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Behavioral profile of farmers in the adoption of agriculture 4.0 technologies in the agri-food system: a case study in Brazil

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Global concerns about food security have driven significant progress in the agri-food system, which is undergoing transformative changes through the adoption of emerging technologies. This shift, known as the fourth agricultural revolution or agriculture 4.0, requires the transition from traditional to modern systems to address future environmental and production challenges. However, to fully benefit from agriculture 4.0, it is essential to understand and overcome the barriers to its adoption. In Brazil, this transition is still emerging and marked by uncertainties, with limited understanding of the obstacles involved. Given this scenario, the objective of this research is to analyze the behavioral profile of Brazilian farmers in the adoption of agriculture 4.0 technologies in the agrifood system. A sample composed of 198 Brazilian farmers from the state of Rio Grande do Sul was analyzed regarding their perception of the barriers that hinder the adoption of any or no agriculture 4.0 technology. The perception of importance was measured using the Likert scale. This data set was divided into two groups of farmers: TAF—Technology Adopter Farmer, and NTAF—Non-Technology Adopter Farmer. Kendall Correlation and Analysis of Variance were also performed on the collected data. The study proposes strategies to address the most relevant barriers identified. Although focused on Brazil, the findings reflect common challenges in other regions and offer insights for stakeholders seeking to expand agriculture 4.0 adoption. The results support the development of tailored strategies to promote inclusive access to technology, particularly for marginalized or less-resourced farmers, and guide more assertive decision-making in regions where such technologies are still underutilized.

KEYWORDS
digital agriculture, agriculture 4.0, emerging technology, farmers, digital technologies, agri-food system

1 Introduction

Recent global challenges, including the COVID-19 pandemic (Hossain et al., 2024), the Russia-Ukraine war (Pörtner et al., 2022; Abay et al., 2023), climate change (Bouteska et al., 2024; Rashidi et al., 2024), food loss (Rodrigues et al., 2024), and low agricultural efficiency (Wei et al., 2024), have disrupted agri-food systems, making it increasingly urgent to ensure access to sufficient and healthy food despite these obstacles (Lee et al., 2024; Rashidi et al., 2024). In response, various strategies have been developed to address these issues (Liguori et al., 2022; Brenya et al., 2024; Myshko et al., 2024), with agriculture 4.0 technologies emerging as a key solution to boost productivity while minimizing resource use, pollution, and greenhouse gas emissions, as well as mitigating negative impacts on soil and air quality (Maffezzoli et al., 2022; Abbate et al., 2023; Da Silva et al., 2023).

The rise of agriculture 4.0 has introduced transformative opportunities, such as significant increases in production efficiency and waste reduction, improved environmental sustainability through optimized use of natural resources, and enhanced resilience of the agri-food system against climatic and economic challenges (Misra and Ghosh, 2024). This shift is reshaping traditional agricultural practices into a more technologically integrated framework (Da Silveira et al., 2021). Encompassing a wide range of emerging technologies, the term "agriculture 4.0[1]" involves innovations such as deep learning (Yang et al., 2024), machine learning (Liu et al., 2024), robotics (Sánchez-Molina et al., 2024), drones (Rejeb et al., 2022), augmented reality (Sara et al., 2024), digital twins (Slob et al., 2023; Føre et al., 2024), and artificial intelligence (Preite and Vignali, 2024), all of which hold significant potential to enhance the sustainability and resilience of the agri-food system (Santos et al., 2024).

Among the critical determinants of adopting emerging technologies in the agri-food system are the behavioral aspects of farmers, which are shaped by a complex interaction of individual, social, and contextual factors (Da Silveira et al., 2021; Langer and Kühl, 2024). Factors such as personal motivation, risk perception, openness to innovation, prior experience, and technical knowledge interact with sociodemographic characteristics including age, education level, farm size, access to resources, and social support networks (Regan, 2019; Zscheischler et al., 2022). This dynamic interplay influences how farmers perceive and decide on adopting Agriculture 4.0 technologies. Notably, studies reveal that the agricultural sector often exhibits skepticism toward new technologies, making it an area of tension (Pfeiffer et al., 2021). Therefore, understanding these behavioral and sociodemographic determinants is essential to identify both facilitators and barriers to technology adoption, thereby enabling the design of more effective and inclusive strategies tailored to local specificities, especially in diverse contexts like Brazil (Da Silveira et al., 2023a).

Despite the growing interest in agriculture 4.0 technologies, a significant gap remains in studies thoroughly investigating how these technologies are adopted within the agri-food sector (Da Silveira et al., 2021; McGrath et al., 2023). In particular, research is lacking that simultaneously considers the profiles of both adopters and non-adopters, an essential approach for understanding the full innovation cycle within the agri-food system (Giua et al., 2022). Recognizing diverse farmer profiles is key to designing tailored strategies that address their unique barriers and needs effectively. Such joint analysis reveals not only the factors encouraging technology use but also the initial barriers faced by those yet to adopt, providing a more comprehensive and realistic understanding of the agriculture 4.0 adoption process (Sutherland et al., 2022; Geng et al., 2024).

To date, the understanding of the effects of agriculture 4.0 technologies on the agri-food system remains inconclusive because existing research often focuses on isolated aspects, emphasizing either technological advancements (Gallardo et al., 2019; Thompson et al., 2019) or social implications (Giua et al., 2022; McGrath et al., 2023). This fragmented perspective overlooks the complex and dynamic interactions among multiple clusters, including political, economic, and environmental barriers, which critically shape the adoption, diffusion, and impact of these technologies (Da Silveira et al., 2023b; Papadopoulos et al., 2024). Additionally, the contextual variability across regions and stakeholder groups further complicates the generalization of findings. Without a comprehensive and integrated approach that considers these interdependent elements, the full potential of agriculture 4.0 technologies is unlikely to be realized in the short term (Klerkx and Begemann, 2020; Ndege et al., 2024).

Moreover, to fully harness the potential of Agriculture 4.0 technologies on a larger scale, it is necessary first to identify, understand, and address the problems, challenges, or barriers hindering their widespread introduction and implementation across different regions within the agri-food system (Benyam et al., 2021; Da Silveira et al., 2021; Hidalgo et al., 2023). Without this understanding and targeted action, successful adoption cannot be achieved, limiting the positive impact of these technologies (Panetto et al., 2020; Da Silveira et al., 2023b). In developing countries, adoption rates are significantly lower than in developed nations (Phillips et al., 2019; Rijswijk et al., 2019; Ceballos et al., 2020; Daum and Birner, 2020; Kernecker et al., 2020; Santoso et al., 2024), leaving many farmers behind in benefiting from Agriculture 4.0 (Addison et al., 2024). This gap largely stems from insufficient knowledge about the barriers compromising the adoption pathway (Porciello et al., 2022; Puntel et al., 2023) and a lack of effective strategies to overcome them (Da Silveira et al., 2023b). Therefore, exploring how developing countries interpret and engage with the advancement of Agriculture 4.0 within their agri-food systems is critical for fostering more inclusive and meaningful technology adoption (Lajoie-O'Malley et al., 2020; Da Silva et al., 2023; Engås et al., 2023).

In Brazil, the development of agriculture 4.0 within the agri-food system is ongoing but marked by numerous uncertainties (Da Silveira et al., 2023a). Limited information exists on the level of technology diffusion (Carrer et al., 2022), and barriers to widespread adoption remain unclear due to wide variation across regions, stakeholders, and types of technologies, which are often context-specific and insufficiently studied (Da Silveira et al., 2023a). Furthermore, there are significant gaps regarding the potential side effects of implementing these technologies (Da Silveira et al., 2023b). Uncovering the systemic impact—that is, the broad and interconnected effects agriculture 4.0 technologies exert across various components of the agri-food system, including social, economic, environmental, and political clusters—is crucial for developing effective solutions that promote adoption. Understanding how these technologies influence not only agricultural properties but also farmers themselves can contribute to the development of strategies addressing specific challenges and maximizing the benefits of Agriculture 4.0 adoption. However, identifying the best direction for agriculture 4.0 in the Brazilian context remains difficult (Bolfe et al., 2020). The cultural, economic, and political heterogeneity across Brazilian agricultural regions

1 This study follows the broad definition of agriculture 4.0 proposed by Da Silveira et al. (2021): "*agriculture 4.0 is the implementation of emerging technologies and innovative services on the agriculture, that requires a cultural and behavioral change in all actors involved in the agricultural production chain, to increase their productivity and efficiency, and support a more sustainable agriculture, using precise and momentary of information that will help make strategic decisions*."

presents a major challenge to widespread acceptance of agriculture 4.0 among farmers (Nunes et al., 2021; Da Silveira et al., 2023b).

In this context, this study analyzes the behavioral profile of Brazilian farmers regarding the adoption of agriculture 4.0 technologies within the agri-food system, based on empirical data collected in Rio Grande do Sul (RS)—one of Brazil's leading agricultural regions. Addressing this issue is essential because facilitating the adoption of emerging technologies requires understanding the specific barriers and contexts influencing farmers' decisions, which directly affect the successful integration of agriculture 4.0 into existing farming practices. Furthermore, the findings contribute to enhancing systemic understanding—that is, a holistic and interconnected perspective of how agriculture 4.0 technologies impact not only individual farms but also broader social, economic, environmental, and political clusters within developing countries (Balkrishna et al., 2023; Da Silveira et al., 2023a; Li et al., 2023). Although farmers' challenges, expectations, and perceptions may vary across countries and regions, much of the information presented here is sufficiently general to capture common barriers and behavioral patterns that transcend local contexts, thus offering insights applicable to similar developing regions globally. Therefore, this study aims to fill this gap by analyzing the perceptions of Brazilian farmers—both adopters and non-adopters of agriculture 4.0 technologies—within the agri-food system, grounded in a case study from RS (Bolfe et al., 2020; Da Silveira et al., 2023a).

This division in farmers' adoption profiles is crucial because the reality faced by one farmer is not always the same as another's. Recognizing these distinct profiles enables the development of tailored and more personalized strategies that address the specific needs, challenges, and contexts of different groups of farmers (Da Silveira and Amaral, 2023). This holistic approach provides a more valuable and comprehensive understanding of the differences in perceptions regarding the barriers hindering the adoption of emerging technologies among farmers already transitioning to Agriculture 4.0 and those yet to adopt it. Thus, the results of this research can not only assist in formulating effective, customized interventions for Brazil but also serve as a reference for other countries with similar contexts, helping to overcome barriers and promote the inclusion of Agriculture 4.0 technologies in marginalized and less privileged rural populations (Ndege et al., 2024).

The article is organized as follows. Section 2 explains the methodology adopted in the development of this research. Section 3 presents the results of the study. Section 4 discusses the findings in greater depth, highlighting the main insights from the research and comparing them with the relevant literature in the field. Finally, Section 5 contains the conclusions, limitations, and proposals for future research.

2 Methodology

2.1 Research context

Brazil is a major player in agricultural commodities, playing a pivotal role in current and future global food security (Berchin et al., 2019; Massruhá et al., 2020). In recent years, Brazil has stood out as the world's largest producer of sugarcane, coffee, and orange juice and the second-largest producer of soybeans, beef, and chicken (Picoli et al., 2018). By 2024, Brazilian agribusiness is expected to account for approximately 21.5% of the country's economy (CEPEA, Centro de Estudos Avançados em Economia Aplicada, 2024). Among the vital Brazilian states that significantly contribute to this is Rio Grande do Sul (RS), where this study was conducted (ABN, Agropecuária Brasileira em Números, 2024).

The RS state is located in southern Brazil, bordering Uruguay and Argentina, and plays a central role in the Southern Common Market due to its geographic location and its importance in regional trade and national agricultural production (Junqueira, 2023). RS is Brazil's largest rice producer, responsible for 68.15% of national production. Additionally, this region excels in wheat cultivation, accounting for 52.6% of the country's output. Soybeans and corn complement the list of major crops grown in RS regarding planted areas and production volume (RS, Rio Grande do Sul, 2023a). Regarding permanent crops, the key highlights are grapes, mate tea, oranges, and apples. For these products, the RS region also ranks among Brazil's top producers (Leusin Júnior and Feix, 2023).

In 2023, agribusiness exports from RS totaled $12 billion. The five main exporting sectors of agribusiness were: soybean complex ($4.4 billion), meats ($2 billion), tobacco and its derivatives ($1.8 billion), cereals, flours, and preparations ($1.2 billion), and forest products ($1 billion). Regarding the leading destinations for RS agribusiness exports, the following markets stand out: China (28.2%), European Union (15.4%), United States (5.2%), Vietnam (4.6%), Indonesia (3.2%), United Arab Emirates (2.5%), South Korea (2.5%), and Mexico (2.4%) (RS, Rio Grande do Sul, 2023b).

By the end of 2023, RS had 369.415 registered jobs in agribusiness, with the temporary crops sector standing out in job generation during this period (RS, Rio Grande do Sul, 2024). RS has about 365.000 agricultural establishments, covering an area of 21.7 million hectares (IBGE, Instituto Brasileiro de Geografia e Estatística, 2017a). Among these agricultural establishments, over 60% have less than 20 hectares. Establishments with more than 1.000 hectares represent 1% of the total agricultural establishments and occupy one-third of the total area (Leusin Júnior and Feix, 2023). This region has the highest average in the agricultural establishment index compared to other Brazilian states regarding access to technical guidance, a higher number of agricultural machines in use, and access to electricity (Souza et al., 2019; Santana and Santos, 2020). Moreover, most of these establishments are classified as family agricultural establishments, with the highest participation of farmers associated with agricultural cooperatives in the country. Smallholder farmers in RS are diversified and multifunctional, producing various crops. In contrast, medium and large farmers tend to be monocultural (Johnston et al., 2020).

White farmers predominantly run the agricultural establishments in RS in 92.23% of cases. Male farmers account for 88% of the establishments, primarily in the age range of 55–64 years. Most farmers in RS still have low levels of education, with about 34.91% having only completed elementary school (IBGE, Instituto Brasileiro de Geografia e Estatística, 2017b). However, most farmers in RS demonstrate acceptance of emerging technological innovations that permeate the agri-food system (Feix et al., 2022; Da Silveira et al., 2023a). Additionally, RS serves as a laboratory for Brazil, as it is a demander, proponent, and beneficiary of agricultural policies, with extensive organizational, technological, and production experience in small, medium, and large rural properties. Furthermore, establishments in RS show results for Gross Value of Production

(GVP) per harvested area that exceed the Brazilian average (Johnston et al., 2020).

The RS state is divided into seven mesoregions: Northeast Rio-Grandense, Northwest Rio-Grandense, Western Central Rio-Grandense, Eastern Central Rio-Grandense, Metropolitan Porto Alegre, Southwest Rio-Grandense, and Southeast Rio-Grandense. The mesoregions of RS exhibit distinct characteristics regarding income dominance, agricultural productivity, and other aspects that generate regional inequalities, demonstrating the importance of studying each mesoregion individually to understand their peculiarities and reduce potential inequalities regarding the introduction of agriculture 4.0 technologies in the agri-food system (Lisbinski et al., 2020; Da Silveira et al., 2023a). Figure 1 shows the mesoregions of RS where the research was conducted.

2.2 Study design

This study used an online survey to collect data on farmers' perceptions in the state of RS regarding the barriers that hinder the adoption of agriculture 4.0 technologies in the agri-food system. According to Jaeger and Cardello (2022), the advantages of online surveys include the ability to reach a broader population, substantial sample sizes, flexibility in survey design, speed and timeliness in administration, ease of data acquisition/input/analysis, simplicity of completion for respondents, and low administrative costs. Furthermore, these types of surveys encourage more honest responses to sensitive questions than in-person surveys due to the greater anonymity perceived by respondents (Nikolaus et al., 2020).

The data collection instrument for this research (online questionnaire) was developed and administered using Google Forms (Jaiswal, 2024). The format and content of the questionnaire were reviewed and tested internally with all research team members. Then, two representatives from the target audience adapted an online questionnaire for various devices that the respondents might use (e.g., smartphones, tablets, desktops, etc.). When used on smartphones, the appearance and functionality of the questionnaire were mainly considered to avoid formatting issues, such as the inability to view the entire page. While smartphones can increase participation rates among farmers in the survey, it often takes longer to complete without proper modifications to the questionnaire. It may reduce completion rates while increasing dropouts among respondents (Revilla et al., 2016). The final structure of the online questionnaire was modified based on feedback from the two farmers who participated in this testing phase. The pilot results were included in the final research sample. The researchers of this study also paid attention to the factors contributing to low data quality in online surveys, as highlighted by Jaeger and Cardello (2022).

The survey was constructed using simple language to convey information objectively and inclusively to farmers. Several important points were considered during the development phase of the online questionnaire by the researchers, such as: (a) taking into account farmers' existing knowledge about the research topic; (b) avoiding difficult words and technical terms; (c) avoiding acronyms; (d) using short paragraphs; and (e) presenting the text in Brazilian Portuguese. The structure of the online questionnaire was divided into four sections, containing both open-ended and closed questions. This separation of questions into different blocks is essential as it helps prevent farmers from returning to previous questions and changing their responses based on information presented later.

Section 1 of the online questionnaire briefly explained the topic and the purpose of the research. Additionally, it included information

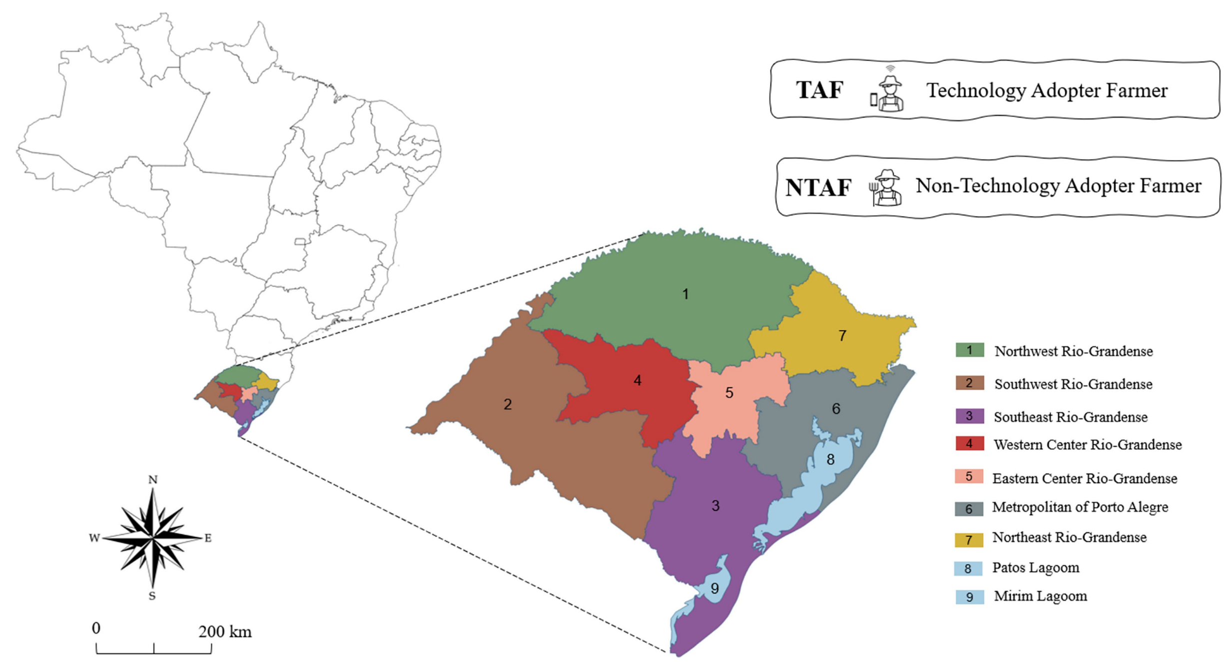

FIGURE 1
Mesoregions of Rio Grande do Sul (RS)—Brazil.

about the names of the researchers, the organizations they represent, their email addresses for inquiries, the use of responses in practice, and assurance of respondent anonymity. At the end of this section, a video[2] containing information related to agriculture 4.0 was added to create a more engaging and interactive experience for farmers participating in the survey. This video also aimed to clarify that the survey applied to farmers in RS integrates actions from the Center for Science for Development in Digital Agriculture (Semear Digital), led by the Brazilian Agricultural Research Corporation (EMBRAPA). The Semear Digital project aims to advance knowledge and generate solutions that meet the needs of small and medium Brazilian rural producers, thereby helping to reduce market imperfections and inequalities in adopting emerging technologies that can promote productivity gains, cost reduction, and increased efficiency in agricultural production.[3]

Section 2 of the online questionnaire includes open and closed questions about demographic aspects that help characterize the research sample regarding gender, age, educational level, location of the farm, size of the cultivated area, the primary type of agricultural crop developed by the farmer, and how long they have worked with that crop. After presenting these questions, the section concludes with a question regarding farmers' understanding of "agriculture 4.0". This question follows a brief self-explanatory note on agriculture 4.0 (Da Silveira et al., 2021). All questions in Section 2 were mandatory for farmers to answer before proceeding to the questions in Section 3.

Section 3 of the online questionnaire presents a set of 25 closed questions[4] aimed at understanding farmers' perceptions of the barriers that hinder the adoption of agriculture 4.0 technologies in the agri-food system of RS. This section was structured into five clusters, each with five questions: technological, economic, political, social, and environmental. The barriers hindering the adoption of agriculture 4.0 technologies in the agri-food system, identified in the literature by Da Silveira et al. (2021) and validated by Da Silveira et al. (2023a), were updated and used as a basis for developing this phase of the online questionnaire—see Table 1. Additionally, a brief explanatory phrase was added next to each selected barrier to facilitate farmers' understanding of what was being asked. To assess farmers' perceptions regarding the importance of these barriers, a five-point Likert scale (Likert, 1932) was applied, ranging from "not important at all = 1" to "very important = 5".

Finally, Section 4 of the online questionnaire includes questions about the current situation of farmers in Rio Grande do Sul (RS) regarding their adoption or non-adoption of agriculture 4.0 technologies on their farms/properties, the type of technology used, the duration of use, and the role of these technologies on their farms/properties. At the end of this section, a thank-you message was added for the farmers in RS who agreed to participate in the research. The data for the survey were collected between August and September 2024. A similar version of the online questionnaire used to collect data from farmers in RS is presented in English in Appendix A.

2.3 Sampling strategy

The research employs a simple random sampling probabilistic strategy (Singh, 2003). An invitation containing the research objective and the link where farmers could access the online questionnaire was initially widely disseminated via email to RS respective leaders of 137 rural unions[5] (SENAR, Serviço Nacional de Aprendizagem Rural, 2024). One week after sending the email, the researchers contacted the leaders of the rural unions via WhatsApp, explaining the importance of reaching the target audience of respondents (farmers). These rural leaders were asked to share the survey link and encourage farmers in their regions to participate in the study. In turn, these farmers were requested to share the survey with other potential participants in their regions. Subsequently, the sampling strategy was supported by promoting the survey on social media (e.g., Facebook, Instagram, and WhatsApp) and through relationships (e.g., private banks, cooperatives, Rural Extension Companies, and the Federal University of Rio Grande) in Brazil's largest multi-sector fair—Fenasoja.[6]

The researchers, therefore, used this entire support network to distribute additional links to the online questionnaire, with the number of participants increasing from this outreach, capturing a growing chain of participants across all mesoregions of RS. Following this, regular reminders (social media posts, email, and WhatsApp contacts) were sent to remind participants and the support network that the survey was still open. All farmers who received the survey were encouraged to email the researchers responsible for the study for more information before answering the questions and to clarify any doubts. Subjects included in this research had to be Brazilian, 18 years or older, and reside in RS. No financial compensation was provided for participation in the survey, and the right to confidentiality and anonymity was guaranteed to all respondents who agreed to participate.

2.4 Sample size

The researchers calculated the minimum sample size of the agricultural population in RS based on the latest agricultural Brazilian census data.[7] The total number of farmers operating agricultural establishments in this region is 992.413 (IBGE, Instituto Brasileiro de Geografia e Estatística, 2017b). The minimum sample size required for a margin of error of 6% within a 90% confidence interval was 188 farmers (Som, 1995; Fuller, 2011). The sample consisted of 198 farmers

2 Access link: https://www.youtube.com/watch?v=VKNtrRRh4lc.

3 Access link: https://www.semear-digital.cnptia.embrapa.br/.

4 In Brazil, the term "agriculture 4.0" is not yet well established among farmers, often being associated with "precision agriculture" and related descriptions (Da Silveira et al., 2023b). In this context, to reliably and validly measure farmers' perceptions of the barriers to adopting agriculture 4.0 technologies, the questionnaire used closed questions based on studies from the relevant literature—see Table 1. Additionally, the response options are directly comparable and can be easily converted into a numerical scale for statistical, descriptive, and inferential analyses (Gaskell et al., 2016).

5 A rural union is a non-profit private law civil association established for studies, coordination, defense, and representation of the economic category of the rural production sectors, regardless of the size of the area explored.

6 Access the official Fenasoja website: https://www.fenasoja.com.br/feira.

7 The agricultural census is a statistical and territorial investigation into agricultural production in Brazil by the Brazilian Institute of Geography and Statistics.

TABLE 1 Barriers that hinder the adoption of agriculture 4.0 technologies in the agri-food system.

Technological		
B1	**Technological Complexity.** This problem can arise due to the lack of usability of agriculture 4.0 technological equipment for farmers (e.g., the usability of autonomous machines, equipment, sensors, applications, and software that collect and analyze agricultural data).	Da Silveira et al. (2021), Da Silveira et al. (2023a), Giua et al. (2022), Gabriel and Gandorfer (2023), Chanchaichujit et al. (2024), Geppert et al. (2024), Islam et al. (2024), Johnson (2024)
B2	**Incompatibility between Components.** This refers to the constraints in adapting the technical aspects of equipment and software from different technology companies to existing agricultural operations (e.g., integrating data from multiple sensors).	Da Silveira et al. (2021), Da Silveira et al. (2023a), Eastwood et al. (2023), Hackfort (2023), Chanchaichujit et al. (2024), Geppert et al. (2024)
B3	**Energy Management Problems.** Energy shortages and consumption may hinder farmers' adoption of some agriculture 4.0 technologies (e.g., battery consumption and autonomy during operation by drones and autonomous robots).	Da Silveira et al. (2021), Da Silveira et al. (2023a), Da Silveira et al. (2023b), Islam et al. (2024)
B4	**Lack of Infrastructure.** Robust infrastructure is needed to improve digital connectivity in rural areas.	Da Silveira et al. (2021), Da Silveira et al. (2023a), Eastwood et al. (2023), Mhlanga and Ndhlovu (2023), Sadjadi and Fernández (2023), Choruma et al. (2024), Islam et al. (2024)
B5	**Concerns about Data Reliability**. A large flow of information is occurring in the agri-food system, which poses a threat to cybersecurity and data privacy issues for farmers.	Da Silveira et al. (2021), Da Silveira et al. (2023a), Glaros et al. (2023), Hackfort (2023), Mhlanga and Ndhlovu (2023), Sadjadi and Fernández (2023), Bissadu et al. (2024), Geppert et al. (2024)
Economic		
B6	**High Cost of Facility Maintenance.** These are the expenses to commission the infrastructure needed for rural communities and the operational costs arising from data interoperability (e.g., autonomous machines, equipment applications, software, telecommunications infrastructure).	Da Silveira et al. (2021), Da Silveira et al. (2023a), Hackfort (2023), Geppert et al. (2024), Islam et al. (2024)
B7	**High Cost of Skilled Labor.** This refers to the costs of skilled labor required to control and maintain agriculture 4.0 technologies in operation.	Da Silveira et al. (2021), Martin et al. (2022), Da Silveira et al. (2023a), Miine et al. (2023a)
B8	**High Cost of Operational Components.** This refers to solutions for the decision-making process that may not be implemented due to high costs (e.g., mighty computer boards, multispectral cameras, and software).	Da Silveira et al. (2021), Barrile et al. (2022), Da Silveira et al. (2023a), Da Silveira et al. (2023b)
B9	**Lack of Affordable Solutions for Farmers.** The high investment required to acquire equipment and technological components discourages the adoption of agriculture 4.0 (e.g., the high cost of autonomous machines, equipment, and agricultural robots).	Da Silveira et al. (2021), Da Silveira et al. (2023a), Eastwood et al. (2023), Mhlanga and Ndhlovu (2023), Bissadu et al. (2024), Chanchaichujit et al. (2024), Islam et al. (2024)
B10	**Concerns about Environmental, Ethical, and Social Costs.** Social, ethical, and environmental implications can generate potential costs in the large-scale introduction of agriculture 4.0, which can hinder its adoption among actors in the agri-food system (e.g., use of environmental preservation areas, solar energy, health of rural workers).	Da Silveira et al. (2021), Pascaris et al. (2021), Da Silveira et al. (2023a), Mengi et al. (2023), Sadjadi and Fernández (2023)
Political		
B11	**Limited Availability and Accessibility.** This refers to the lack of availability and accessibility of agriculture 4.0 technologies for farmers. A new agricultural policy framework needs to be developed to stimulate the implementation of agriculture 4.0 technologies in the agri-food system (e.g., a few drone and robot companies).	Da Silveira et al. (2021), Da Silveira et al. (2023a), Mhlanga and Ndhlovu (2023), Chanchaichujit et al. (2024), Choruma et al. (2024)
B12	**Lack of Farm and Farmer-Centered Approaches.** This refers to the structures needed to accelerate the development of agriculture 4.0 (e.g., farmer cooperatives, rural government organizations, private agricultural companies).	Da Silveira et al. (2021), Abiri et al. (2023), Da Silveira et al. (2023a), Eastwood et al. (2023), Chanchaichujit et al. (2024), Johnson (2024)
B13	**Need for an Action Plan for Implementation of Agriculture 4.0 Technologies.** The development of agriculture 4.0 requires an action plan that facilitates the implementation of emerging technologies (e.g., government proposals from chamber 4.0).	Da Silveira et al. (2021), Da Silveira et al. (2023a), Eastwood et al. (2023), Sadjadi and Fernández (2023), Choruma et al. (2024), Geppert et al. (2024), Islam et al. (2024)
B14	**Political Challenges and Lack of Procedures and Agreements Regarding Data Use.** Agriculture 4.0 requires an update of policies as new technologies are adopted in the agri-food system (e.g., land ownership regulation, laws, agreements, and rules on using agricultural data and the operation of autonomous agricultural machinery and equipment in the fields).	Da Silveira et al. (2021), Da Silveira et al. (2023a), Eastwood et al. (2023), Hackfort (2023), Mhlanga and Ndhlovu (2023), Bissadu et al. (2024), Geppert et al. (2024)
B15	**We must promote R&D (Research and development) and innovative business models.** There is a lack of integration between universities and technology incubation centers (e.g., innovation hubs, startups) and investment in R&D to facilitate the development of agriculture 4.0 technologies.	Da Silveira et al. (2021), Da Silveira et al. (2023a), Eastwood et al. (2023), Sadjadi and Fernández (2023), Johnson (2024)

(Continued)

TABLE 1 (Continued)

Social		
B16	**Problems in Education.** The agricultural education system must include the competencies required by agriculture 4.0 (e.g., education, qualification, training, capacity building in agricultural data analysis, transfer of data into practical knowledge).	Da Silveira et al. (2021), Sadjadi and Fernández (2023), Da Silveira et al. (2023a), Bampasidou et al. (2024), Choruma et al. (2024), Geppert et al. (2024), Johnson (2024)
B17	**Risk by Age Group.** The use of technologies related to agriculture 4.0 decreases as the farmer's age increases.	Da Silveira et al. (2021), Prause (2021), Da Silveira et al. (2023a), Johnson (2024)
B18	**Lack of Digital Skills and/or Skilled Labor.** Refers to the skills needed to practice agriculture 4.0 (e.g.: technical knowledge, digital and technological skills).	Da Silveira et al. (2021), Martin et al. (2022), Alarcón-Ferrari et al. (2023), Da Silveira et al. (2023a), Mhlanga and Ndhlovu (2023), Bampasidou et al. (2024), Chanchaichujit et al. (2024), Geppert et al. (2024)
B19	**Lack of Information on the Advantages of Agriculture 4.0.** There is still a need to develop guidelines for farmers that provide a clearer understanding of the advantages of adopting agriculture 4.0 technologies.	Da Silveira et al. (2021), Da Silveira et al. (2023a), Eastwood et al. (2023), Chanchaichujit et al. (2024), Geppert et al. (2024), Islam et al. (2024), Johnson (2024)
B20	**Adaptation to New Technologies.** It is defined as the disruptions in existing work caused by the introduction of new technologies into the agri-food system.	Da Silveira et al. (2021), Martin et al. (2022), Abiri et al. (2023), Da Silveira et al. (2023a), Eastwood et al. (2023), Bampasidou et al. (2024), Bissadu et al. (2024), Chanchaichujit et al. (2024), Islam et al. (2024), Johnson (2024)
Environmental		
B21	**Influence of Climate and Weather on New Technologies (rain, sun, wind).** The hostile agricultural environment can reduce the life cycle of technologies.	Da Silveira et al. (2021), Abiri et al. (2023), Alarcón-Ferrari et al. (2023), Da Silveira et al. (2023a), Islam et al. (2024)
B22	**Lack of effectiveness in Rural Data.** This refers to the effectiveness of climate forecast data in the rural environment (e.g.: ambient temperature, air humidity, soil moisture, solar radiation incidence and precipitation).	Righi et al. (2020), Da Silveira et al. (2021), Da Silveira et al. (2023a), Hackfort (2023)
B23	**Sustainable Constraints.** Refers to the restrictions on the radical mode of food production, food consumption and food waste disposal that can be developed by consumers in the era of agriculture 4.0 (e.g.: food developed by 3D printers).	Da Silveira et al. (2021), Da Silveira et al. (2023a), Eastwood et al. (2023), Johnson (2024)
B24	**Limited Techniques for Data Collection on Farms.** It is a challenge to develop useful techniques for data collection in the agri-food system.	Da Silveira et al. (2021), Da Silveira et al. (2023a), Eastwood et al. (2023), Hackfort (2023)
B25	**Equipment with Sustainable Characteristics.** Refers to agriculture 4.0 technologies for the agri-food system that have sustainable characteristics (but low productivity).	Arvanitis and Symeonaki (2020), Da Silveira et al. (2021), Da Silveira et al. (2023a), Sadjadi and Fernández (2023)

distributed among the seven mesoregions of RS. According to official data from the Brazilian government, this research sample represents the agricultural population in the RS agri-food system (IBGE, Instituto Brasileiro de Geografia e Estatística, 2017b; Feix et al., 2022).

2.5 Statistical analysis

The collected data were reviewed, and respondents with inconsistent answers or evidence of duplication were excluded. The farmers who participated in the survey were divided into two analysis groups: TAF—Technology Adopter Farmer and NTAF—Non-Technology Adopter Farmer. However, farmers who identified as technology adopters but did not specify which technology/technologies they were using were eliminated from the analyses. Subsequently, the homogeneity of responses for each variable was verified by comparing the two analysis groups. For this purpose, we verified the response homogeneity between the two groups by conducting the Test of Equality of Variances (Moore et al., 2012). In addition, we tested significant differences between the two groups. When a significant difference occurred, we performed additional analysis to explore the evolution of responses.

We used JASP software version 0.17.2.1 to perform the statistical analyses, which include descriptive analyses, contingency tables, and correlation tests among the variables. The descriptive analyses of the data present the mean and standard deviation as summary measures and interval plots. The contingency analysis investigated differences between the producer groups—TAF and NTAF. The intensity of the correlation among variables was measured using Student's t-test for parametric data and Mann–Whitney U tests, Welch-Aspin (biserial correlation), or Chi-square tests for non-parametric data (Sellke et al., 2001). All tests were conducted as appropriate for the assumptions of the samples for each variable.

2.6 Limitations in the research approach

Although this study has made some progress in understanding the barriers that affect farmers' behavioral intention to adopt any of the agriculture 4.0 technologies in the agri-food system, it is important to recognize its limitations. First, online surveys present certain difficulties in obtaining representative samples of the farmer population due to the lack of connectivity in rural areas of Brazil (Ziegler et al., 2020). Thus, socioeconomically privileged individuals may represent the survey sample (Da Silveira et al., 2023a). Additionally, it should be noted that farmers with higher education levels are likely more inclined to respond to this type of survey. Considering the entire set of farmers in RS, the average education level will certainly be much lower (IBGE, Instituto Brasileiro de Geografia e Estatística, 2017b). This fact may influence the survey's evidence. Another issue relates to the findings of this study, which are primarily based on quantitative data. However, adopting a mixed-methods approach (Venkatesh et al., 2013), which also incorporates qualitative data, could have enriched the analysis by providing more in-depth details to uncover some of the barriers affecting the adoption of agriculture 4.0 technologies by the two groups of farmers in more specific cases that were not initially addressed in this research. Geographically, the study is confined to a sample of Brazilian farmers from the state of RS. Therefore, while the findings may not be fully generalizable to other parts of the country due to variations in sociodemographic variables that influence the behavioral profiles of farmers, some insights could still be applicable in regions that share similar characteristics or contexts. To increase the external validity of this study, additional research should be conducted in other Brazilian agricultural regions, replicating the survey or even considering international samples. Nevertheless, the study remains relevant, as its findings provide a robust foundation for understanding the complex and interrelated barriers that hinder the adoption of agriculture 4.0 technologies. By capturing the nuances of diverse behavioral profiles among Brazilian farmers in the agri-food system, the research generates actionable insights to guide the design of more effective and context-specific strategies. Moreover, these insights hold applicability beyond Brazil, offering valuable guidance to farmers in other regions facing similar socioeconomic, cultural, and technological challenges in advancing agriculture 4.0 adoption.

TABLE 2 Characteristics of farmers in the study sample (n = 198).

Sociodemographic characteristics	NTAF	TAF
Number of farmers (n)	128	70
Farmer's sex (% female)	14.1%	14.3%
Farmer's age (years: Mean ± SD)	35.2 ± 13.4	37.7 ± 13.6
Schooling (% farmers)		
Basic Education	4.7%	2.9%
Middle Education	21.1%	11.4%
Technical Middle Education	14.8%	10%
Undergraduate	46.1%	55.7%
Master's	8.6%	12.9%
Doctorate	4.7%	7.1%
Total	100%	100%
Characteristics of the agri-food system	**NTAF**	**TAF**
Land Surface (hectares: % farmers)*		
Up to 20	32%	20%
21–100	32.8%	24.3%
Over 100	35.2%	55.7%
Total	100%	100%
Main crop produced (% farmers)		
Maize	49.2%	47.1%
Rice	9.4%	8.6%
Soybeans	17.2%	18.6%
Wheat	3.9%	7.1%
Fruticulture	13.3%	8.6%
Other**	7%	10%
Total	100%	100%
Time working with the crop (years: Mean ± SD)	15.9 ± 10.9	17.4 ± 10.7
Level of understanding of agriculture 4.0 (1–5 scale: Mean ± SD)*	3.0 ± 1.2	3.6 ± 1.0

*Significant effect on determining adoption of technologies of agriculture 4.0. **Other: (oats, tobacco, pasture, and native field).

3 Results

3.1 Statistical analysis

Among the characteristics of farmers in RS, only farm size and the level of understanding of the term "agriculture 4.0" are related and show statistically significant differences (p-value < 0.005) between the TAF and NTAF groups. Representing 35.4% (n = 70) of the farmers in the research sample, the TAF has larger areas than the NTAF and claims to have a greater level of understanding of the term "agriculture 4.0". Table 2 presents these and other data on the characteristics of the two groups of farmers that make up the total sample of the research (n = 198).

The presence of women in rural establishments is similar for both groups, with 14.1% (NTAF) and 14.3% (TAF), respectively. The average age of TAF is 2.5 years older than that of NTAF. However, age is not related to the adoption of agriculture 4.0 technologies. Regarding educational level, both groups have a higher concentration in undergraduate courses, with 46.1% (NTAF) and 55.7% (TAF). However, the groups differ in the second most frequent educational level. The TAF group has a higher concentration at the master's level (12.9%), while the NTAF group has the second highest frequency for high school (21.1%). There are also individuals with doctoral degrees in both groups, but this is more frequent in the TAF group (7.1%). Although not statistically significant, it is noticeable that higher educational levels are more common in the TAF group than in NTAF. Finally, the type of agricultural crop is similar between TAF and NTAF, which may lead to the conclusion that it is not the agricultural crop that determines the use of agriculture 4.0 technologies in the agri-food system—this holds regardless of the size of the farm area where this agricultural crop is grown.

In the TAF group, the adoption of agriculture 4.0 technologies in the agri-food system of RS occurs more frequently on farms with over 100 hectares of arable land (55.7%). The primary agricultural crop reported by respondents in the TAF group is maize (47.1%), followed by soybeans (18.6%). Additionally, adoption is more prevalent among farmers who believe they have a greater understanding of the term "agriculture 4.0" (TAF = 3.6 ± 1.0).

Adopting is slightly more significant for the NTAF group for farms with between 21 and 100 hectares (32.8%). In this group, maize is also the most prominent crop (49.2%), followed by soybeans (17.2%). Farmers in the NTAF group demonstrate a lower understanding of agriculture 4.0 (NTAF = 3.0 ± 1.2).

When evaluating the perceptions of the two groups regarding their level of understanding of the term "agriculture 4.0," a trend toward adoption was identified, as scores of 3 and 4 were most frequent among farmers in the TAF group. In contrast, scores of 2 and 3 were more common for farmers in the NTAF group. This trend is highlighted by the fact that 10.2% of NTAFs rated their level of understanding as 1, whereas this rating represented only 1.4% among TAFs. This indicates that higher levels of understanding of the term "agriculture 4.0" are associated with higher adoption rates of agriculture 4.0 technologies in the agri-food system of RS. Figure 2 illustrates the farmers' perceptions regarding the different levels of understanding of agriculture 4.0.

3.2 Farmers' perceptions of barriers to the adoption of agriculture 4.0 technologies in the agri-food system

Figure 3 shows the 25 barriers that hinder the adoption of agriculture 4.0 technologies in the agri-food system. The analysis

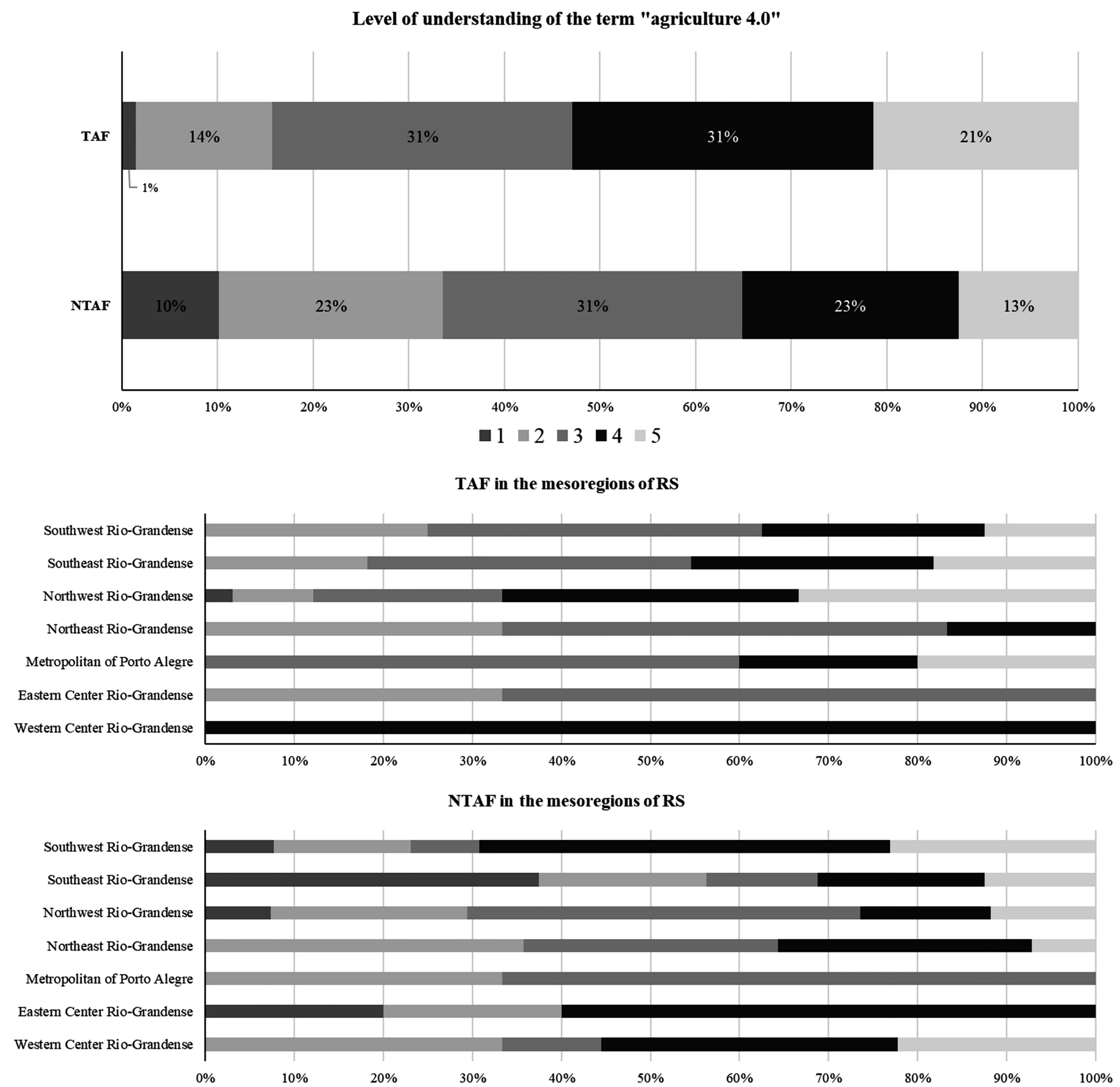

FIGURE 2
Farmers' perception of understanding the term agriculture 4.0.

10.3389/fsufs.2025.1624753

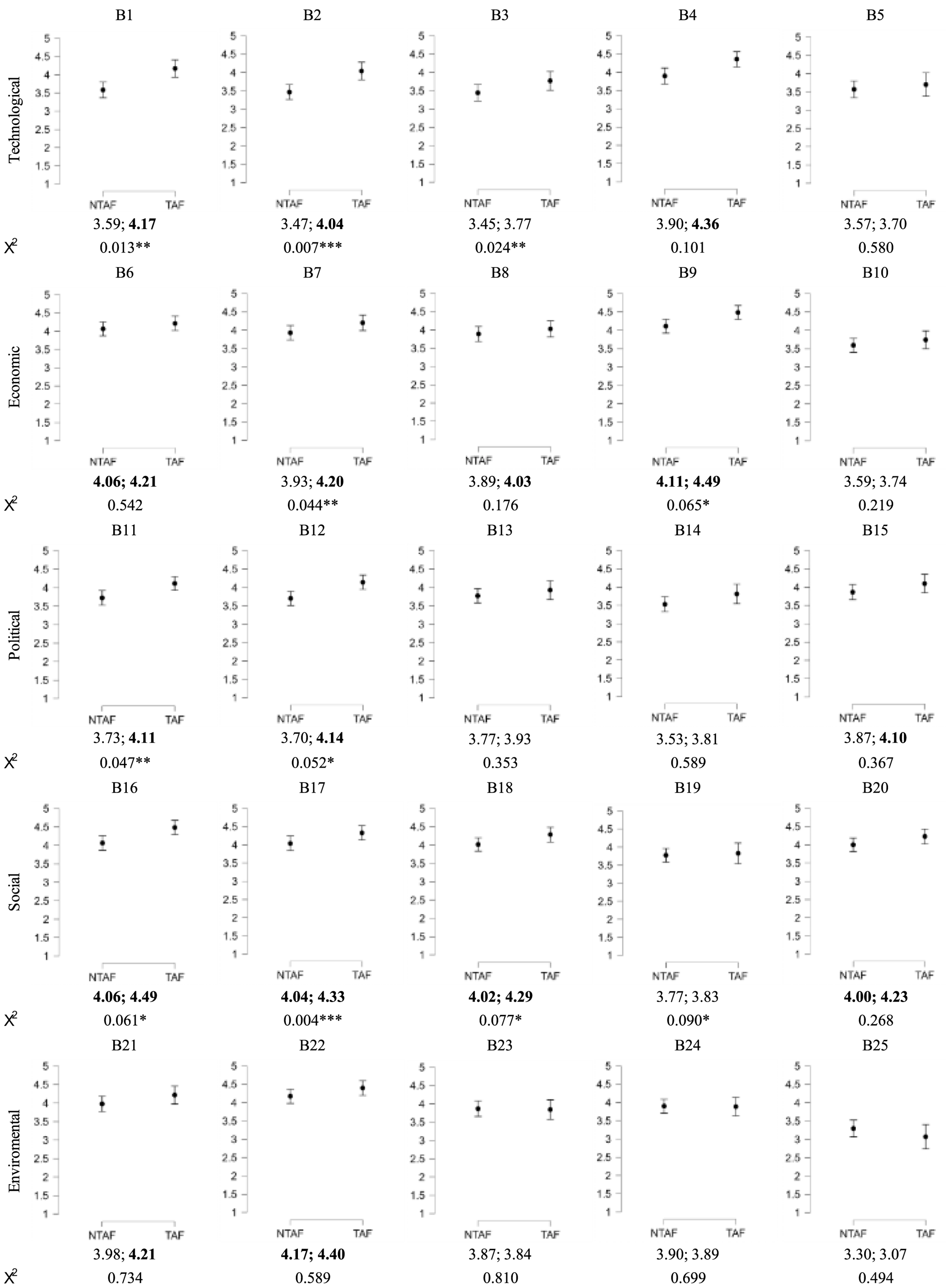

FIGURE 3
Perception of the barriers that hinder the adoption of agriculture 4.0 technologies in the agri-food system by farmers in the NTAF and TAF groups. The highlighted information pertains to average values above four and emphasizes the *p*-value from the chi-square test. **p*-value < 0.1; ***p*-value < 0.05; ****p*-value < 0.01.

presents the perceptions of the two groups of farmers from RS across the five previously established clusters (technological, economic, political, social, and environmental). For the TAF group, the highest indicators include the barriers from the economic cluster (*B9 – Lack of Affordable Solutions for Farmers* (4.49)) and social cluster (*B16 – Problems in Education* (4.49) and *B22 – Lack of Effectiveness in Rural Data* (4.40)). On the other hand, the least representative barrier for the TAF group was identified in the environmental cluster (*B25 – Equipment with Sustainable Characteristics* (3.07)). In the NTAF group, the barriers most frequently cited by farmers belong to the environmental cluster (*B22 – Lack of Effectiveness in Rural Data* (4.17)) and economic cluster (*B9 – Lack of Affordable Solutions for Farmers* (4.11)). The lowest perception in the NTAF group occurred in the environmental cluster (*B25 – Equipment with Sustainable Characteristics* (3.30)). A more detailed analysis of the perceptions of the two groups of farmers regarding each of the clusters will be conducted in the following subsections.

3.2.1 Technological barriers

For all barriers in the technological cluster, the average perception of farmers in the TAF group is lower than that of the NTAF group. Additionally, only the barriers *B1 – Technological Complexity* ($x^2 = 0.013$**), *B3 – Energy Management Problems* ($x^2 = 0.024$**), and *B2 – Incompatibility between Components* ($x^2 = 0.007$***) have a statistically significant relationship. The barriers *B4 – Lack of Infrastructure* ($x^2 = 0.101$) and *B5 – Concerns about Data Reliability* ($x^2 = 0.580$) are not statistically related between the two groups. The barriers with the highest scores for farmers in the TAF group were *B4 – Lack of Infrastructure* (4.36), *B1 – Technological Complexity* (4.17) and *B2 – Incompatibility between Components* (4.04). The least significant barrier in the TAF group was *B5 – Concerns about Data Reliability* (3.70). In the NTAF group, the following barriers received the highest scores: *B4 – Lack of Infrastructure* (3.90) and *B1 – Technological Complexity* (3.59). The least significant barrier in the TAF group was *B3 – Energy Management Problems* (3.45).

3.2.2 Economic barriers

Again, farmers in the TAF group have a higher average perception of barriers in the economic cluster compared to farmers in the NTAF group. However, only the barriers *B9 – Lack of Affordable Solutions for Farmers* ($x^2 = 0.065$*) and *B7 – High Cost of Skilled Labor* ($x^2 = 0.044$**) show a statistically significant difference. In this cluster, the barriers that are not statistically related are: *B6 – High Cost of Facility Maintenance* ($x^2 = 0.542$), *B8 – High Cost of Operational Components* ($x^2 = 0.176$), and *B10 – Concerns about Environmental, Ethical, and Social Costs* ($x^2 = 0.219$). The barrier *B9 – Lack of Affordable Solutions for Farmers* (4.49) has the highest observed frequency in the TAF group and differs the most between the two groups. The barriers observed by farmers in the TAF group are *B8 – High Cost of Operational Components* (4.03) and *B6 – High Cost of Facility Maintenance* (4.21). However, barrier *B10 – Concerns about Environmental, Ethical, and Social Costs* (3.74) received the fewest observations from the TAF group. For farmers in the NTAF group, the most considered barrier was *B9 – Lack of Affordable Solutions for Farmers* (4.11), while the least considered barrier was *B10 – Concerns about Environmental, Ethical, and Social Costs* (3.59).

3.2.3 Political barriers

The average perception of barriers in the political cluster is higher for farmers in the TAF group. However, only the barriers *B11 – Limited Availability and Accessibility* ($x^2 = 0.047$**) and *B12 – Lack of Farm and Farmer-Centered Approaches* ($x^2 = 0.052$*) have a statistically significant difference between the two groups. In the TAF group, the barriers with the highest indications were *B12 – Lack of Farm and Farmer-Centered Approaches* (4.14) and *B11 – Limited Availability and Accessibility* (4.11). In this same group of farmers, the barriers with the lowest indications were *B14 – Political Challenges and Lack of Procedures and Agreements Regarding Data Use* (3.81) and *B13 – Need for an Action Plan for Implementing Agriculture 4.0 Technologies* (3.93). For the NTAF group, the highest scores from farmers were attributed to barriers *B13 – Need for an Action Plan for Implementation of Agriculture 4.0 Technologies* (3.77) and *B15 – Need to Promote R&D (Research and Development) and Innovative Business Models* (3.87). Additionally, the barrier that received the lowest scores in this group was *B14 – Political Challenges and Lack of Procedures and Agreements Regarding Data Use* (3.53).

3.2.4 Social barriers

In the social cluster, farmers in the TAF group also have a higher average perception than farmers in the NTAF group. However, the perceptions of farmers in the NTAF group in the social cluster were quite significant compared to the perceptions of both groups in the other clusters. Furthermore, in this cluster, almost all barriers have a statistically significant relationship between the two groups of farmers, such as *B16 – Problems in Education* ($x^2 = 0.061$*), *B18 – Lack of Digital Skills and Skilled Labor* ($x^2 = 0.077$*), *B19 – Lack of Information on the Advantages of Agriculture 4.0* ($x^2 = 0.090$*), and *B17 – Risk by Age Group* ($x^2 = 0.004$***). Only barrier *B20 – Adaptation to New Technologies* ($x^2 = 0.268$) does not have a statistically significant relationship. The highest indications from farmers in the TAF group occurred for the following barriers: *B16 – Problems in Education* (4.49), *B17 – Risk by Age Group* (4.33), *B18 – Lack of Digital Skills and Skilled Labor* (4.29), and *B20 – Adaptation to New Technologies* (4.23). In the NTAF group, the highest indications from farmers occurred for the following barriers: *B16 – Problems in Education* (4.06), *B17 – Risk by Age Group* (4.04), and *B18 – Lack of Digital Skills and Skilled Labor* (4.02). The lowest indication in both groups occurred for barrier *B19 – Lack of Information on the Advantages of Agriculture 4.0* (TAF = 3.83 and NTAF = 3.77).

3.2.5 Environmental barriers

The barriers in the environmental cluster have a higher average perception among farmers in the NTAF group, except for barriers *B25 – Equipment with Sustainable Characteristics* (NTAF = 3.30 and TAF = 3.07), *B24 – Limited Techniques for Data Collection on Farms* (NTAF = 3.90 and TAF = 3.89) and *B23 – Influence of Climate and Weather on New Technologies (rain, sun, wind)* (NTAF = 3.87 and TAF = 3.84). Furthermore, unlike the other clusters, none of the barriers in the environmental cluster show a statistically significant difference between the two groups of farmers. According to the perceptions of farmers in the TAF group, the following barriers received the highest scores: *B22 – Lack of effectiveness in Rural Data* (4.40) and *B21 – Influence of Climate and Weather on New Technologies (rain, sun, wind)* (4.21). Among farmers in the NTAF group, barrier *B22 – Lack of effectiveness in Rural Data* (4.17) stood out above the others. The barrier B25 scored lowest in both groups.

3.3 Distribution of farmers in the mesoregions of RS

In RS, 64.6% (128) of the sampled farmers belong to the NTAF group. Table 3 presents this and other information regarding the distribution of the two groups of farmers by mesoregion in RS. The results indicate no significant difference between the TAF and NTAF groups by mesoregion. In other words, the mesoregion in RS alone is not a determining factor in adopting agriculture 4.0 technologies within the agri-food system.

However, it is observed that in the TAF group, the mesoregion Metropolitan of Porto Alegre (62.5%) has the highest adoption rate in percentage terms. Conversely, the Northeast Rio-Grandense (30.0%) and the Western Center Rio-Grandense (30.8%) mesoregions exhibit the lowest adoption rates in percentage terms. Meanwhile, the Northwest Rio-Grandense mesoregion has the highest absolute number of farmers in the TAF group (33). In contrast, the Eastern Center Rio-Grandense mesoregion has the lowest absolute number of farmers in the TAF group (3).

In the NTAF group, the Northeast Rio-Grandense mesoregion (70%) stands out as the area with the highest percentage of farmers in RS who do not adopt any agriculture 4.0 technologies in the agri-food system. Following closely is the Western Center Rio-Grandense mesoregion (69.2%). The Northwest Rio-Grandense mesoregion (68) also ranks as the area with the highest absolute number of farmers in the NTAF group. Additionally, the Metropolitan mesoregion of Porto Alegre (3) shows this group's lowest absolute number of farmers.

TABLE 3 Distribution of farmers in the Rio Grande do Sul (RS) mesoregions.

Mesoregions	TAF	NTAF	Total	IM*
Northwest Rio-Grandense	33 (32.7%)	68 (67.3%)	101 (100%)	1
Southeast Rio-Grandense	11 (40.7%)	16 (59.3%)	27 (100%)	3
Southwest Rio-Grandense	8 (38.1%)	13 (61.9%)	21 (100%)	2
Northeast Rio-Grandense	6 (30.0%)	14 (70.0%)	20 (100%)	7
Western Center Rio-Grandense	4 (30.8%)	9 (69.2%)	13 (100%)	4
Metropolitan of Porto Alegre	5 (62.5%)	3 (37.5%)	8 (100%)	6
Eastern Center Rio-Grandense	3 (37.5%)	5 (62.5%)	8 (100%)	5
Total	70 (35.4%)	128 (64.6%)	198 (100%)	

*IM, Identifier on the Map (Figure 1).

3.3.1 Characteristics of farmers in the TAF and NTAF groups

Tables 4, 5 present the profiles of farmers from the TAF and NTAF groups across the mesoregions of RS. The main characteristics of farmers in these groups are described according to their mesoregions, considering factors such as age, gender, education level, cultivated area, main crops, years of agricultural experience, and level of understanding of the term agriculture 4.0.

3.4 Perception of farmers in the clusters of barriers that hinder the adoption of agriculture 4.0 technologies in the agrifood system of RS

3.4.1 TAF

Table 6 presents farmers' perceptions in the TAF group regarding the clusters of barriers that hinder the adoption of agriculture 4.0 technologies in the agrifood system of RS. It can be observed that the social cluster (4.35) received the most attention in this group. Furthermore, this is more evident in the mesoregions of Western Center Rio-Grandense (4.55), Southeast Rio-Grandense (4.38), and Southwest Rio-Grandense (4.38). In the TAF group, it is also possible to notice that in some mesoregions, the difficulty level in adopting agriculture 4.0 technologies in the agrifood system is more significant than in others. This is particularly evident in the following clusters: technological—Eastern Center Rio-Grandense (4.60); environmental—Metropolitan of Porto Alegre (4.56); economic—Metropolitan of Porto Alegre (4.48); and political—Western Center Rio-Grandense (4.45).

In the TAF group, farmers from the Metropolitan of Porto Alegre mesoregion (4.43) have the highest overall perception of the barriers that hinder the adoption of agriculture 4.0 technologies in the agrifood system of RS. In contrast, farmers from the Northwest Rio-Grandense mesoregion (3.96) have the lowest overall perception.

3.4.2 NTAF

Table 7 presents farmers' perceptions in the NTAF group regarding the clusters of barriers that hinder the adoption of agriculture 4.0 technologies in the agrifood system of RS. It is noted that the social cluster (4.04) also gained greater overall prominence in the NTAF group. Furthermore, some mesoregions face more incredible difficulty in adopting agriculture 4.0 technologies in the agrifood system in the following clusters: economic—Eastern Center Rio-Grandense (4.44); social—Western Center Rio-Grandense (4.42); technological—Eastern Center Rio-Grandense (4.36); environmental—Eastern Center Rio-Grandense (4.24); and political—Northeast Rio-Grandense (4.23).

In the NTAF group, farmers from the Eastern Center Rio-Grandense mesoregion (4.25) show a higher overall perception of the barriers that hinder the adoption of agriculture 4.0 technologies in the agrifood system of RS. In contrast, farmers from the Metropolitan of Porto Alegre mesoregion (3.53) have the lowest overall perception. When considering all regions, the average overall perception of farmers in the NTAF group (3.90) was lower than that of the TAF group (4.15).

TABLE 4 Profile of farmers in the TAF group across the mesoregions of RS.

Farmer descriptors	TAF	Mesoregion of the state of RS						
		Western	Eastern	Metropolitan	Northeast	Northwest	Southeast	Southwest
Number of farmers (n)	70	4	3	5	6	33	11	8
Farmer's sex (% female)	14.3%	–	–	–	50%	15.2%	9.1%	12.5%
Farmer's age (years: Mean ± SD)	37.7 ± 13.6	37.2 ± 10.2	37 ± 19	34 ± 18.6	45 ± 10	30.7 ± 8.64	50.5 ± 12.4	45.8 ± 14.6
Schooling (% farmers)								
Basic Education	2.9%	–	33.3%	–	–	–	9.1%	–
Middle Education	11.4%	–	–	40%	50%	9.1%	–	–
Technical Middle Education	10%	–	–	–	33.3%	12.1%	9.1%	–
Undergraduate	55.7%	50%	66.7%	60%	16.7%	57.6%	45.5%	87.5%
Master's	12.9%	–	–	–	–	12.1%	36.4%	12.5%
Doctorate	7.1%	50%	–	–	–	9.1%	–	–
Total	100%	100%	100%	100%	100%	100%	100%	100%
Land Surface (hectares: % farmers)								
Up to 20	20%	25%	–	20%	66.7%	21.2%	9.1%	–
21–100	24.3%	–	100%	20%	33.3%	24.2%	18.2%	12.5%
Over 100	55.7%	75%	–	60%	–	54.5%	72.7%	87.5%
Total	100%	100%	100%	100%	100%	100%	100%	100%
Main crop produced (% farmers)								
Maize	47.1%	25%	66.7%	20%	16.7%	66.7%	27.3%	37.5%
Rice	8.6%	–	–	40%	–	–	9.1%	37.5%
Soy beans	18.6%	25%	33.3%	–	–	21.2%	27.3%	12.5%
Wheat	7.1%	25%	–	20%	–	6.1%	9.1%	–
Fruticulture	8.6%	–	–	–	83.3%	–	9.1%	–
Other*	10%	25%	–	20%	–	6.1%	18.2%	12.5%
Total	100%	100%	100%	100%	100%	100%	100%	100%
Time working with the crop (years: Mean ± SD)	17.4 ± 10.7	17 ± 11.1	6.33 ± 3.21	15.2 ± 9.65	27 ± 9.69	15.9 ± 9.52	17.2 ± 9.46	22.6 ± 15
Level of understanding of agriculture 4.0 (1–5 scale: Mean ± SD)	3.6 ± 1	4 ± 0	2.66 ± 0.57	3.6 ± 0.89	2.83 ± 0.75	3.84 ± 1.09	3.45 ± 1.03	3.25 ± 1.03

*Other: (oats, tobacco, pasture, and native field).

3.4.3 TAF × NTAF

Table 8 shows that farmers in the TAF group have a higher perception of the barriers to adopting agriculture 4.0 technologies in the agrifood system of RS across all clusters considered, with a notable emphasis on the technological cluster (0.36). Additionally, in the environmental cluster, the perceptions between the two groups of farmers are almost identical (0.08). When examined by region, the overall perception of the clusters is more heterogeneous. However, the most significant difference is in the Metropolitan of Porto Alegre mesoregion (0.90). This may be related to the strong perception of both groups of farmers regarding the barriers in the economic cluster (1.75).

TABLE 5 Profile of farmers in the NTAF group across the mesoregions of RS.

Farmer descriptors	NTAF	Mesoregion of the state of RS						
		Western	Eastern	Metropolitan	Northeast	Northwest	Southeast	Southwest
Number of farmers (n)	128	9	5	3	14	68	16	13
Farmer's sex (% female)	14.1%	–	20%	33.3%	28.6%	11.8%	–	30.8%
Farmer's age (years: Mean ± SD)	35.2 ± 13.4	32.5 ± 12.1	52 ± 20.5	32.6 ± 17.6	33.4 ± 11.4	34 ± 11.3	34.4 ± 14.9	40 ± 17.2
Schooling (% farmers)								
Basic Education	4.7%	–	–	–	7.1%	5.9%	6.3%	–
Middle Education	21.1%	–	20%	66.7%	42.9%	19.1%	25%	7.7%
Technical Middle Education	14.8%	33.3%	–	–	7.1%	17.6%	6.3%	15.4%
Undergraduate	46.1%	55.6%	40%	33.3%	35.7%	45.6%	50%	53.8%
Master's	8.6%	11.1%	40%	–	–	8.8%	6.3%	7.7%
Doctorate	4.7%	–	–	–	7.1%	2.9%	6.3%	15.4%
Total	100%	100%	100%	100%	100%	100%	100%	100%
Land Surface (hectares: % farmers)								
Up to 20	32%	22.2%	20%	33.3%	71.4%	33.8%	12.5%	15.4%
21–100	32.8%	–	40%	–	21.4%	41.2%	31.3%	30.8%
Over 100	35.2%	77.8%	40%	66.7%	7.1%	25%	56.3%	53.8%
Total	100%	100%	100%	100%	100%	100%	100%	100%
Main crop produced (% farmers)								
Maize	49.2%	44.4%	40%	–	7.1%	70.6%	37.5%	15.4%
Rice	9.4%	–	–	33.3%	–	–	18.8%	61.5%
Soy beans	17.2%	22.2%	60%	66.7%	7.1%	17.6%	12.5%	–
Wheat	3.9%	–	–	–	–	5.9%	–	7.7%
Fruticulture	13.3%	22.2%	–	–	85.7%	1.5%	12.5%	–
Other*	7%	11.1%	–	–	–	4.4%	18.8%	15.4%
Total	100%	100%	100%	100%	100%	100%	100%	100%
Time working with the crop (years: Mean ± SD)	15.9 ± 10.9	15.2 ± 10.9	21.4 ± 12	13.6 ± 14.1	18.3 ± 9.77	17.2 ± 10.3	11.5 ± 11.1	10.3 ± 12.5
Level of understanding of agriculture 4.0 (1–5 scale: Mean ± SD)	3 ± 1.2	3.44 ± 1.23	3 ± 1.41	2.66 ± 0.57	3.07 ± 0.99	3.01 ± 1.07	2.5 ± 1.50	3.61 ± 1.26

*Other: (oats, tobacco, pasture, and native field).

3.5 Technologies of agriculture 4.0 adopted by farmers in the state of RS

Table 9 presents the technologies of agriculture 4.0 that are being adopted by farmers in the TAF group within the agri-food system of Rio Grande do Sul (RS). Drones are the most frequently mentioned technology by farmers in this group, followed by smart sensors. Other technologies rank third, highlighting farmers' uncertainty in explaining which technologies they are utilizing. The fact that the internet is the least reported technology in the survey may relate to the greater ambiguity respondents experience, as most do not consider it a technology of agriculture 4.0 itself but

TABLE 6 Perception of farmers in the TAF group.

Mesoregion of the state of RS	Cluster					Region average
	Technological	Economic	Political	Social	Environmental	
TAF average perception						
Western Center Rio-Grandense	4.15	4.25	4.45	4.55	4.00	4.28
Eastern Center Rio-Grandense	4.60	4.00	4.20	4.40	4.07	4.25
Metropolitan of Porto Alegre	4.36	4.48	4.28	4.48	4.56	4.43
Northeast Rio-Grandense	3.90	4.00	4.20	4.17	3.87	4.03
Northwest Rio-Grandense	4.00	4.10	3.83	4.07	3.81	3.96
Southeast Rio-Grandense	3.84	4.04	4.13	4.38	3.69	4.01
Southwest Rio-Grandense	3.85	4.28	4.08	4.38	3.90	4.10
Dimension average	4.10	4.16	4.17	4.35	3.99	4.15

*The intensity of the color corresponds to the higher perception of farmers in the TAF group.

TABLE 7 Perception of farmers in the NTAF group.

Mesoregion of the state of RS	Cluster					Region Average
	Technological	Economic	Political	Social	Environmental	
NATF average perception						
Western Center Rio-Grandense	3.71	4.16	3.98	4.42	3.98	4.05
Eastern Center Rio-Grandense	4.36	4.44	4.20	4.00	4.24	4.25
Metropolitan of Porto Alegre	3.80	2.73	3.93	3.60	3.60	3.53
Northeast Rio-Grandense	3.84	4.20	4.23	4.06	4.00	4.07
Northwest Rio-Grandense	3.53	3.84	3.52	3.83	3.74	3.69
Southeast Rio-Grandense	3.03	3.94	3.76	4.24	4.11	3.82
Southwest Rio-Grandense	3.94	3.88	3.77	4.12	3.68	3.88
Dimension average	3.74	3.88	3.91	4.04	3.91	3.90

*The intensity of the color corresponds to the higher perception of farmers in the NTAF group.

rather a facilitator for using technology. Additionally, the mesoregions of Northwest Rio-Grandense (38) and Southeast Rio-Grandense (12) stand out with the highest frequency of adopting some agriculture 4.0 technology. Regarding the role these technologies play on farms, farmers cite the following aspects: spraying, area monitoring, production improvement, climate forecasting, assistance in management and decision-making, cost reduction, reduction of agrochemical products used, ease of work, and seamless sowing.

4 Discussion

Although the introduction of agriculture 4.0 technologies into the Brazilian agri-food system is underway, there is a need to accelerate their adoption among farmers, given the immense benefits that can be achieved through their use (e.g., increasing food production while consuming fewer natural resources and having a lower environmental impact) (Lajoie-O'Malley et al., 2020; Ammann et al., 2022; Mühl and Oliveira, 2022). However, for the advancement of agriculture 4.0

TABLE 8 Difference in perception between farmers in the TAF and NTAF groups.

Mesoregion of the state of RS	Cluster					Region average
	Technological	Economic	Political	Social	Environmental	
Contrast (TAF—NTAF)						
Western Center Rio-Grandense	0.44	0.09	0.47	0.13	0.02	0.23
Eastern Center Rio-Grandense	0.24	−0.44	–	0.40	−0.17	0.01
Metropolitan of Porto Alegre	0.56	1.75	0.35	0.88	0.96	0.90
Northeast Rio-Grandense	0.06	−0.20	−0.03	0.11	−0.13	−0.04
Northwest Rio-Grandense	0.47	0.26	0.31	0.24	0.07	0.27
Southeast Rio-Grandense	0.81	0.10	0.36	0.14	−0.42	0.20
Southwest Rio-Grandense	−0.09	0.40	0.31	0.25	0.22	0.22
Dimension average	0.36	0.28	0.25	0.31	0.08	0.25

*The intensity of the color corresponds to the higher perception of farmers in the TAF and NTAF groups.

technologies to be more successful in this sector, it is important to assess how prepared Brazilian farmers are to adopt them, as this readiness directly influences the effectiveness, speed, and sustainability of the implementation process (Bolfe et al., 2020; Da Silveira et al., 2023a). Understanding farmers' preparedness helps identify gaps in knowledge, access, and support systems, allowing policymakers and stakeholders to design more effective interventions and avoid the risk of excluding vulnerable groups.

In this context, the main objective of this study was to investigate the behavioral profile of Brazilian farmers regarding the adoption of agriculture 4.0 technologies. By analyzing the perceptions of 198 producers from Rio Grande do Sul (RS), the study aims to generate insights that can support strategies to accelerate agriculture 4.0 technologies adoption in the agri-food system. The analysis is based on a pre-established set of 25 barriers, organized into five key clusters—technological, economic, political, social, and environmental—that influence the pace and nature of this adoption process. The following sections 4.1 and 4.2 will address these aspects in detail. Unlike previous studies, which have predominantly examined external constraints such as limited infrastructure, inadequate connectivity, lack of digital skills, and insufficient policy support in regions like Europe, North America, and sub-Saharan Africa (Phillips et al., 2019; Thompson et al., 2019; Kernecker et al., 2020; Bontsa et al., 2023), this research provides a behaviorally oriented and comparative perspective grounded in the context of a developing economy. Specifically, the sample was segmented into two distinct groups: TAF—Technology Adopter Farmers ($n = 70$) and NTAF—Non-Technology Adopter Farmers ($n = 128$). This typology enabled a more in-depth examination of how perceived barriers vary not only across structural dimensions but also according to adoption profiles and behavioral patterns of farmers.

This analytical framework advances the scientific debate on agriculture 4.0 by demonstrating that adoption is not merely a function of access to resources or exposure to innovations but is also shaped by farmer-specific behavioral traits, embedded social norms, and regional structural conditions. Farmers differ significantly in their propensity to take risks, the degree of trust they place in agriculture 4.0 technologies, and the nature and intensity of their engagement with institutional structures and support systems. By highlighting these internal divergences, the study contributes to a more nuanced understanding of adoption patterns and reveals the limitations of generalized policy prescriptions.

Beyond its national scope, this study offers relevant insights to the broader discussions on sustainable agriculture and food security, particularly by emphasizing the importance of context-aware and farmer-centered strategies. The findings provide practical considerations that may be valuable for shaping interventions in other developing countries facing similar socio-technical and institutional challenges. In this sense, the study supports the view that inclusive agricultural transformation benefits from tailored, evidence-based approaches that account for local realities and behavioral diversity, rather than relying on standardized solutions.

Recognizing the heterogeneity in how farmers perceive and respond to adoption barriers is essential for guiding more effective and inclusive policy and practice. Stakeholders—such as policymakers, extension services, agritech developers, and farmer organizations—can draw on these insights to design adaptive regulatory frameworks, targeted financial incentives, and capacity-building initiatives aligned with farmers' diverse profiles and local realities. By grounding interventions in differentiated needs, this study contributes to a more equitable transition toward agriculture 4.0, while reinforcing the resilience and sustainability of agri-food systems on a global scale.

The sociodemographic and crop-type results obtained in this research coincide with those of previous research in certain aspects and differ in others. As observed in the NTAF group, the lack of a greater understanding of the term agriculture 4.0 (Figure 2) highlights that there is a gap to be explored to increase awareness of the advantages of adopting emerging technologies available in the

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TABLE 9 **Technologies of agriculture 4.0 adopted in the agri-food system of RS.**

Mesoregion of the state of RS	Adopted technologies									Total
	Drone	Smart sensors	Others*	GPS	Cloud Computing	Fieldview	Autonomous Robotic	Smartphone Application	Internet	
Western Center Rio-Grandense	1	2	1							4
Eastern Center Rio-Grandense		1		2						3
Metropolitan of Porto Alegre	2	2		1			1			6
Northeast Rio-Grandense	4		1					1		6
Northwest Rio-Grandense	14	6	4	4	5	4			1	38
Southeast Rio-Grandense	8		1				1	1	1	12
Southwest Rio-Grandense	5		2		1					8
Total	34	11	9	7	6	4	2	2	2	77

*Technologies with different functionalities, such as soil mapping, satellite imagery, autonomous weather stations with real-time data, and Starlink.

agri-food system and that are not yet widely known or disseminated in Brazil. This is in line with the evidence of Al-Ammary and Ghanem (2023), where farmers from the Persian Gulf countries often fail to adopt them due to a lack of knowledge about the benefits that can be achieved through their implementation. In contrast, farmers in the TAF group, characterized by having the largest farm size and the second most frequently more advanced level of education compared to the NTAF group, demonstrate a higher level of understanding of the term agriculture 4.0. This information corroborates the findings of Mhlanga and Ndhlovu (2023), where smallholder farmers in Africa, without sufficient knowledge and training, may not be able to successfully understand, use, or benefit from agriculture 4.0 technologies, which further worsens adoption. This trend is also observed in Nigeria, where farmers with higher levels of education are more likely to engage with and adopt these emerging technologies, highlighting the importance of education in fostering the transition to agriculture 4.0 (Amoussohouia et al., 2023).

In respect to gender roles, this study found that both male and female farmers in RS have access to agriculture 4.0 technologies when operating under similar environmental and contextual conditions. However, the likelihood of adoption remains lower among women in both the TAF and NTAF groups. This pattern may reflect persistent sociocultural structures in rural areas of RS and Brazil, where agricultural establishments are predominantly managed by men (IBGE, Instituto Brasileiro de Geografia e Estatística, 2017b), potentially limiting women's autonomy in decision-making processes related to technological innovations. These findings are consistent with Aryal et al. (2020), who observed that in India, women—particularly when not recognized as household heads—have minimal influence over the adoption of agriculture 4.0 technologies. This study also found that the type of agricultural activity is not a critical determinant of technology adoption, regardless of the farmer's profile. This result aligns with the findings of Vargas-Canales (2023) in Mexico, who, despite addressing a different research question, arrived at a similar conclusion.

Some researchers claim that, among the agriculture 4.0 technologies, the more complex they are to implement or whose immediate return is less noticeable to farmers, they are clearly the least adopted in the agri-food system (Bellon-Maurel et al., 2023). Other researchers argue that among the most used agriculture 4.0 technologies, the current focus is on easy-to-use solutions that reduce the workload of farmers (Gabriel and Gandorfer, 2023). The results of this research are in line with these claims, where the technology most frequently mentioned by farmers in the TAF group was the drone. According to Rejeb et al. (2022), the multiple advantages provided by the use of drones in the agri-food system are fundamental to achieving this popularity among farmers. Furthermore, from a global perspective, the USA, China, India, and Italy lead the number of scientific publications on the subject, evidencing the academic and technological interest in these countries. The authors also highlight that research on the agri-food system is largely concentrated in countries in North America and Asia, which may reflect greater investment and a faster pace of adoption of this specific technology in these regions. However, McCarthy et al. (2023) point out some obstacles that prevent the widespread adoption of drones in this sector by farmers, such as concerns about the costs of the technology and the accuracy and interpretation of the data. There is also some skepticism about the usefulness of the information provided by drones, as well as about the privacy and security measures to protect their personal information. These obstacles may be particularly relevant within the NTAF group.

Among the seven mesoregions of RS, the Metropolitan region of Porto Alegre stood out in the TAF group in terms of the percentage adoption of agriculture 4.0 technologies in the agrifood system. This evidence may be anchored by the region, including the city of Porto Alegre—the capital of RS, where there is a diversified innovation ecosystem that indirectly positively favors the perceptions of farmers in this sector regarding agriculture 4.0 technologies. The main characteristics of this region that influence this dynamic are the technology parks, incubators, several educational and technology institutions, agrotechnology fairs, workshops, and courses on emerging technological applications to overcome the current challenges of agribusiness, among others, which allow greater dissemination of information about the advantages of agriculture 4.0 technologies. Meanwhile, the Northwest Rio-Grandense mesoregion was the one that contemplated the largest absolute number of farmers in the TAF group. It is important to highlight that this region is recognized as the National Cradle of Soybeans in Brazil[8]—the first city where soybeans were planted in the country and is also responsible for housing multinational companies that lead the development of emerging technologies for agribusiness (e.g., AGCO and John Deere). Thus, this local production arrangement involuntarily triggers relationships of cooperation and learning among agricultural stakeholders—especially with regard to farmers' perceptions of the innovations that are being developed for the Brazilian agrifood system scenario. In contrast, the Northeast Rio Grande do Sul mesoregion had the highest percentage of farmers in RS who do not adopt agriculture 4.0 technologies in this sector.

This fact may be related to the large number of small farmers, also known as fruit and vegetable growers (e.g., grapes, apples, persimmons, vegetables, and tomatoes), who are located in the cities of this region. Furthermore, most agricultural establishments located in the Northeast Rio Grande do Sul mesoregion are classified as family farms. This reinforces the idea that there is a public that does not see the adoption of agriculture 4.0 technologies as beneficial. Thus, these small farmers seem to have a fairly fixed opinion about what good or bad agrifood systems are, which may be rooted in moral values. One reason for this situation may be that the discussion around agriculture 4.0 has focused little on real environmental and social outcomes and more on the food production process (Wilmes et al., 2022).

In both groups of farmers in the study (TAF and NTAF), the barriers of the social cluster were more significant than other barriers. Similar results were observed in the studies by Kernecker et al. (2020) and Gaber et al. (2024). These authors highlighted this trend in countries such as France, Germany, Greece, the Netherlands, Serbia, Spain, and the United Kingdom, indicating that social factors play a critical role in the adoption of agriculture 4.0 technologies in different contexts. In the words of McGrath et al. (2023), these adverse impacts of agriculture 4.0 technologies on the agri-food system should inform and guide the design and development of these technologies for on-farm implementation. One alternative to achieving this is to

8 Access link: https://www.gov.br/secretariageral/pt-br/noticias/2022/maio/presidente-sanciona-projeto-de-lei-que-confere-ao-municipio-de-santa-rosa-rs-o-titulo-de-berco-nacional-da-soja.

integrate more inclusive approaches to technological design. According to the same authors, these approaches will help mitigate the negative effects of agriculture 4.0 technologies, help to create more successful and responsible innovations, address problems of low adoption, and help to create more equitable and inclusive technological futures.

To advance this vision and foster the adoption of agriculture 4.0 technologies in Brazil and other countries facing similar challenges, we outline below a set of implementation strategies aimed at addressing the main barriers to their effective integration within the agri-food system. These strategies can also serve as a reference for international contexts with comparable socioeconomic and structural characteristics. Below, each section explores these strategies in detail, addressing the most critical barriers and proposing tailored solutions to foster effective adoption.

4.1 TAF

This section provides a comprehensive analysis of the most critical barriers experienced by farmers who have already adopted agriculture 4.0 technologies (TAF). It highlights the challenges these adopters face across multiple dimensions and presents strategic approaches to support sustained and optimized use of these technologies within diverse contexts.

4.1.1 Technological cluster

Technological challenges remain among the most immediate (i.e., those that arise first and require urgent attention) and impactful barriers for both current and potential adopters of agriculture 4.0. Limited infrastructure—such as unreliable internet connectivity and insufficient technical support—continues to constrain effective implementation, especially in rural and remote areas. This subsection examines the main technical obstacles experienced by farmers who are already implementing these technologies, while also proposing targeted strategies to enhance usability, adaptability, and contextual relevance—thus facilitating broader adoption.

B4 – Lack of Infrastructure (4.36): Robust infrastructure is fundamental for enabling the consistent and efficient use of agriculture 4.0 technologies. In rural areas—particularly in developing contexts like many regions of Brazil—the scarcity of high-speed internet, unreliable electricity, and limited access to support services continues to hinder digital transformation on farms (Bolfe et al., 2020; Da Silveira et al., 2023a). These infrastructural gaps affect not only non-adopters but also those who have adopted technologies, leading to operational inefficiencies, data loss, and reduced system performance, ultimately diminishing the return on technological investments. To address this barrier, the following strategies are recommended: (i) deploy localized connectivity solutions such as private 4G/5G networks or satellite internet like Starlink to enhance coverage in remote areas; (ii) adopt offline-capable tools and edge computing devices that process data locally and sync with the cloud once connectivity is restored; and (iii) create Peer-to-Peer (P2P) farm networks with nearby adopters to build decentralized networks that allow for localized data sharing and coordination. These networks can serve as an alternative communication and support infrastructure when broader systems are unavailable.

B1 – Technological Complexity (4.17): To increase the adoption of agriculture 4.0 technologies, they must be simple and user-friendly, especially for farmers and rural workers. Involving end-users in the development process—through feedback and daily on-farm experiences—enhances relevance and usability (Calafat-Marzal et al., 2023; Da Silveira et al., 2023a). Co-design approaches and allowing farmers to test and customize technologies can also help overcome this barrier (Hansen et al., 2022; Georgopoulos et al., 2023). Recommended actions include: (i) designing solutions tailored to local agri-food system characteristics (climate, soil, crops); (ii) providing interfaces and technical support in local languages; (iii) ensuring compatibility with existing infrastructure, including limited rural connectivity; (iv) promoting co-creation programs with farmers from different regions; and (v) creating regional technology-sharing hubs to support small-scale producers.

4.1.2 Economic cluster

Economic issues for adopters typically involve managing ongoing costs and scaling investments. This subsection examines financial constraints specific to active users and suggests economic models and supports designed to maintain and expand technology use.

B9 – Lack of Affordable Solutions for Farmers (4.49): Business models for agriculture 4.0 must reflect the limited financial capacity of small and medium farmers. Strategies like the inverted pyramid—where larger sector players absorb most of the costs—can help. Subscription-based and pay-per-use models also lower entry barriers, making technologies more accessible (Eastwood et al., 2021; Georgopoulos et al., 2023). Government support through subsidies, tax incentives, and easier credit access can further drive adoption (Aparo et al., 2022; Miine et al., 2023b). Key approaches include: (i) subscription and pay-per-use models to reduce upfront costs; (ii) rural credit lines for agri-food system modernization; (iii) support for local startups to develop region-specific solutions; (iv) expansion of international agricultural funding for low-income countries.

4.1.3 Political cluster

Institutional support and policy alignment are essential to sustain adoption among experienced farmers. This part addresses political and governance-related barriers affecting adopters, alongside collaborative frameworks that facilitate continued technological integration.

B12 – Lack of Farm and Farmer-Centered Approaches (4.14): Adoption of agriculture 4.0 technologies requires alignment with farmers' real needs. Innovation hubs—like agri-tech parks, incubators, and accelerators—can foster collaboration and practical solutions (Lassoued et al., 2023). Strengthening networks between stakeholders (e.g., governments, NGOs, cooperatives, companies, and banks) is also crucial to co-create relevant technologies (Kieti et al., 2022; Mendes et al., 2022; Charatsari et al., 2024). Key strategies include: (i) establishing agri-tech parks for shared experimentation and knowledge exchange; (ii) supporting incubators/accelerators tailored to farmers already using agriculture 4.0; (iii) implementing policies with tax incentives and subsidies for ongoing tech use; and (iv) expanding rural extension services to offer technical and strategic support.

4.1.4 Social cluster

Social factors, including education, skill development, and workforce capacity, are fundamental for enabling adopters to fully capitalize on the benefits offered by agriculture 4.0 technologies. This section analyzes key challenges related to training, knowledge transfer, and community engagement among users.

B16 – Problems in Education (4.49): Agriculture 4.0 demands updated curricula across all educational levels, focusing on data skills, digital literacy, and practical tech use (Puntel et al., 2023; Bampasidou et al., 2024). Effective learning should include field-based training and regular engagement with rural communities (Rose et al., 2023). Key initiatives to address this barrier include: (i) offering continuous training for farmers already using agriculture 4.0 tools, enhancing usability and adoption; (ii) creating practice-based courses through partnerships between universities, tech companies, and farmers; (iii) establishing regional training centers to expand access to agriculture 4.0 education, especially in remote areas; and (iv) supporting applied research on how early adopters learn and what challenges remain, to refine educational strategies.

4.1.5 Environmental cluster

Environmental factors shape both the effective use of diverse data sources and the durability of agriculture 4.0 technologies. This section addresses how adopters manage data integration challenges alongside climate impacts on technology performance and maintenance.

B22 – Lack of effectiveness in Rural Data (4.40): For farmers already using agriculture 4.0 technologies, the challenge lies less in data availability and more in the integration and real-time application of diverse datasets (e.g., local sensors, remote sensing, and weather forecasts) (Mühl and Oliveira, 2022). Although current agrometeorological models are accurate, their practical utility depends on effective data management and interpretation. Key factors influencing continued and effective use include data reliability, system interoperability, and actionable insights. Suggested strategies to address this barrier include: (i) enhancing interoperability between sensor networks and farm management platforms to ensure seamless data flow; (ii) employing advanced analytics and AI-driven decision support tools to translate data into precise recommendations; (iii) providing continuous training on data interpretation tailored to specific crop and regional contexts; and (iv) developing feedback loops where farmers validate data-driven decisions against field outcomes to build trust and refine models.

B21 – Influence of Climate and Weather on New Technologies (rain, sun, wind) (4.14): While agriculture 4.0 technologies are generally built to withstand environmental conditions, farmers often lack information on their durability and maintenance. Clear communication about technical specifications and proper use can build confidence, especially for mobile robots with replaceable components (Shamshiri et al., 2024). To address this barrier: (i) promote the development of weather-resistant equipment using robust materials and protective coatings; (ii) establish preventive maintenance protocols and train farmers on storage and handling of sensitive tools; (iii) create testing environments to assess technology performance under extreme weather before deployment.

4.2 NTAF

This section examines the predominant barriers impeding initial adoption among farmers who have not yet embraced agriculture 4.0 technologies (NTAF). It emphasizes targeted strategies aimed at overcoming these obstacles and encouraging first-time adoption.

4.2.1 Technological cluster

Limited infrastructure and inadequate technical access are major impediments for non-adopters. This subsection outlines technological shortcomings hindering first-time adoption and proposes foundational improvements to facilitate accessibility.

B4 – Lack of Infrastructure (3.90): Limited connectivity in remote rural areas remains a major barrier to agriculture 4.0 adoption. While expanding 5G infrastructure is the long-term goal (Tang et al., 2021), interim solutions like local data processing during offline periods and later synchronization (e.g., edge and cloud computing) are gaining traction (Aboubakar et al., 2022; Gackstetter et al., 2023). Strategies to address this issue include: (i) offer government incentives for telecom expansion in rural zones; (ii) deploy LoRaWAN and satellite internet (e.g., Starlink) to boost coverage; (iii) install free Wi-Fi hotspots in rural communities and cooperatives; (iv) use drones and autonomous sensors with local storage for delayed transmission; (v) explore radio frequency and off-grid connectivity options; and (vi) design offline-capable apps and software with data sync functionality.

4.2.2 Economic cluster

High upfront investment and ongoing maintenance costs pose significant economic barriers for potential adopters of agriculture 4.0 technologies. This subsection explores the financial challenges faced by farmers yet to adopt these innovations, as well as strategies and support mechanisms designed to reduce both initial acquisition and operational expenses, facilitating broader access and sustained use.

B9 – Lack of Affordable Solutions for Farmers (4.11): The high initial cost of acquiring agriculture 4.0 technologies still represents a significant barrier for small and medium-sized producers (Islam et al., 2024). Beyond financial models, it is essential to consider practical alternatives to facilitate access to innovation in the field. Strategies to overcome this limitation include: (i) promoting community partnerships for shared equipment use, reducing individual costs and increasing access; (ii) encouraging the adaptation and customization of simple, modular technologies that can be implemented gradually according to the producer's financial capacity; (iii) implementing field demonstration programs that demonstrate real, cost-effective results, helping to build confidence in the return on investment; and (iv) exploring low-cost digital solutions, such as mobile apps and simple sensors, that provide initial gains without requiring large investments. These alternatives focus on the practical feasibility and gradual use of technologies, helping farmers who have not yet adopted them overcome the cost barrier and begin the journey toward agriculture 4.0.

B6 – High Cost of Facility Maintenance (4.06): While most agriculture 4.0 technologies do not require dedicated facilities, some with higher operational costs present maintenance challenges. Solutions include financial support via subsidies, favorable credit lines, and public-private partnerships (Aparo et al., 2022; Abbate et al., 2023; Gumbi et al., 2023). Strategies include: (i) support shared infrastructure (e.g., telecom towers, data centers) via public-private initiatives; (ii) promote modular technologies to lower maintenance costs and increase flexibility; (iii) offer low-interest loans and microcredit for tech upkeep and modernization; (iv) encourage collective leasing models through cooperatives and tech companies; (v) provide user-friendly maintenance manuals with visuals for farmers; and (vi) train local leaders to serve as tech maintenance facilitators in rural areas.

4.2.3 Political cluster

The lack of structured implementation plans and coordinated public policies remains a major barrier for non-adopters of agriculture 4.0. Many farmers are uncertain about where to start and how to choose suitable technologies. This subsection explores institutional and political challenges that limit early adoption and emphasizes the need for integrated action among governments, research institutions, and the private sector to create a supportive environment for innovation and uptake.

B15 – Need to Promote R&D (Research and Development) and Innovative Business Models (3.87): The absence of a clear strategy for the implementation of agriculture 4.0 technologies hinders their adoption by farmers who have not yet embraced these innovations (Da Silveira et al., 2021). Many farmers remain uncertain about the practical applicability, cost-effectiveness, and compatibility of emerging solutions with their specific farming conditions. This gap is closely linked to the lack of coordination among research efforts, development initiatives, and public policies directed at the agri-food systems. To address this barrier, it is essential to foster an institutional and market environment that promotes innovation and strengthens the connection between technology developers and end users. Suggested strategies include: (i) developing government action plans with specific targets for the dissemination of agriculture 4.0, particularly among small and medium-sized producers; (ii) expanding public research programs focused on affordable technologies adapted to diverse regional contexts; (iii) supporting the emergence of innovative business models, such as technology cooperatives and rural incubators; (iv) promoting partnerships between startups, universities, and agribusiness organizations to co-develop scalable and user-friendly technologies; and (v) organizing fairs, technology showcases, and demonstration units to illustrate the tangible benefits of agriculture 4.0 technologies in real-world farming environments. These initiatives can help close the gap between technological supply and farmers' needs, enabling a gradual and confident transition into the agriculture 4.0 era.

B13 – Need for an Action Plan for Implementation of Agriculture 4.0 Technologies (3.77): The diversity of available agriculture 4.0 technologies can overwhelm farmers, making it difficult to choose suitable solutions. A structured implementation plan—ideally blending public and private efforts—is crucial for guiding adoption (Lidder et al., 2025). Such plans should also foster AgriFoodTech startups and support marginalized farmers (Choruma et al., 2024; Klerkx and Villalobos, 2024; Sun et al., 2024). Recommended actions include: (i) create a national agriculture 4.0 plan tailored to diverse farmer profiles; (ii) offer tax incentives and subsidies for key technologies; (iii) establish certification programs to help farmers identify reliable solutions; (iv) conduct regional diagnostics to identify local adoption barriers; (v) develop comparison tools for tech cost–benefit analysis and support access; (vi) support incubators and accelerators to develop farmer-centric technologies; (vii) promote pilot projects to allow low-risk tech trials; and (viii) provide funding and venture capital for scalable, problem-solving innovations.

4.2.4 Social cluster

Deficiencies in education and training considerably limit adoption among non-users. This subsection highlights the need for capacity-building programs and knowledge dissemination initiatives tailored to new and potential users.

B16 – Problems in Education (4.06): Training is crucial to overcome this barrier. Agricultural extension divisions and NGOs should incorporate agriculture 4.0 technologies into their training programs to help farmers recognize their benefits (Arthur et al., 2024). Suggested actions include: (i) expand training for extension workers to disseminate agriculture 4.0 knowledge to vulnerable farmers; (ii) encourage peer learning through exchanges and technical visits between farmers; (iii) establish partnerships between governments, companies, and universities to create agriculture 4.0 curriculum; (iv) implement mobile agricultural training schools in remote areas; (v) support startups and incubators developing educational solutions for agriculture 4.0; and (vi) provide free audio and video educational materials to ensure greater learning accessibility.

4.2.5 Environmental cluster

Skepticism regarding the reliability of environmental data and technology effectiveness often characterizes non-adopters. This subsection discusses perception challenges and accessibility issues related to environmental information that impede first-time use.

B22 – Lack of Effectiveness in Rural Data (4.17): Agrometeorological models need constant updates, but current models already have high accuracy. The issue may lie more in farmers' perceptions than in the technology itself, as many have not used these tools to verify their effectiveness. A key factor influencing adoption is whether these technologies are reliable and deliver the promised results (Georgopoulos et al., 2023). Suggested approaches to overcome this barrier include: (i) installing low-cost weather stations and soil sensors in rural areas for more accurate, localized data; (ii) using AI and machine learning to improve the accuracy of agrometeorological models and predict weather more reliably; (iii) creating incentive programs to facilitate access to agricultural sensors and software; and (iv) implementing pilot projects and experimental farms to demonstrate the effectiveness of data generated by agriculture 4.0 technologies.

4.3 Unequal technological trajectories: overcoming challenges and fostering synergies

The results of this analysis demonstrate that the adoption of agriculture 4.0 technologies within the Brazilian agri-food system should be understood as an evolutionary and dynamic process, whose pace and intensity vary according to the specific challenges and contexts faced by each group. It is a trajectory marked by obstacles that transform as technological maturity advances in the sector. Both groups—TAFs and NTAFs—face similar structural and educational barriers, such as the lack of quality connectivity and technical training, indicating that without adequate infrastructure and robust educational policies, there is no foundation for effective technological transformation for farmers. The analysis also examined the relationships between perceptions of barriers and enablers, clustering both sets of factors, which provided deeper insights into how these elements interact and influence farmers' adoption trajectories.

In this scenario, solutions developed for one group can benefit the other synergistically: TAFs, by accumulating successful experiences and strategies in technology use, can share this knowledge with NTAFs through mentorship, cooperative networks, and practical demonstrations. At the same time, the challenges faced by NTAFs provide valuable insights to adapt technologies to more demanding realities, enriching the innovation process with concrete demands from the field. Practices such as shared use of equipment and technologies, formation of local networks, and creation of territorially based innovation hubs have the potential to build trust among NTAFs and deepen TAFs engagement, while also reducing technological and social isolation.

However, it is crucial to recognize that despite these synergies, the distinct trajectories of the groups require specific responses. While TAFs progress in optimizing and expanding technology use, NTAFs face the challenge of breaking the cycle of digital exclusion and taking the first steps toward digital transformation. Therefore, overcoming these barriers depends on the articulation of integrated and flexible public policies that acknowledge the specificities and diverse needs of each group. Inclusive economic models and collaborative, farmer-centered approaches should both foster cooperation between groups and develop customized solutions for unique challenges.

Thus, the key to scaling agriculture 4.0 equitably within the agri-food system lies in breaking exclusion cycles through co-creative, regionally adapted, and institutionally coordinated strategies that promote real and sustainable inclusion, respecting farmer diversity and ensuring balanced and continuous progress.

4.4 Implications for stakeholders in the agri-food system

This research provides insights for more equitable adoption of agriculture 4.0 technologies. Key points for stakeholders include:

- Addressing the barriers and solutions to agriculture 4.0 adoption is crucial for effectively managing the ongoing evolution and complexities of these technologies. The study identifies key barriers for two farmer groups (TAF and NTAF) and proposes deployment solutions, using Kendall's correlation and variance analysis to highlight significant variables in farmer behavior.
- The study categorizes 25 critical barriers into five clusters, offering a detailed analysis of how these barriers are perceived by TAF and NTAF farmers. Policymakers can use this understanding to develop strategies that address the distinct needs of each group, with some strategies requiring more engagement than others.
- While analyzing all 25 barriers is complex, the study focuses on those most relevant to each farmer group and proposes solutions. The research is based on farmers in RS but can be extended to other regions and agricultural sectors.
- The study offers guidance for policymakers to implement agriculture 4.0 technologies effectively, especially considering less privileged farmers (NTAF). It also supports the "Semear Digital" initiative, which aims to increase productivity among small and medium-sized Brazilian farmers, and can serve as a reference for other countries facing similar adoption challenges.
- This research helps various stakeholders—including academics, governments, companies, startups, banks, cooperatives, and farmers—develop strategies for transitioning to a modern agri-food system, addressing global food security challenges. The study is innovative in differentiating barriers faced by TAF and NTAF farmers and offers a model that can be adapted internationally.

5 Conclusion

The advent of agriculture 4.0 brings several advantages for those who embrace it. Regardless of the size of their farm, many farmers strive to adopt the main technologies of agriculture 4.0 in the agri-food system and reap its benefits. Despite the clear opportunities provided by adopting agriculture 4.0 technologies, farmers face a series of challenges in their effective implementation, and the reality perceived by one is not always the same for another. Therefore, to help developing countries, especially Brazil, motivate and promote a more inclusive adoption of emerging technologies in the agri-food system, this study analyzes the behavioral profile of farmers in RS regarding the barriers that hinder the adoption of agriculture 4.0 technologies. A sample of 198 farmers distributed across the seven mesoregions of RS was divided into two groups: TAF—Technology Adopter Farmer ($n = 70$) and NTAF—Non-Technology Adopter Farmer ($n = 128$). The results provide a holistic analysis of the perception of barriers in these two groups of farmers.

For TAFs, the most critical barriers were concentrated in the following areas:

- Technological cluster: *B4 – Lack of Infrastructure* (4.36) and *B1 – Technological Complexity (4.17)*;
- Economic cluster: *B9 – Lack of Affordable Solutions for Farmers* (4.49);
- Political cluster: *B12 – Lack of Farm and Farmer-Centered Approaches* (4.14);
- Social cluster: *B16 – Problems in Education* (4.49) and
- Environmental cluster: *B22 – Lack of effectiveness in Rural Data* (4.40) and *B21 – Influence of Climate and Weather on New Technologies (rain, sun, wind)* (4.14).

For NTAFs, the key barriers included:

- Technological cluster: *B4 – Lack of Infrastructure* (3.90);
- Economic cluster: *B9 – Lack of Affordable Solutions for Farmers* (4.11) and *B6 – High Cost of Facility Maintenance (4.06)*;
- Political cluster: *B15 – Need to Promote R&D (Research and Development) and Innovative Business Models* (3.87) and *B13 – Need for an Action Plan for Implementation of Agriculture 4.0 Technologies (3.77)*;
- Social cluster: *B16 – Problems in Education* (4.06); and
- Environmental cluster: *B22 – Lack of Effectiveness in Rural Data* (4.17).

The study further revealed that only two variables—farm size and level of understanding of the term "agriculture 4.0"—presented statistically significant differences between TAF and NTAF groups (p-value < 0.005). These findings underscore the relevance of tailored communication strategies and capacity-building initiatives to bridge the knowledge and adoption gap between farmer profiles.

Drawing on this evidence, the study advances a set of practical recommendations aimed at overcoming the specific barriers identified for each group. These proposals are intended to foster a broader and more effective integration of agriculture 4.0 technologies within agri-food systems—particularly in emerging economies such as Brazil, where regional and structural disparities can hinder inclusive digital transformation.

While this research is grounded in the Brazilian context, the insights it provides hold relevance for other developing countries facing comparable challenges. By illuminating the behavioral and structural dynamics underlying emerging technology adoption, the study contributes to the global discourse on inclusive innovation in agri-food systems.

Future research should build on these findings by:

i Conducting longitudinal studies to track changes in adoption behavior and perceptions of barriers over time—including the duration of technology use, potential abandonment, and transitions between adoption profiles (TAF and NTAF)—while also examining how institutional, political, and educational factors influence these trajectories;
ii Assessing the effectiveness of targeted intervention strategies, such as customized policy incentives, educational and training programs, and technical support mechanisms designed to meet the distinct needs of each group; and
iii Undertaking comparative cross-country analyses to explore how socio-political, economic, and infrastructural differences influence agriculture 4.0 adoption patterns, thereby informing more context-sensitive and evidence-based policy frameworks.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the patients/participants OR patients/participants legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

FS: Formal analysis, Supervision, Writing – review & editing, Project administration, Methodology, Data curation, Writing – original draft, Software, Resources, Investigation, Visualization, Funding acquisition, Conceptualization, Validation. RC: Software, Investigation, Data curation, Visualization, Writing – review & editing, Methodology, Validation, Formal analysis, Writing – original draft. IB: Formal analysis, Methodology, Visualization, Writing – original draft, Validation, Writing – review & editing. RL: Resources, Writing – original draft, Visualization, Validation, Data curation, Writing – review & editing. JB: Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Visualization, Resources, Validation, Project administration.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Correction note

A correction has been made to this article. Details can be found at: 10.3389/fsufs.2025.1702988.

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