



## Characterization of the adoption of digital technologies in beef cattle feedlots in Brazil

Leticia Caroline da Silva David<sup>1\*</sup>  Marcela de Mello Brandão Vinholis<sup>2</sup>   
Marcelo José Carrer<sup>1</sup>  Hildo Meirelles de Souza Filho<sup>1</sup>   
Gabriela dos Santos Eusébio<sup>2</sup>  Waldomiro Barioni Junior<sup>2</sup> 

<sup>1</sup>Programa de Pós-graduação em Engenharia de Produção, Departamento de Engenharia de Produção, Universidade Federal de São Carlos (UFSCar), 13565-905, São Carlos, SP, Brasil. E-mail: leticiadavid@estudante.ufscar.br. \*Corresponding author.

<sup>2</sup>Embrapa Pecuária Sudeste, São Carlos, SP, Brasil.

**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: electronic animal identification; management software; automatic meteorological station; automatic food dispensing in troughs; automatic weighing scales; infrared thermography; and 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, larger feedlot operations, with more head of cattle, increased workforce size, use of price risk management tools, provision of calf-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.

**Key words:** precision livestock farming, digital technologies, beef cattle, diffusion of innovations.

## Caracterização da adoção de tecnologias digitais em confinamentos de bovinos de corte no Brasil

**RESUMO:** O estudo identifica as principais tecnologias digitais difundidas em confinamentos de bovinos de corte no Brasil e os fatores que diferenciam grupos de produtores com níveis diferentes de intensidade tecnológica. Dados primários de 184 confinamentos, coletados por meio de questionário estruturado em 2021, foram analisados por meio de estatísticas descritivas, testes de hipóteses e Análise de Correspondência Múltipla. Identificou-se a adoção das tecnologias digitais: identificação eletrônica dos animais; softwares para gestão; estação meteorológica automática; distribuição automática da ração no cocho; dispositivo eletrônico de auto-pesagem; termografia infravermelha; e cocho com aferição automática de consumo. A adoção destas inovações está associada às seguintes características: produtores mais jovens e com maior nível de escolaridade; contratação de consultoria especializada; maior quantidade de bovinos confinados; maior número de funcionários; utilização de mecanismos de gestão de risco de preço; oferta de serviços de boitel, e; recebimento de bonificação na venda para frigoríficos. Os resultados contribuem para programas de difusão de tecnologias de pecuária de precisão no Brasil, com impactos positivos sobre a produtividade dos fatores de produção, sustentabilidade ambiental e bem estar animal.

**Palavras-chave:** pecuária de precisão, tecnologias digitais, bovinos de corte, difusão de inovações.

## 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 et al., 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 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; GARCIA 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 et al., 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 et al., 2017; CARRER et al., 2022; DREWRY et al., 2019; GARGIULO et al., 2018; GIUA et al., 2021; GROHER

et al., 2020; JELINSKI et al., 2020; MENDES et al., 2023; MOZAMBANI et al., 2023; ROJO-GIMENO et al., 2019; SOOD et al., 2022; TEY & BRINDAL, 2022; VINHOLIS et al., 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 et al., 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.

## MATERIALS AND METHODS

### *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.

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, including in fields 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 1 and Figure 1).

### 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 2 presents the description of the

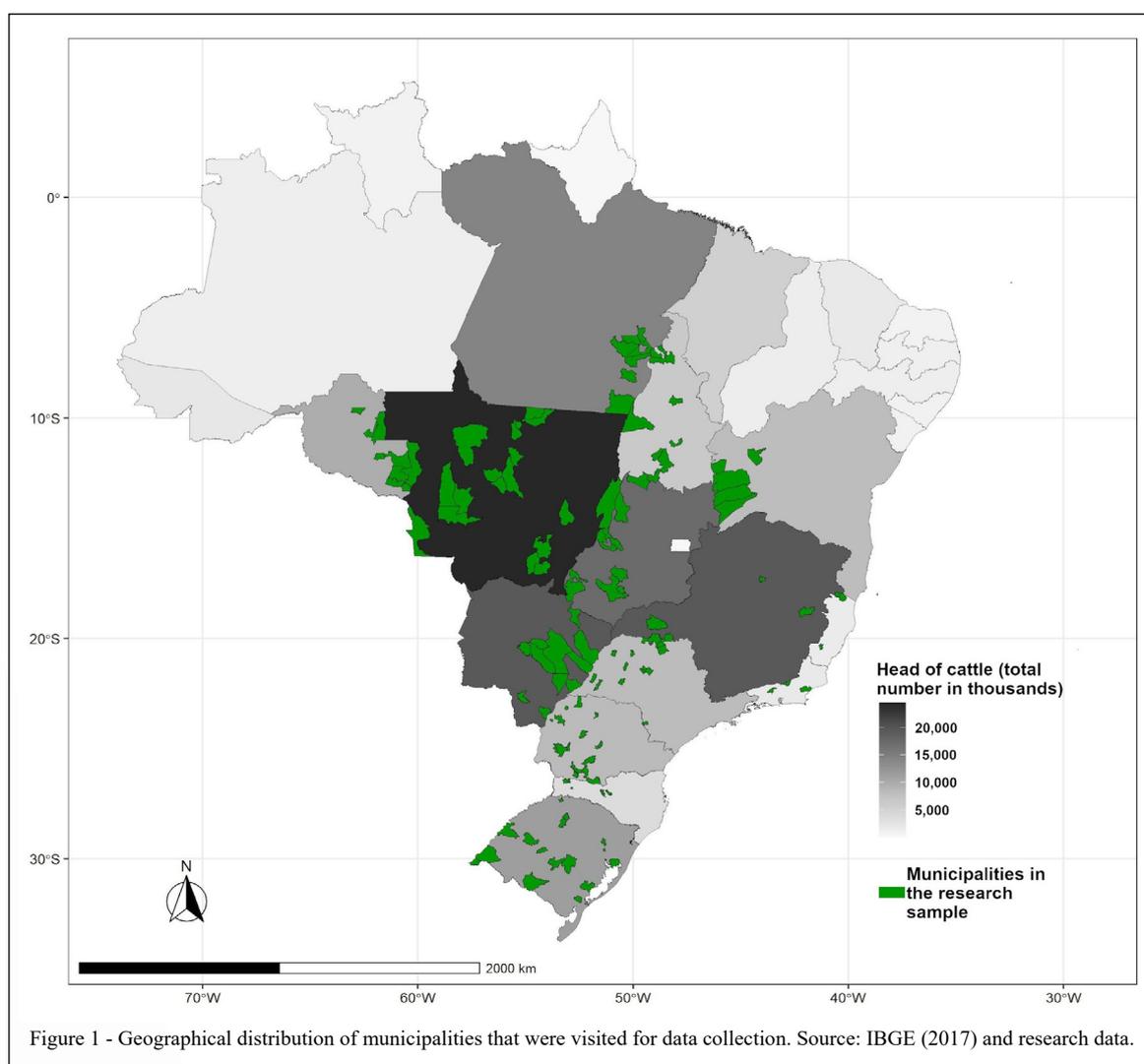


Table 1 - Farms and confined livestock sampled in 2021, by state.

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: Research data.

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, 2022). The specifications used for analysis are described in the supplementary material.

## RESULTS AND DISCUSSION

### *Diffusion of digital technologies and technological groups*

Table 3 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.

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 3) because they are at their early stage of diffusion.

Figure 2 shows the bidimensional map generated through the MCA, based on variables related to the adoption of each digital technology presented in table 3. 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".

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);

Table 2- 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**
-----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	Calf-fattening services	1, if the farmer provides calf-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.

\*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).

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.

*Farmers' and production characteristics that differentiate the technological groups*

Table 4 presents the descriptive statistics of the characteristics of decision-makers.

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 et al., 2017; CARRER et al., 2022; DREWRY et al., 2019; GIUA et al., 2021; ISGIN et al., 2008; MENDES et al., 2023; MTHETHWA et al., 2022; ROJO-GIMENO et al., 2019; and VINHOLIS et al., 2017). Individuals with a higher educational level may have an easier time processing and interpreting sensor information

Table 3 - Frequency of adoption of 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

and selecting vital data for decision-making (ROJOGIMENO 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 et al., 2021).

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 et al. (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 et al., 2017). Farmers make decisions based on the information

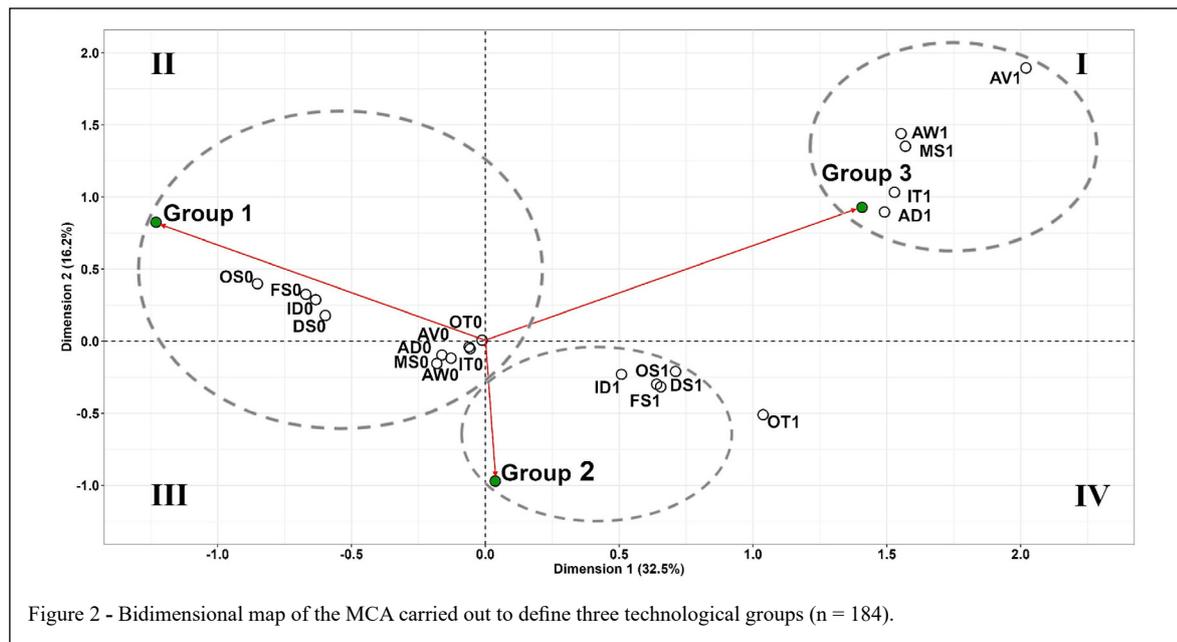


Table 4 - Frequencies and hypothesis tests of the variables related to the characteristics of decision-makers.

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	
-----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	

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

they receive, which influences the timing of adopting innovations (early or late) (SOOD et al., 2022). Information reduces uncertainty about the performance 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 5 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 et al., 2020; JELINSKI et al., 2020; ROJO-GIMENO et al., 2019; VINHOLIS et al., 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.

Table 5 - Frequency 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-----						
Calf-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	

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

Calf-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.

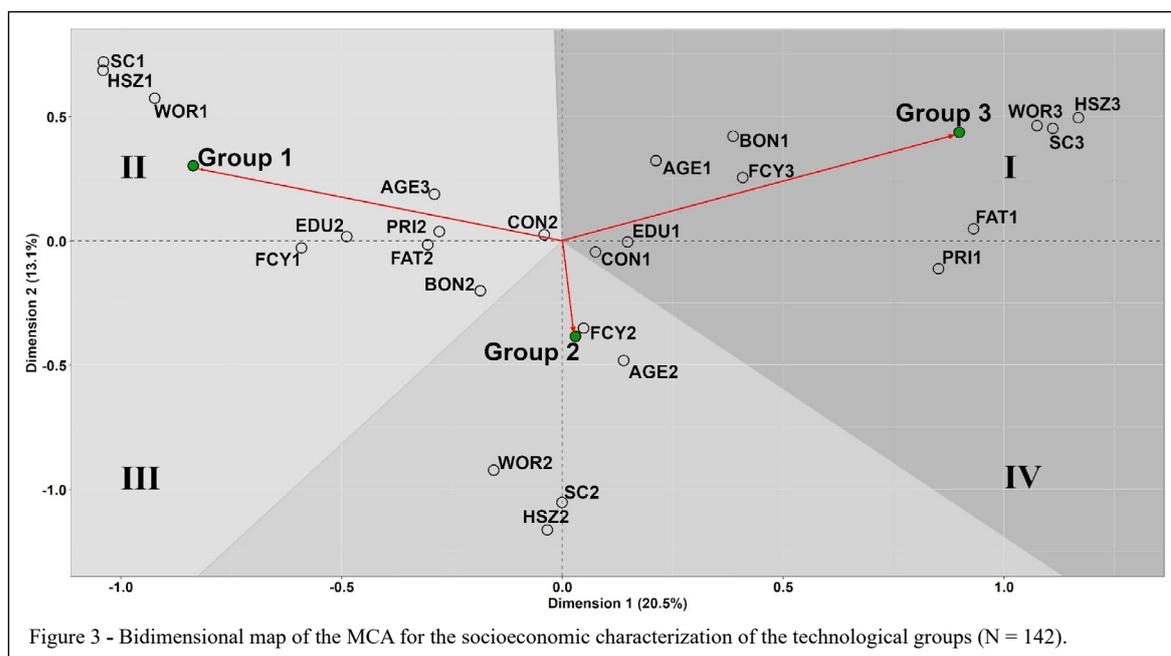
The use of tools for price risk management, such as forward and future contracts (PRI), is related to a higher intensity of adoption of digital technologies (P-value < .001). Digital technologies enhance input management to meet production goals and fulfill commitments, particularly with forward contracts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

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 3 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 calf-fattening services (FAT2), do not use tools for price risk management (PRI2), do not hire management consulting (CON2), and do not receive bonuses (BON2).

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 calf-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).

## CONCLUSION

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 calf-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.

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## DECLARATION OF CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

## AUTHORS' CONTRIBUTION

The authors contributed equally to the manuscript.

## BIOETHICS AND BIOSECURITY COMMITTEE APPROVAL

The authors declare that this study did not involve the use of animals or genetically modified organisms. Therefore, approval from a bioethics or biosafety committee was not required.

## DATA AVAILABILITY STATEMENT

The data used in this study are available in a permanent repository. Available at: <<https://doi.org/10.5281/zenodo.15392330>>.

## DECLARATION OF USE OF ARTIFICIAL INTELLIGENCE

The authors declare that no artificial intelligence tools were used in the preparation of the manuscript, data analysis, or image processing. The writing, hypotheses, results, and conclusions were entirely developed by the authors, and the final language review was conducted by human reviewers.

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