technologies to surpass the knowledge gap and to foster adoption among older farmers. Additionally, strategies to overcome the scale and investment barriers are necessary to include smaller feedlots in the digital transformation.

4. Paper 3: Digitalization, supply chain coordination and farm performance: an empirical study in Brazilian feedlots

Abstract: Digitalization in agricultural processes has recently increased. However, few studies have investigated how and to which extent digitalization and complementary capabilities of farms are associated with the performance of these farms. This study empirically analyzes the associations between farm performance and digitalization, human capabilities, marketing capabilities, and supply chain integration of beef cattle feedlots in Brazil. We use the resource-based view (RBV) approach and dynamic capabilities theories as theoretical background and to raise hypotheses for our research. Stochastic production frontier models with inefficiency drivers were applied to a unique firm-level panel dataset comprising 359 observations from years 2020 to 2023. The econometric estimations corroborate that digitalization is positively associated with the operational performance of feedlots. The formulation of optimal diets using intelligent algorithms, real-time data collection through electronic devices, automated feed distribution using precision sensors, and predictive data analysis were associated with better decision-making and more efficient utilization of production factors. Additionally, supply chain integration showed positive and statistically significant associations with feedlot operational performance. The findings of the article have important managerial and political implications.

Keywords: digital technologies; farm performance; human capabilities; supply chain integration; technical efficiency.

4.1. Introduction

The adoption of digital technologies has been a path chosen by many firms to improve the decision-making process and increase the integration with other firms along the supply chain (YANG; FU; ZHANG, 2021). These technologies can enhance the processes of acquiring, storing, sharing, and applying knowledge within a firm's operations and across supply chains (TEROUHID; RIES, 2016; YANG; FU; ZHANG, 2021). The collection and processing of large volumes of data in real-time became possible, generating useful information for decision-making (LIU; CHEN; LIANG, 2023). Managers become able to evaluate a larger set of solutions and make more assertive decisions in an environment of increasing complexity and uncertainty. Information and strategies can be shared quickly and at low cost among partners within the supply chain (SUBRAMANI, 2004). Operational problems can be detected and solved more quickly, increasing the efficiency in the use of production resources (GUNASEKARAN *et al.*, 2018). Leaner operations and improved product quality can also be achieved through digital management systems. Therefore, adoption of digital technologies has the potential to increase firm performance (MITHAS and RUST, 2016; CARRER *et al*., 2022; LIU; CHEN; LIANG, 2023; TSOU; CHEN, 2023).

The diffusion of digital technologies has been accelerated in the operations of many industries, including beef cattle farming, which is investigated in this article. Integrated management systems such as Enterprise Resource Planning (ERP) and Manufacturing Resource Planning (MRP), which are highly diffused among firms in some industries, can be a starting point for digitalization and integration in the supply chain (HUANG; HANDFIELD, 2015; GIUA; MATERIA; CAMANZI, 2021). ERP and MRP can facilitate the efficient and quick sharing of strategies and information between firms in the supply chain (VERDOUW; ROBBEMOND; WOLFERT, 2015). At a high diffusion rate of new digital technology, sensors, robots, cloud computing platforms, internet of things, and systems with artificial intelligence have been adopted to serve not just one, but a larger set of companies within the supply chain (BÜYÜKÖZKAN; GÖÇER, 2018; YANG; FU; ZHANG, 2021; FARAJPOUR *et al*., 2022).

Some empirical studies have analyzed the adoption and impacts of digital technologies across different farming production systems (ZHU *et al*., 2021; ZHENG *et al*., 2021; DELAY *et al*., 2022; CARRER *et al*., 2022; MCFADDEN; ROSBURG; NJUKI, 2022; MENDES *et al*., 2023).[1] In beef cattle farming, sensors help monitoring animal health, feed requirements and water intake; software integrates real-time data for livestock management, nutrition management, and economic analysis; radio frequency identification (RFID) ear tags enable animal tracking and can store additional individual data (GARCÍA *et al*., 2020; MORRONE *et al*., 2022). Most of these technologies have been embedded into processes, shaping a digital operational capability to increase operations management efficiency. Furthermore, these technologies have been employed to enhance the integration of beef cattle farmers with input suppliers and the slaughterhouse industry. Nevertheless, studies that investigate the association between digital technology adoption, supply chain integration and the performance of beef cattle farms are very scarce.

[1] Although the terms 'impact' and 'effects' have been adopted in many of these studies, the econometric designs applied are not always suitable for identifying causal effects. In our study, we acknowledge the limitations of the empirical approach applied and interpret the relationships between z-variables (indicators of digitalization, human capabilities, marketing capabilities, and supply chain integration) and farm technical efficiency (performance) as associations rather than causal impacts/effects. Readers interested in an overview of the main econometric approaches used to estimate causal effects with observational data (and their limitations) should consult the study by Henningsen *et al*. (2024).

The objective of this article is to empirically investigate how and to which extent digitalization, human capabilities, marketing capabilities, and supply chain integration are associated with the performance of beef cattle feedlots in Brazil. Our empirical analysis is based on a firm-level panel dataset covering the period from 2020 to 2023, with 359 observations from 238 feedlots across all Brazilian regions. We apply Stochastic Production Frontier (SPF) models with inefficiency effects to investigate the association between technical efficiency and indicators of digitalization, human capabilities, marketing capabilities, and supply chain integration of Brazilian feedlots.[2] Technical efficiency (TE) can be interpreted as a measure of a firm's ability to achieve the maximum possible output from a given set of inputs and production technology. Thus, the estimated TE scores can be used as proxies for feedlots' performance.

Feedlots are land-saving systems in which energy and protein concentrates (such as corn and soybean) and bulk products (such as corn silage and grass silage) are used to feed cattle. The main costs of fattening cattle in feedlots are the acquisition of cattle and feed (CEZAR *et al*., 2005). The complexity of feedlot management can increase substantially when buyers and government agencies impose quality, health and traceability requirements. A lot of internal and external information is needed for feedlot managers to make decisions to optimize technical and economic performance. Much of this information comes from other firms in the supply chain, such as feed suppliers, animals' suppliers, slaughterhouses and consumers. The adoption of digital technologies to collect, process and analyze data, as well as strategies to enhance integration with other firms in the beef cattle supply chain, can significantly improve feedlot management. For instance, real-time internal and external data can be stored and processed by management software to provide optimized solutions for feed and calf acquisition. The amount of valuable information generated can lead to more assertive decision-making by the farmer. Furthermore, the use of formal contracts in transactions between beef cattle farmers and slaughterhouses has been a strategy adopted to increase integration and facilitate the fulfillment of beef requirements from different markets (CARRER; SOUZA FILHO; VINHOLIS, 2014). Therefore, we are particularly interested in empirically testing hypotheses on positive relationships between digital technology adoption, supply chain integration, and feedlot performance (technical efficiency).

[2] Beef cattle farming in Brazil can be divided into three phases, breeding, rearing and fattening, which can be carried out separately or combined. In the breeding phase, calves are raised from birth until weaning. They are then raised for 12 to 18 months until they are ready to be fattened. Fattening is the last phase before slaughter. All three phases are carried out mainly in pasture-based systems. However, feedlot systems for fattening have been diffused rapidly. Approximately 34 million bovines are slaughtered annually in Brazil (IBGE, 2023), of which 20% come from feedlots (ABIEC, 2023).

The remainder of the article is organized as follows. The next section presents the theoretical framework that we used to formulate hypotheses on the relationship between farm capabilities and operational performance. The method that is used in our empirical analysis is detailed in section 3, comprising the sampling, dataset, variables, and the SPF models that we used to test the research hypotheses. Section 4 presents and discusses empirical results. Conclusions and implications are in section 5.

4.2. Theoretical framework and hypotheses

The resource-based view (RBV) approach emphasizes that firms are heterogeneous regarding their resources and capabilities. Resources are tradable and nonspecific attributes, while capabilities are firm-specific attributes used to exploit the core resources of the firm (AMIT; SCHOEMAKER, 1993). Capabilities can be operational or dynamic (EISENHARDT; MARTIN, 2000; TEECE; PISANO; SHUEN, 2005). Operational capabilities focus on transforming inputs into outputs and improving firm performance in the short term. Dynamic capabilities refer to the firm’s ability to adapt and modify its operational capabilities in a changing and uncertainty environment to keep superior performance in the long term (TEECE; PISANO; SHUEN, 1997; WINTER, 2003; TEROUHID; RIES, 2016).

Both operational capabilities and dynamic capabilities of firms can be affected by changes in firms' technological resources (TEECE; PISANO; SHUEN, 1997). The adoption of digital technologies is such a change. When a company introduces a set of digital technologies into its operations, it is shaping its digital operational capability (MARTÍNEZ-CARO; CEGARRA-NAVARRO; ALFONSO-RUIZ, 2020; YANG; FU; ZHANG, 2021; ARROYABE *et al.*, 2024). This set of digital technologies includes, for example, traditional management information systems, such as ERP, sensors installed on production lines for data collection and transmission, and devices for data visualization and processing. ERP software is part of a management information system that receives and stores data that is processed and transmitted within the company and between companies in the supply chain. Routine operations of the firm can become more efficient, such as strategic sourcing and supplier relationship management (HUANG; HANDFIELD, 2015). In agricultural supply chains, the diffusion of integrated management software such as ERP has played a central role in shaping digital capabilities (CARRER *et al.*, 2015; VERDOUW; ROBBEMOND; WOLFERT, 2015; GIUA; MATERIA; CAMANZI, 2021).

Digital operational capabilities also include devices to connect sensors to storage systems, such as cloud storage, and processing software to analyze and provide optimal solutions. Radio frequency technologies that have been used to transmit inventory and equipment data, with real-time visualization, can also shape operational digital capability. At a higher level of digital capability, companies have explored the possibility of using IoT and big data to increase efficiency in both their internal operations and their operations with suppliers (PAUNOV; ROLO, 2016; ZHU *et al*., 2021; ZHANG; HU; CHEN, 2024).

Data collected in real time, both internally and across the supply chain, can be used to forecast demand and identify necessary changes in production, logistics and procurement planning. Intelligent systems provide optimized solutions, reducing the effort and time managers would spend making decisions in routine operations (YANG; FU; ZHANG, 2021). Managers can focus on more relevant strategic decisions. Response time to unforeseen internal or external events, such as changes to purchase orders, can be reduced when information flows in real time through the supply chain. Decision-making becomes much more agile and less uncertain in an increasingly complex market environment (SCHOENHERR; SPEIER‐PERO, 2015).

The exchange of information within supply chain actors is essential for risk management, joint definition of strategies, collaborative behavior and prediction of crises such as the interruption of raw material supply or the lack of end-products (SCHOLTEN; SCHILDER, 2015). Digital operational capabilities can provide more efficient supply chain coordination and thus reduce transaction costs (REPKINE, 2008; CARRER *et al*., 2015; NDUBUISI *et al*., 2022). Digital capabilities allow firms to accumulate much more information than in the past. Internal and external information, combined with greater processing capacity, allows for faster and more accurate identification of market trends. Overall, digital operational capabilities might be positively associated with operational efficiency and firm’s competitiveness. The first research hypothesis can be raised:

H1: Adoption of digital technologies is positively associated with firm performance.

The complementarity of the firm's specific resources with the experience and knowledge of supply chain firms can reduce costs, increase flexibility, and raise production efficiency (KIM, 2009). Complementarity between firms can occur upstream, downstream or in both directions of the supply chain (HAN *et al*., 2013). Some form of transaction coordination must be created to increase the level of integration of the firm's operations.

Transaction governance must be mutually agreed upon to regulate both the flow of information and the flow of products and services between firms (FROHLICH and WESTBROOK, 2001). In most cases, a formal and clearly specified contract is agreed upon. This is particularly the case when firms must invest in specific assets, such as those dedicated exclusively to fulfilling specific requirements of a supply chain partner. Formal contracts, social networks and reliable agreements can reduce transaction costs and enable access to complementary resources (SHEU; YEN; CHAE, 2006; HENNINGSEN; HENNINGSEN; HENNING, 2015). Once agreements are established and integration in the supply chain increases, firms' performance improves (WANG *et al*., 2017). Studies suggest that the greater the level of integration with suppliers and buyers, the greater the firm's performance (SCHOLTEN; SCHILDER, 2015; DUBBERT, 2019; FU *et al*., 2021). Therefore, the second research hypothesis is:

H2: A higher integration of firms in the supply chain is positively associated with their performance.

Digital capability can be created to carry out R&D. Real-time information can be used to optimize resource allocation and more quickly develop solutions to operational problems (SHANG *et al*., 2017; LIU; CHEN; LIANG, 2023). IoT and sensors enable real-time data collection on different firm’s production processes (HOPKINS; HAWKING, 2018). The data collected by these devices becomes an additional resource for the company, which can be used for innovation and the creation of new value. Big Data Analytics (BDA) and Artificial Intelligence (AI) can be used for this purpose (KACHE; SEURING, 2017).

Blichfeldt and Faullant (2021) and Liu, Chein and Liang (2023) highlighted the positive association between digital technologies and innovation capacity. Digitalization in production processes creates new opportunities, such as the use of technology itself and the large amount of information in real time to develop new products, new processes and new forms of integration with supply chain agents (PIENING; SALGE, 2015). Goni and Van Looy (2022) highlighted the importance of process innovation capabilities in creating competitive advantages, mainly by increasing production efficiency. Furthermore, process innovation can also increase product quality (ALIASGHAR; ROSE; CHETTY, 2019; GONI; VAN LOOY, 2022). Sensors for automated feed distribution are in early stages of diffusion in Brazilian feedlots. These technologies allow precise, real time delivery of feed to individual animals, potentially reducing waste and improving feed conversion efficiency. The adopters of this technology could be classified as innovators, according to the classic technology adopter categories proposed by Rogers (1962).[3] The third research hypothesis can be stated as follows:

H3: Use of sensors for automation of feed distribution is positively associated with firm performance.

Digital capabilities and higher firm performance cannot be achieved without human capabilities. Digital technologies are useful for collecting, storing and analyzing data, while people are responsible for using the technology and making decisions to improve processes (GONI; VAN LOOY, 2022). The digitalization of the firm, in its different departments and processes, depends on different human capabilities (AYDINER *et al*., 2019; KORHERR; KANBACH, 2023). Factory managers and workers perform many different tasks using digital hardware and software. The efficient use of these digital resources depends on the human ability to understand them. Digital capability does not create value by itself, and human capabilities are not easily purchased on the market.

Developing new skills can be a difficult but necessary step not only to enable initial digital capabilities, but also to prepare the firm for the next steps in digital transformation. Therefore, the availability of human capabilities to operate and take advantage of digital technologies is an essential component of digitalization. Mahoney (2004) pointed out one of Penrose's contributions to the resource-based view: "Services that material resources will yield depend upon the knowledge possessed by human resources". The fourth hypothesis can be raised:

H4: Human capabilities are positively associated with firm performance.

A firm can develop a competitive advantage by understanding market signals and identifying market opportunities ahead of its competitors. Firm´s marketing capabilities comprise the ability to process market information, select suppliers, negotiate prices, choose distribution channels, and manage the market effectively (MORGAN; VORHIES; MASON, 2009). A high level of marketing capabilities provides the basis for developing lower-risk strategies, choosing the appropriate time to purchase inputs and sell products, and negotiating more effectively with supply chain partners. These factors might increase firm performance (KAMBOJ; RAHMAN, 2015; CACCIOLATTI; LEE, 2016). Therefore, the fifth hypothesis can be raised:

[3] In the classic definition by Schumpeter (1934), innovation involves inventing something new (new products, new production methods, new markets, new sources of supply, or new forms of organization). Acquiring a technology developed by other companies is not considered innovation under this lens. Nonetheless, most innovations in agriculture are developed by the inputs industry. Therefore, the categories of technology adopters proposed by Rogers (1962) can be useful for studying innovation from the perspective of farmers.

H5: Marketing capabilities are positively associated with firm performance.

The five research hypotheses are summarized in Figure 8.

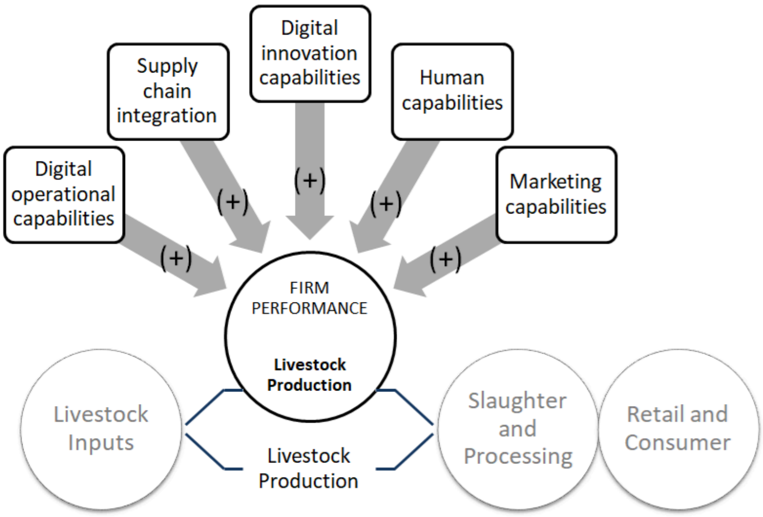

Figure 8. Framework and hypotheses. Source: Authors' own work.

4.3. Material and methods

4.3.1. Sample

The microdata set used in the article consists of an unbalanced panel comprising 359 observations of 238 cattle feedlots located in all Brazilian regions. The sampled feedlots fattened approximately 30% of the total number of beef cattle in feedlots across Brazil. The panel data comprises the period 2020 to 2023. All farmers in the sample adopted feedlot as their main production system to fatten beef cattle. The sampling strategy was designed to control for the high heterogeneity of beef cattle production systems in Brazil. The small heterogeneity in production systems adopted by cattle farmers ensures that the farms use the same types of inputs and similar production technologies to produce the same output. Therefore, some part of observed heterogeneities that might affect farms' performance over time was controlled by our sampling strategy.

The data were collected through on-site visits in the years 2020, 2021, 2022 and 2023. The localization of the municipalities is shown in Figure 9 and the annual distribution of feedlots is shown in Table 9. The data collection has been part of a research project in partnership with a private company that provides consulting services to beef cattle farmers in Brazil. This company conducts annual in-person visits to approximately 150 feedlots across all regions of Brazil between June and October. The sampling strategy combined multiple channels to identify feedlot owners/managers, including lists provided by industry associations, agribusiness input companies, technical events, and referrals from previously interviewed producers. This approach aimed to expand the sample over time and ensure regional diversity. The first phase of data collection occurred in 2020, with 118 participants. In the following years, the same producers were recontacted and invited to participate voluntarily, either in person or remotely depending on logistical feasibility, and new respondents were added to the sample. Each interview lasted an average of two hours. The interviewers were professionals in Agrarian Sciences, such as agronomists and veterinarians.

During these field visits, there are three main objectives: (i) to collect primary data applying a structured questionnaire; (ii) to introduce feedlot managers to the project sponsors (e.g., sales managers from companies that produce livestock feed), which aims to initiate or strengthen commercial partnerships; and (iii) to produce videos and photos that present a new and improved perspective of beef cattle production to Brazilian society. The structured questionnaire applied to feedlot owners or managers comprises questions related to: (a) personal characteristics of farmer; (b) structural aspects of production (use of inputs, production, and technology); (c) aspects of the decision-making process (strategies adopted in supply chain to buy inputs and sell beef cattle, perceptions about market difficulties, etc.) and (d) adoption of digital technologies.

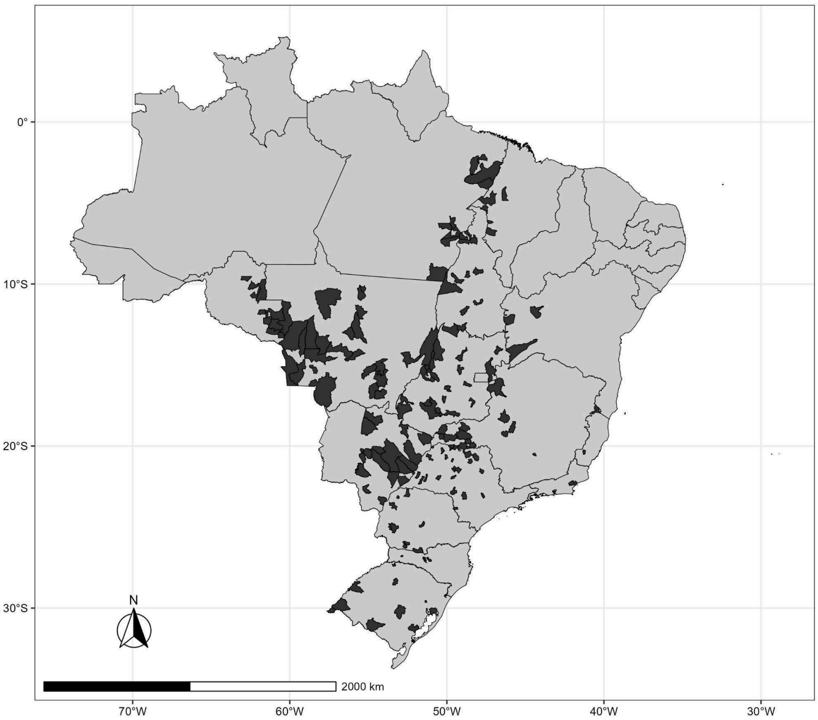

Figure 9. Geographical distribution of the municipalities that were visited for data collection. Source: Authors' own work.

Table 9. Annual sample composition and representativeness of Brazilian feedlot operations (2020–2023)

Year	Sample	States	Municipality	Sample total cattle in feedlots	Brazilian total cattle in feedlots (ABIEC)
2020	62	5	46	1,055,188	6,900,000
2021	124	15	106	1,330,783	7,200,000
2022	51	11	48	825,162	7,620,000
2023	122	14	96	1,435,215	6,700,000

Source: Authors' own work.

As shown in Table 9, the number of interviews increased over the four-year period, reflecting both the growing scope of the research and the success of the multi-channel recruitment strategy. In 2023, the dataset encompassed feedlots from 14 Brazilian states and nearly 100 municipalities, with sampled feedlots representing approximately = 25% of the total number of cattle fattened in feedlots in Brazil as reported by ABIEC (2024). This consistent and substantial coverage across years provides strong support for the external validity of the findings. The longitudinal nature of the dataset, combined with its broad regional distribution, offers a unique empirical basis for understanding performance heterogeneities in the Brazilian feedlot sector.

4.3.2. Econometric model

SPF models with inefficiency effects were applied to test the hypotheses presented in Section 2. The basic SPF can be written as:

$$y_{it} = f(x_{it}, \beta) + v_{it} - u_{it} \qquad (1)$$

where y_{it} is the output for the ith sample farm ($i = 1, ..., N$) in the tth time period ($t = 1, ..., T$); x_{it} is a vector of inputs used by the ith sample farm in the tth time period, as defined in Table 10; β is a vector of unknown parameters of the production technology to be estimated; $f(.)$ is the functional form of the production technology (e.g., Cobb Douglas or translog); v_{it}s are independent and identically distributed (idd) $N(0, \sigma_v^2)$ error terms; and u_{it}s are non-negative disturbance terms associated with the technical inefficiency of production in farms – the overall productive performance. The term u_{it} represents factors under the firm's control, while the two-sided error term (v_{it}) represents factors beyond the farm's control.

As the output is usually specified in natural logs, at least for small deviations the inefficiency term, u_{it}, can be interpreted as the percentage deviation of observed output from the frontier (maximum) output. The technical efficiency (TE) score can be defined as the relationship between the observed output and the maximum output (y_{it}^{MAX}) that could be produced by the firm *i* in *t*th period:

$$TE_{it} = \frac{y_{it}}{y_{it}^{MAX}} = \frac{e^{x_{it}\beta_i - u_{it} + v_{it}}}{e^{x_{it}\beta_i + v_{it}}} = e^{-u_{it}} \tag{2}$$

in which TE_{it} is the technical efficiency of firm *i* in period *t* calculated with estimators obtained from the SPF represented by the equation (1). TE can be interpreted as a proxy for operational management performance of farms.

The main empirical interest of the article is to estimate the relationships between z variables (proxies for digital, supply chain, innovation, human, and marketing capabilities) and the technical (in)efficiency of farms. Wang and Schmidt (2002) and Alvarez *et al*. (2006) developed an econometric approach with scaling property in inefficiency term that allows for time-varying effects. Their formulation incorporates a truncated normal distribution that scales the overall effect of individual farm capabilities, as represented by the variables z_{it}, as follows:

$$u_{it}\left(z_{it}, \delta\right) = h\left(z_{it}, \delta\right).\, u_{it}^{*} \tag{3}$$

where $h\left(z_{it}, \delta\right) \geq 0$, and $u_{it}^{*} \geq 0$ has a distribution that does not depend on z_{it}. Wang and Schmidt (2002) and Alvarez *et al*. (2006) called $h\left(z_{it}, \delta\right)$ as the scaling function and the distribution of u_{it}^{*} as the basic distribution. The essential feature of the scaling property is the fact that changes in z_{it} change the scale but not the shape of the distribution of u_{it}. This is so because the shape is determined by the basic distribution, which does not depend on z_{it}, whereas the scaling function $h\left(z_{it}, \delta\right)$ determines the scale. Thus, the farms differ in their mean efficiency, but not in the shape of the distribution of inefficiency, which is one of the advantages of this specification (ALVAREZ *et al*., 2006; PARMETER; KUMBHAKAR, 2014).

The coefficients δ presented in equation (3) indicate the associations of *z* variables with technical inefficiency of farms. In other words, they allow the empirical test of hypotheses presented in Section 2. Following the guidelines presented by Henningsen *et al*. (2024), we acknowledge the limitation of not having a robust and convincing identification strategy, which hampers the estimation of causal effects between z-variables and the technical inefficiency of feedlots. Therefore, we consider and interpret the results of the z-variable estimates as associations rather than causal effects/impacts. The 'sfaR' package (DAKPO *et al.*, 2024) was applied to estimate the scaling property in the statistical environment R (R CORE TEAM, 2024).

Some additional observations about the econometric modeling strategy should be noted. Considering that the dataset comprises a relatively large number of cross-sectional units and a limited number of periods, we pooled the panel dataset to perform the econometric estimation. Therefore, when a farm is observed in two or more time periods, it is treated as two independent observations, and as a result, the panel data structure is not fully accounted for. We do not account for farm-fixed effects that control for unobserved differences between farms (e.g., different management quality) because we want to exploit these differences for the estimation of (in)efficiency. The time-varying effects were controlled in two ways: (i) including a time trend variable in the production frontier; and (ii) including dummy variables for years to control for time-fixed effects. These two specifications were estimated, and a likelihood ratio test was applied to choose the more appropriate one. The econometric strategy that we applied to our panel dataset is not uncommon and can be observed in several relevant studies within the SPF and inefficiency determinants empirical literature (e.g., BLANK, 2020; DAKPO *et al.*, 2021; JI *et al.*, 2023).

4.3.3. Variables

Table 10 presents a description of the variables used in econometric analysis. The quantity of kilos of fattened beef cattle is the output of the production frontier model. The primary operational goal of a feedlot is to maximize the production of fattened cattle. The inputs include the total expenditure on animal feed (intermediate input), the static production capacity of feedlots (proxy for capital investment and herd), and the number of feedlot workers (labor). The variableBreedSynt was used to capture and control for different beef cattle breeds in feedlots, which might affect the quantity and quality of the output. The year variable was included to control and test for linear time trend in the econometric models (a Hicks neutral technical change).

Five variables were included in the inefficiency effects models to test the hypotheses presented in Section 2. The variable *Digital* measures the adoption of integrated management software (ERP) to assist the decision-making process within the feedlot, and to increase integration and information sharing with feed suppliers and consultants (Hypotheses 1 and 2). The management software analyzed in this article comprehends financial, operational, and animal nutrition formulation functionalities. Within the nutrition formulation function, there is a high level of information and strategies exchanged with the feed supply industry. The other functionalities can be connected with consulting companies.

Table 10. Description of variables.

Variable	Description
	Stochastic production frontier model
Output (y)	Quantity of kilos of fattened beef cattle.
Feed (x_1)	Total expenditure on animal feed (in Brazilian Real). The variable was deflated to the year 2020 using the Feedlot Cattle Production Cost Index (ICBC) calculated by the University of São Paulo.
Capital (x_2)	Feedlot statical capacity (in number of animals).
Labor (x_3)	Number of feedlot workers.
BreedSynt (d_1)	Dummy variable equal to 1 if the farmer has animals of synthetic beef cattle breeds in their feedlot; and 0 otherwise.
Year (t)	Year of observation. The year of observation was included as a time trend variable in the production frontier (model to account for technical change – Hicks neutral).
	Inefficiency drivers
Digital (z_1)	Dummy variable equal to 1 if the farmer adopted integrated management software to collect, organize, store, integrate, process, analyze and share data; and 0 otherwise. The integrated software encompasses financial, operational and animal nutrition functionalities.
SCMCap (z_2)	Dummy variable equal to 1 if the farmer used formal contracts in beef cattle sales transactions; and 0 otherwise. Proxy variable for supply chain coordination.
InnovCap (z_3)	Dummy variable equal to 1 if the farmer adopted sensors for automation of the feed distribution on the n; and 0 otherwise.
HumanCap (z_4)	Dummy variable equal to 1 if the farmer has an undergraduate education; and 0 otherwise. Proxy variable for the human capability of the decision-maker. Proxy variable for human capabilities.
MarketCap (z_5)	Dummy variable equal to 1 if the farmer stated considerably difficulties in understating relevant markets (such as beef cattle, calf and credit markets) and in coordinating transaction within supply chain; and 0 otherwise. Proxy variable for marketing capabilities.

Source: Authors' own work.

The variable *SCMCap* is an additional proxy for integration and supply chain coordination (Hypothesis 2). The diffusion of feedlot production system has facilitated the raising of animals whose meat has the tenderness and flavor valued by specific segments of the beef cattle supply chain (e.g., barbecue restaurants, supermarkets in high-income areas, and certain export markets). On the other hand, the high capital investment and feed intensification in feedlots increase the risk and complexity of the business. Strict control over animals' weight gain and the timing of their slaughter is crucial to the success of this activity. The marginal cost increases significantly faster than the marginal revenue when cattle reach their target weight (VINHOLIS *et al*., 2014). Thus, the adoption of formal contracts that establish price, quantity, quality and timing for transactions might be a solution to reduce risks, ensure sales of animals at the right time, and improve supply chain coordination. On the demand side, the contract guarantees the optimal production scale of the processing plant and compliance with specific market requirements (CARRER; SOUZA FILHO; VINHOLIS, 2014).

The variable *InnovCap* measures the adoption of sensors for automating the feed distribution process in feedlots. These systems control the delivery of feed to animals in real time with greater accuracy, seeking to optimize feed efficiency and reduce waste. This technology enhances the efficiency of feed delivery, which can improve input utilization, animal performance, and overall production planning. This technology is in an early stage of diffusion in Brazilian livestock farming. Indeed, only 20,7% of farmers in the sample adopted it. These farmers can be classified as innovators, according to the classic technology adopter categories proposed by Rogers (1962). Innovators are characterized by their willingness to take risks, their high capacity for processing information and their independence in decision-making. The variable InnovCap was used to test Hypothesis 3.

The variable *HumanCap* is a proxy for human capability. It is assumed that farmers with higher education have a better ability to understand, process and analyze information and technologies, which might be positively associated with feedlot productive performance (Hypothesis 4). The variable *MarketCap* is a proxy for marketing capabilities (Hypothesis 5). It measures the decision-marker's difficulty in understanding the market and coordinating purchase and sale transactions within the supply chain.

Table 11 presents some descriptive statistics of the variables.

Table 11. Descriptive statistics of the variables used in the econometric analysis.

Variable	Mean	S.D.	Minimum	Maximum
Output (y)	7,360,071	11,856,155	69,600	116,100,000
Feed (x_1)	16,977,715	30,220,700	61,674	254,412,800
Capital (x_2)	7,856	10,800	140	82,000
Labor (x_3)	13.61	18.62	1	180
BreedSynt (d_1)	0.1532	0.4743	0	1
Digital (z_1)	0.3398	0.4743	0	1
InnovCap (z_2)	0.2069	0.4071	0	1
SCMCap (z_3)	0.3677	0.4828	0	1
HumanCap (z_4)	0.8301	0.3761	0	1
MarketCap (z_5)	0.2897	0.4543	0	1

Source: Authors' own work.

4.4. Results and discussion

The estimated parameters of Cobb-Douglas and translog production frontiers with inefficiency effects and time trend linear effects are shown in Table 12. LR and Wald tests supported the choice of the translog functional form against Cobb-Douglas at the 1% level. Therefore, the base model for the interpretation and discussion of the results will be the translog production frontier.

Table 12. Estimates of Cobb-Douglas and translog stochastic production frontiers with inefficiency effects.

	Cobb-Douglass	Translog
Variable	Estimate	Estimate
Constant	- 0.17738***	-0.13270*
$\ln x_1$ (Feed)	0.48938***	0.41869***
$\ln x_2$ (Capital)	0.44338***	0.47260***
$\ln x_3$ (Labor)	0.08886***	0.10000***
d1 (BreedSynt)	0.09289*	0.09886*
t (year)	0.07633***	0.08001***
$\ln x_1 \times \ln x_1$		-0.13767***
$\ln x_1 \times \ln x_2$		0.15429***
$\ln x_1 \times \ln x_3$		-0.03749
$\ln x_2 \times \ln x_2$		-0.20465***
$\ln x_2 \times \ln x_3$		0.02532
$\ln x_3 \times \ln x_3$		-0.02027
Inefficiency drivers		
z_1 (*Digital*)	-1.61239***	-1.84667***
z_2 (*InnovCap*)	-1.33481**	-1.31001*
z_3 (*SCMCap*)	-1.05678*	-0.96622**
z_4 (*HumanCap*)	-0.26443	-0.01078
z_5 (*MarketCap*)	0.37351	0.38489
Variance Parameters		
σ_s^2	0.42029	0.41416
γ	0.55587	0.57743
Number of observations in panel	359	359

*** Significant at 1%, ** significant at 5%, * significant at 10%.

Source: Authors' own work.

The first-order coefficients of the translog production frontier can be interpreted as partial output elasticities at the sample mean because mean-scaled variables for output (y) and inputs (x) were used in the estimation, a common approach in empirical analyses (CARRER *et al*., 2015; HERWARTZ; SCHLEY, 2018). The first-order coefficients of feed, capital and labor presented expected signs and statistical significance at the 1% level. A 1% increase in feed expenditure results in a 0.42% increase in feedlot output, assuming other inputs are kept constant and considering inputs and output at the sample means. For the capital, a 1% increase in feedlots' statical capacity results in an increase of 0.47% in output, ceteris paribus. A 1% increase in the number of feedlot workers results in an increase of 0.1% in output, assuming other inputs are kept constant.

The elasticity of scale at the mean values was 1.03, indicating constant returns to scale at the average level of inputs. This result is notable and suggests that, considering the sample means, feedlots are operating within (or at least very close to) the optimal scale region. The translog production frontier enables the calculation of the elasticity of scale for each feedlot in the sample. Table 13 summarizes the findings. It is noted that the optimal (static) capacity is around 14,600 animals per year. This capacity yields an average output of 13,401,538 kilos, which corresponds to approximately 36,700 fattened cattle per year. It is important to highlight that many Brazilian feedlots complete more than one production cycle per year - which is a necessary condition to produce 36,700 animals with a static capacity of 14,600.

Table 13. Elasticities of scale of feedlots.

Group	Elasticity of scale	Number of observations	Average capital[a]	Average output[b]
I	≤ 0.95	22	38,363.64	40,888,906
II	0.951 to 1	85	14,674.71	13,401,538
III	1.0001 to 1.05	124	4,479.92	3,864,961
IV	≥1.0501	128	1,355.57	980,966

a statical capacity of production, in number of animals.

b in quantity of kilos effectively produced by feedlots per year.

Source: Authors' own work.

The estimate of the dummy control variable BreedSynt was statistically significant at 10%. This result corroborates the importance of controlling for beef cattle breed differences in production frontier estimations, as breed differences can significantly influence feedlots output. The industrial crosses are obtained from planned crossbreeding between different beef cattle breeds, aiming to combine the best characteristics of each (e.g., the resistance and feed efficiency of Nellore with the meat quality of Angus) (ARTHUR *et al*., 1995; LIU;

MAKARECHIAN; BERG, 1991). Empirical studies have shown that synthetic or composite breeds tend to outperform purebreds in growth performance, fertility, and calf survival, especially in extensive or semi-intensive systems (ARTHUR *et al*., 1995; GONÇALVES *et al*., 2018; UALBERTA, 2014). However, it is important to note that genotype and environment interactions play a crucial role: while crossbred or synthetic animals can express higher productivity in more intensive or resource-rich systems, they may present higher nutritional and management requirements, which can limit their performance in extensive conditions (TEIXEIRA *et al*. 2006). The estimate of BreedSynt indicates that having these breeds increases the productivity of feedlots by 9.9 percentage points, a result aligned with the literature on heterosis and breed complementarity (BOURDON, 2000). These results highlight the relevance of genetic planning to enhance productivity in beef cattle operations.

The time trend variable (year) indicates a positive technological change of 8 percentage points per year during the period analyzed. This result can be attributed to technological innovations in equipment, feed formulation, and management practices adopted by feedlots during the analyzed period. Notably, the years 2020 and 2021 were characterized by elevated profit margins in feedlots due to a considerable increase in the price of fat cattle. Farmers reinvested part of these profits into equipment, technology, and improved animals, further enhancing productivity.

Figure 10 shows the distribution of estimated technical efficiency scores of feedlots over time. On average, the sampled feedlots produced 86.7% (in 2020), 75.2% (in 2021), 76.2% (in 2022) and 83.9% (in 2023) of the maximum they could have produced with the same endowment of inputs and considering the available production technology. This result indicates that there is some potential to increase feedlots beef cattle production by improving management capabilities. Notwithstanding, the feedlots operated a little closer to the production frontier in the year 2020 – approximately 83% of them operated with TE scores higher than 80%.

Among the five Z-variables used to test the research hypotheses, three were statistically significant and presented the expected results: *Digital*, *InnovCap* and *SCMCap*. The coefficients of Z-variables are not directly interpretable. Thus, we also estimated the marginal effects of these variables on technical inefficiency of farms. Z-variables with negative coefficients (and marginal effects) are positively associated with feedlots technical efficiency (and vice-versa).

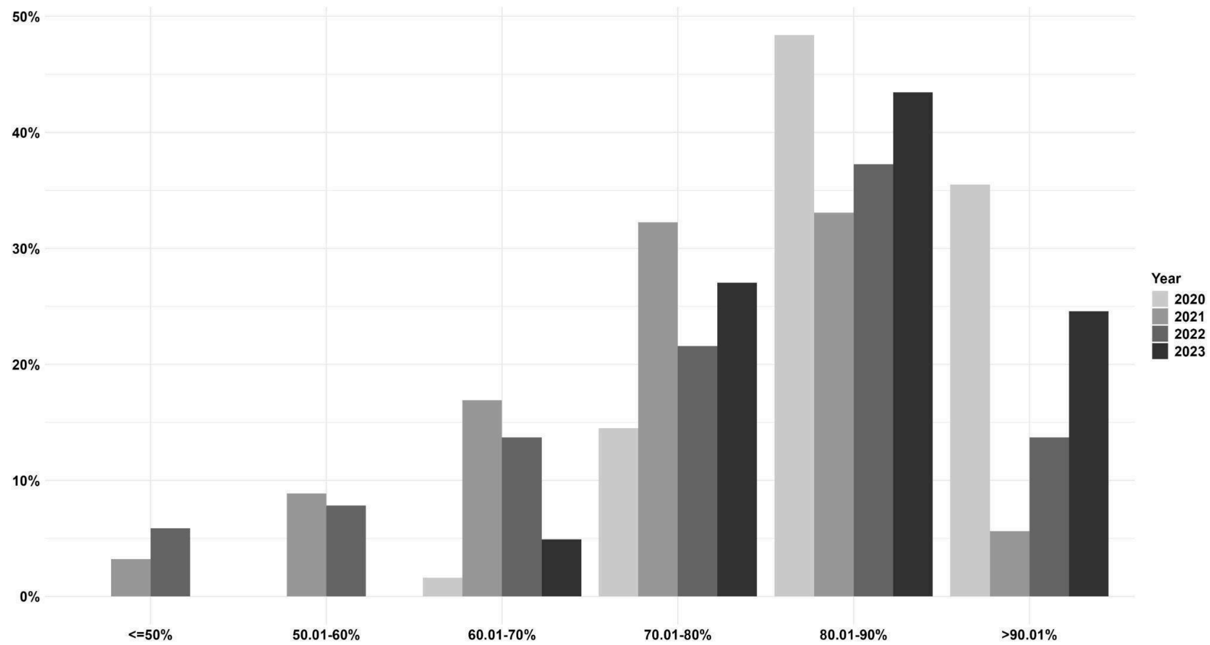

Figure 10. TE scores distribution. Source: Authors' own work.

The variable *Digital* is positively and significantly associated with feedlots' performance, corroborating Hypotheses 1 and 2. The marginal effect of this variable, calculated at the sample mean over the four years, indicates that beef cattle farmers who adopted integrated management software are approximately 15 percentage points more efficient than beef cattle farmers who did not adopt this digital technology. Feedlot management is complex and risky, which considerably increase the benefits of management information systems adoption. The acquisition of steers and their diet represent a great proportion of feedlot costs. In most cases, the steers have different origins and characteristics with different prices (MAPLES; DEVUYST; WADE BRORSEN, 2022). Beef cattle sales decisions are also complex, because the timing is crucial and marketing channels value different quality attributes in animals (CARRER; SOUZA FILHO; VINHOLIS, 2014). These conditions require efficient supplier and price risk management, effective control of the steer entry protocol within the feedlot, as well as the strict monitoring of the animals' fattening process. The formulation of an adequate diet for each stage of the fattening process can be achieved by combining appropriate products from both nutritional and economic points of view.

The adoption of integrated management software facilitates the integration and management of input suppliers, the formulation of optimal diets, real-time data collection through electronic devices and internet, the generation of technical and economic reports, and predictive data analysis for better allocation and use of production resources (feed, labor, and capital). These functionalities increase digitalization in feedlots and also supply chain coordination, which are positively associated with technical efficiency. This finding is in line with the literature that associates digitalization and farm operational performance (CARRER *et al*., 2022; DELAY *et al*., 2022; MCFADDEN; ROSBURG; NJUKI, 2022).

The adoption of formal contracts in transactions with slaughterhouses, a proxy for supply chain integration, is also positively and significantly associated with feedlot performance. The marginal effect of this variable indicates that, on average, beef cattle farmers who adopted formal contracts are approximately 11 percentage points more efficient than those who sold cattle using the spot market. Feedlot production demands substantial working capital, is sensitive to market uncertainties, and has temporal specificity for fattening cattle. The adoption of contracts to coordinate output transactions with the processing industry has been an efficient strategy to reduce transaction costs, manage price risk, and improve production planning (DUBBERT, 2019; FU *et al*., 2021). These benefits are associated with feedlot production efficiency.

The variable *InnovCap* was statistically significant at the 10% level and negatively associated with technical inefficiency of feedlots. This result provides empirical support for Hypothesis 3. Automated feed distribution technologies improve process efficiency by reducing waste and ensuring uniform feed delivery. However, these gains do not eliminate biological inefficiencies, as part of the feed energy is inherently lost through metabolic processes and animal variability. The marginal effect of *InnovCap* indicates that feedlots using this technology operate approximately 10 percentage points more efficiently than those that rely on manual or less controlled feeding systems. The use of automatic feed distribution sensors associated with radio frequency identification (RFID) allows data collection and analysis in real time to improve management and operational efficiency in livestock farming (GARCÍA *et al.*, 2020; MORRONE *et al*., 2022; TZANIDAKIS *et al*., 2023). Since feed constitutes the major input cost in beef finishing systems, apart from the purchase of animals, even small improvements in feed efficiency can have a substantial impact on overall productivity and profitability. These findings align with previous literature highlighting the role of automation and precision livestock technologies in improving operational efficiency.

Finally, the variables *HumanCap*, and *MarketCap* presented the expected signs and marginal effects. However, these variables were not statistically significant at the 10% level or below. Therefore, we cannot assume that hypotheses 4 and 5 can be corroborated based on our estimates. Table 14 shows a summary of the main empirical findings of the article.

Table 14. Summary of results.

Hypothesis	Result
H1: Adoption of digital technologies is positively associated with firm performance.	Supported
H2: A higher integration of firms in the supply chain is positively associated with their performance.	Supported
H3: Use of sensors for real-time information is positively associated with firm performance.	Supported
H4: Human capabilities are positively associated with firm performance	Not supported
H5: Marketing capabilities are positively associated with firm performance	Not supported

Source: Authors' own work.

4.5. Conclusions and implications

This study investigated how and to which extent digital, human, marketing, innovation, and supply chain coordination capabilities are associated with the performance of beef cattle feedlots in Brazil. An original panel micro dataset with 359 observations over four years was used. We applied the SPF model with a scaling property in the inefficiency term to estimate the associations of farm digital technology adoption and capabilities with performance, while controlling for time linear effects. Digital technology adoption, use of sensors for real-time information and supply chain integration are positively and significantly associated with the operational performance of feedlots. The estimates of human and marketing capabilities also presented the expected results, but without statistical significance.

The study offers novel empirical evidence by using original primary data on digital technology adoption in Brazilian feedlots. Additionally, it contributes methodologically by applying a stochastic frontier approach to assess the associations between digital capabilities and technical efficiency. The findings have important managerial and political implications. They empirically corroborate that under complex management and economic environments, digitalization through the adoption of integrated software has proven to be important in improving the allocation and use of production resources within the firm. Better management of resource use can reduce losses and waste of inputs, increase production and reduce idle capacity, which could benefit the environment and food security. Furthermore, the software can reduce informational asymmetries both within the firm and between supply chain partners. Strategies for adequate cattle' diet formulation and management of inputs, quality protocols, and traceability practices have been collaboratively defined by farmers, consultants, the input industry, and slaughterhouses. Without ERP systems, the costs of coordinating and monitoring these strategies could be significantly higher.

Additionally, the integration with slaughterhouses through formal contracts was also associated with better management and resource utilization in feedlots. These contracts may enhance supply chain coordination, reduce transaction costs, and create additional incentives (e.g., better prices) that influence farmers' decision-making and the use of inputs in the production process.

5. Conclusion

This study aimed to identify the key factors driving the digital technology adoption in beef cattle farming and to analyze the associations of these technologies with feedlots technical efficiency (operational performance). Three articles that applied different methods were developed to achieve the objectives.

The literature review revealed that the intention to adopt digital technologies varies between dairy and beef cattle producers worldwide. Dairy farmers tend to adopt more automation and data acquisition technologies focused on animal welfare, reproduction, and health. In contrast, beef cattle producers show a greater interest in data acquisition technologies and information systems. The main factors influencing adoption decisions include age, education level, gender, production scale, facility conditions, and the type of milking system. The primary barriers to adoption include high initial costs, uncertainties regarding cost-benefit, data privacy concerns, and the complexity of using these technologies.

The findings from the literature review were corroborated by an empirical analysis using primary microdata from beef cattle feedlots in Brazil. The most widely adopted technologies were information systems (software for financial, nutritional, and feedlot management) and data acquisition technologies (electronic identification and automatic weighing scales). The identification of three groups of feedlots with different levels of technological intensity allowed for the evaluation of the key factors associated with adoption decisions. These factors include the farmer's age and education level, the use of specialized consulting services, production scale, number of employees, use of price risk management tools, provision of third-party cattle feeding services, and receipt of financial incentives when selling cattle to slaughterhouses.

The third article applied SPF models with inefficiency effects to assess how and to what extent digital, human, marketing, innovation, and supply chain coordination capabilities are associated with technical/production efficiency of feedlots. The results indicated that digital technology adoption, real-time automation, and supply chain integration are positively associated with the operational performance of feedlots. In complex management and economic environments, digitalization through the adoption of integrated software has proven essential for optimizing resource allocation and utilization within farms. Therefore, the digital transformation of livestock farming should be accompanied by technical training programs and public policies that promote the adoption and diffusion of innovations. The increased use of digital technologies can enhance the competitiveness and sustainability of beef cattle farming in Brazil, fostering productivity gains while reducing environmental impact and improving animal welfare.

As highlighted in both the literature review and the empirical analysis, the adoption of automation technologies, such as sensors, remains limited among beef cattle producers compared to digital management tools. However, when integrated with these tools, automation holds strong potential to improve production efficiency and reduce operational losses. Overcoming adoption barriers is therefore essential for realizing the full benefits of precision livestock farming.

When effectively implemented, digital technologies, particularly integrated software and automation sensors, contribute to improved operational efficiency, more rational use of resources, and waste reduction. Additionally, they foster greater supply chain coordination, improve traceability, and help reduce informational asymmetries between producers and downstream actors, such as slaughterhouses.

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Appendix A

This questionnaire was developed through a collaborative effort between researchers and a private company, as part of a broader data collection instrument on beef cattle feedlot systems in Brazil. Due to confidentiality agreements and the collaborative nature of the instrument, only a subset of the questions is presented here for illustrative and methodological purposes. The full questionnaire is not publicly available.

The selected questions below exemplify the main thematic sections covered in the study, including property characteristics, management practices, decision-maker profile, technology adoption, and operational management. The responses were collected in a standardized format through interviews with feedlot operators and technical staff.

Parte 1 – Dados E Informações Sobre A Propriedade:

1a) Número de animais confinados:

Em 2020: _____________ animais.

Em 2021: _____________ animais.

( ) Não confinará em 2021.

( ) Não respondeu.

1b) Capacidade estática do confinamento:

Em 2020: _____________ animais.

Em 2021 (caso seja prevista alguma alteração): _____________ animais.

1c) Qual é o mês de início do confinamento (1º ciclo)? _____________.

Número de ciclos (giros): _____________.

Meses de confinamento (estratégico ou roda o ano inteiro): _____________.

Quantidade anual confinada: _____________.

Parte 2 – Nutrição

2a) Pratica algum tipo de integração?

( ) Sim, ILPF: Culturas: _____________

( ) Sim, ILP: Culturas: _____________

( ) Não.

( ) Estou planejando.

( ) Não respondeu.

Parte 3 – Gestão e Perfil dos Animais Confinados

Tecnologia e gestão:

3a) Eu gosto de tentar tecnologias novas na propriedade rural.

( ) Concordo totalmente

( ) Concordo

( ) Nem concordo, nem discordo

( ) Discordo

( ) Discordo totalmente

3b) Quando se trata de negócios, eu prefiro a opção mais segura, mesmo sabendo que eu possa ganhar menos.

( ) Concordo totalmente

( ) Concordo

( ) Nem concordo, nem discordo

( ) Discordo

( ) Discordo totalmente

3c) Considero minha capacidade de gestão da atividade agropecuária superior à média dos produtores rurais.

( ) Concordo totalmente

( ) Concordo

( ) Nem concordo, nem discordo

( ) Discordo

( ) Discordo totalmente

3d) Fontes de informação importantes para a tomada de decisão (resposta múltipla):

( ) Cooperativa agropecuária

( ) Associação de produtores rurais

( ) Sindicato rural

( ) Extensão rural governamental

( ) Consultor privado

( ) Universidades e centros de pesquisa

( ) Plataformas digitais de conteúdo técnico (ex. Scot, DBO, Beefpoint, etc.)

( ) Outros produtores rurais/vizinhos/parentes

( ) Fornecedores de insumos (ex. nutrição animal, saúde animal, máquinas, etc.)

( ) Compradores (ex. frigoríficos e outros)

( ) Outro: ____________________

3e) Uso de tecnologias digitais (resposta múltipla):

( ) Identificação individual dos animais com leitura eletrônica (chip/código de barras/QRCode)

( ) Dispositivos eletrônicos de pesagem dos animais (auto pesagem)

( ) Termografia infravermelha (sensores)

( ) Cocho com distribuição da ração automatizada

( ) Bebedouro ou cocho com aferição de consumo automatizada

( ) Estações meteorológicas automatizadas

( ) Software para gestão financeira

( ) Software para gestão operacional

( ) Software para formulação da dieta

( ) Outro sensor/tecnologia digital: __________________________

3f) Quantos colaboradores exclusivos para a atividade de confinamento?

______ colaboradores.

( ) Não respondeu

3g) Idade do tomador de decisões: ____________.

3h) Gênero do tomador de decisões: ____________.

3i)Grau de escolaridade do tomador de decisões: ____________.

3j) Utilizou algum tipo de ferramenta de proteção contra oscilações de preço do boi gordo em 2021?

( ) Não

( ) Sim, contratos futuros B3.

( ) Sim, mercado de opções B3.

( ) Sim, contrato a termo.

( ) Sim, outro. Qual? _________________

( ) Não respondeu

3k) Trabalha com animais de terceiros (boitel)?

( ) Sim.

( ) Não.

( ) Não respondeu.

3l) Possui algum contrato de parceria ou conta com algum tipo de incentivo (crédito ou bonificações) por parte do frigorífico parceiro?

( ) Não.

( ) Sim. Quantidade de animais vendidos nesta modalidade: _______% dos animais.

Se possível, descreva a parceria superficialmente: ______________________

( ) Não respondeu.

Appendix B

```
#### PACOTES E FUNÇÕES ####
library(tidyverse)
library(FactoMineR)
library(factoextra)

Base_Grupo=BASE_GRUPO

BASE_ACM_Char=BASE_GRUPO
# Grupo    n
# Grupo 1  39
# Grupo 2  69
# Grupo 3  34

#ACM 1 - Grouping Tech
rex.mca_char_ING = MCA(Base_Grupo,graph=FALSE)
Acm_1_Grupo=fviz_mca_var(rex.mca_char_ING,
            geom=c(""),
            repel = TRUE,
            col.var = "#08306B",
            shape.var = 1,
            xlim = c(- 1.25, 2.25),
            ylim = c(- 1.25, 2),
            font.var=4)
Acm_1_Grupo+
 geom_point(aes(size=1,stroke=1),shape=19,colour = "#006400")+#
    geom_text_repel(colour="#000000",hjust = 0, nudge_x = 0.05, size = 5,label=Acm_1_Grupo$data$name, fontface = "bold")+
 labs(title = "",y="Dimension 2",x="Dimension 1")+
 theme_bw()+
 theme(plot.title = element_text(hjust = 0.5),
   axis.title.y=element_text(colour = "black", face = "bold",size=15),
   axis.text.y=element_text(colour = "black", face = "bold",size=15),
   axis.title.x=element_text(colour = "black", face = "bold",size=15),
   axis.text.x=element_text(colour = "black", face = "bold",size=15),
   title=element_text(colour = "black", face = "bold"),
   legend.position="none")+
 scale_x_continuous(breaks=c(seq(-4,4,0.5)))+
 scale_y_continuous(breaks=c(seq(-4,4,0.5)))

#ACM 2 - Characterization
rex.mca_char = MCA(BASE_ACM_Char,graph=FALSE)
ACM_Char=fviz_mca_var(rex.mca_char,
            geom=(""),
            repel = TRUE,
            col.var = "#08306B",
            shape.var = 1,
            xlim = c(- 1, 1.25),
            ylim = c(-1.25, 0.75),
            font.var=4)
```

```
ACM_Char+
 geom_point(aes(size=1,stroke=1),shape=19,colour = "#006400")+#
     geom_text_repel(colour="#000000",hjust = 0, nudge_x = 0.035, size = 5,label=ACM_Char$data$name, fontface = "bold")+
 labs(title = "",y="Dimension 2",x="Dimension 1)")+
 theme_bw()+
 theme(plot.title = element_text(hjust = 0.5),
    axis.title.y=element_text(colour = "black", face = "bold",size=15),
    axis.text.y=element_text(colour = "black", face = "bold",size=15),
    axis.title.x=element_text(colour = "black", face = "bold",size=15),
    axis.text.x=element_text(colour = "black", face = "bold",size=15),
    title=element_text(colour = "black", face = "bold"),
    legend.position="none")+
 scale_x_continuous(breaks=c(seq(-4,4,0.5)))+
 scale_y_continuous(breaks=c(seq(-4,4,0.5)))
```