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Agricultural sustainability index in Brazil

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ABSTRACT

Agriculture faces the challenge of increasing food production while reducing environmental impacts like soil erosion and greenhouse gas emissions. This study introduces a comprehensive Agricultural Sustainability Index for Brazil, integrating economic, social, and environmental indicators. The quantitative index includes seven environmental indicators (e.g., Burned Area, Carbon Loss, Soil Erosion), five social indicators (e.g., Education, Gender Inequality, Land Distribution), and five economic indicators (e.g., Credit Access, Economic Income, Infrastructure). Results show that Agricultural Sustainability Index values range from 0.12 to 0.67, with a mean and median of 0.42. Since 1 represents the highest sustainability and 0 the lowest, half of Brazil's municipalities fall below 0.42, indicating room for improvement. Municipalities in the South and Southeast perform better, while those in the North and Northeast face economic constraints and lower scores. Environmental challenges are particularly significant in the Pantanal and Cerrado biomes. These findings emphasize the need for region-specific strategies and infrastructure improvements. Future research should refine the index and incorporate dynamic factors like climate change to enhance agricultural sustainability in Brazil.

1. Introduction

The escalating global environmental challenges—such as climate change, biodiversity loss, and resource degradation—draw attention to the urgent need for sustainable agricultural development (Agnusdei and Coluccia, 2022; Ali and Ali, 2023). Agriculture, a major driver of these issues, faces increasing pressure to enhance food production for a growing population while combating its own environmental impacts, including soil erosion and greenhouse gas emissions (KC et al., 2018). Intensive resource use, inadequate agricultural practices, and the uncontrolled expansion of agricultural areas result in significant negative impacts, such as soil erosion, water body contamination, and greenhouse gas emissions, rendering the agricultural system unsustainable (Pretty et al., 2018). To address these challenges, adopting sustainable agricultural practices is crucial for ensuring food security, preserving ecosystems, and mitigating climate change effects (Ali and Ali, 2023).

In 2015, 193 countries committed to achieving the 17 United Nations Sustainable Development Goals (SDGs), aiming for transformation across social, economic, and environmental aspects, as outlined by the 2030 Agenda (Xu et al., 2020). Although Brazil is globally recognized as one of the largest food producers and exporters, representing 50 % of global food trade in 2023 (USDA PSD, 2024), the country has not shown satisfactory progress in meeting the targets of the 17 SDGs of the 2030 Agenda, established by the United Nations General Assembly in 2015. Of the 169 targets, 54.4 % are regressing, 16 % are stagnant, 12.4 % are threatened, and 7.7 % show insufficient progress (CSWG, 2021).

The formulation of sustainable rural development policies depends on territorial analyses at different scales, where ecological processes occur, and decisions are made (Bjørn et al., 2019). While some processes operate globally, such as climate change, others act at regional levels, but their cumulative impacts can generate significant responses globally (e.g., alterations in biogeochemical cycles, contamination of water sources, soil degradation, reduced agricultural productivity) (Rockström et al., 2009). The development of technological tools that diagnose and evaluate territorial limits of ecological processes and social well-being conditions has been extensively explored in national governance,

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simplifying complex dynamics and providing clear and accessible quantitative metrics for decision-makers (Fang et al., 2015; X. Zhang et al., 2021).

Especially in Brazil, being a continental country, there are distinct trajectories and patterns of land use and occupation in each region (Safanelli et al., 2023; C.M. Souza et al., 2020), as well as different legal protection requirements (Tavares et al., 2019) and extents of protected areas. In this sense, the creation of such tools is fundamental for guiding land use planning and sustainable rural development policies, directing efforts and resources towards environmental protection, and quantifying, predicting, and mediating possible impacts arising from changes in ecological processes.

These potentials can be observed, for example, in the work of Cole et al. (2014), who developed an assessment methodology based on adapting the Planetary Boundaries and their Social Dimensions approach to the national scale, creating a"*sustainability thermometer*" for South Africa, encompassing 20 indicators of environmental stress and human deprivation. This product was evaluated by a panel of 43 experts, including national, provincial, and metropolitan government officials, national research institutes, universities, and international non-governmental organizations. The "*sustainability thermometer*" was deemed valid and useful in supporting the country's National Development Plan, serving as an important starting point for further refinement of the tool through dialogue among scientists, civil society, and government. Its specific uses include identifying gaps in underlying databases and knowledge, as well as raising new questions in the national discourse on social deprivation and environmental sustainability.

Another example of a similar tool was developed by the United Nations. In this case, a set of analytical modeling tools was created by the United Nations Department of Economic and Social Affairs within the context of the 2030 Agenda for Sustainable Development, the United Nations Development Programme. This set of tools tracks the complex interactions of different dimensions of sustainable development. Countries are using these tools to advance the SDGs, such as achieving sustainable economic growth, combating climate change, and promoting social inclusion. >240 topics are presented with indicators related to the 17 SDGs, many of them containing sub-indicators, resulting in a structure with over 300 indicators. However, the general focus still allows for specific delimitations for agriculture and the particular characteristics of countries and regions of the world, as exemplified in the quantitative framework by Zhang et al. (2021) for evaluating sustainability in agriculture.

In Brazil, it is crucial to advance the development of databases, analytical techniques, and artificial intelligence for territorial monitoring and management, as well as other technologies for sustainable development evaluation, action planning, socio-environmental projects, and law establishment, among others. In this context, quantifying sustainability in Brazilian agricultural indices is highly relevant, considering the country's central role in global agriculture. This study allows for the assessment and mitigation of environmental and social impacts, such as deforestation and the well-being of rural communities. Therefore, rigorous measurement of sustainability not only addresses environmental concerns but also strengthens Brazil's position as a key player in the global agricultural landscape, contributing to a more resilient and equitable agricultural system.

This study aims to develop an Agricultural Sustainability Index for Brazil by integrating quantitative factors across economic, social, and environmental dimensions to provide a comprehensive measure of sustainability. By creating this index, we seek to provide a comprehensive tool for assessing sustainability at the municipal level, thereby supporting targeted policies and programs aligned with sustainable development goals. This approach will improve decision-making, guide land use planning, and contribute to more resilient and equitable agricultural systems in Brazil.

2. Material and methods

The Sustainable Agriculture Matrix (SAM), proposed by X. Zhang et al. (2021), is a comprehensive quantitative framework designed to assess the sustainability impacts of agricultural production across environmental, economic, and social dimensions. SAM provides an integrated structure for a thorough evaluation of agricultural sustainability in various contexts.

In this study, the SAM framework was utilized to calculate the *Agricultural Sustainability Index* (ASI) across Brazil, encompassing its vast area of 8.5 million km^2, six biomes, and 5570 municipalities. The *Agricultural Sustainability Index* was constructed at the municipal level. SAM operates through specific indicators selected based on their scientific and practical relevance, data availability, and consistent measurability across different regions and over time. The choice of indicators was based on the literature. As reported by Lafortune et al. (2018), the 2018 SDG Index and Dashboards Reports prioritize official indicators endorsed by the UN Statistical Commission, while also incorporating metrics from both official and non-official providers to fill data gaps when necessary. The selection of these indicators is based on five main criteria: global relevance and applicability to different national contexts, statistical adequacy, timeliness, data quality, and coverage, which is defined as data availability for at least 80 % of countries with a population over 1 million. These criteria ensure that the indicators are internationally comparable, valid, and reliable for monitoring progress towards the SDGs (Lafortune et al., 2018). The methodological approach for this study is based on quantitative analysis, utilizing sustainability indicators quantified by official agencies as the foundation for the SAM framework, as described below.

The decision to utilize municipal-level data for the ASI was based on the availability of most economic, social, and environmental indicators, which are often reported at this scale. This spatial resolution allows for a detailed assessment of sustainability challenges and opportunities specific to each municipality, such as variations in land use, agricultural practices, and local governance. Additionally, the municipal scale corresponds to the administrative level at which many agricultural policies are implemented in Brazil, ensuring greater relevance for policy application. However, certain sustainability indicators, such as soil erosion, are available at finer spatial scales. Advancing this index to a more detailed spatial scale will depend on national census efforts to provide data below the municipal level to better capture local indicators dynamics.

According to Jiang et al. (2022), the index structure should address the three classic dimensions of sustainability: social equity, economic development, and environmental protection. Therefore, it is essential to select indicators that represent each of these dimensions, preferably those with detailed spatial sources over traditional statistical indicators. Examples include inequalities in resource distribution, educational status, employment rates, greenhouse gas emissions, and land cover data.

For this study, we began with a search of existing public and reliable databases. We then defined the indicators for the three dimensions of sustainability:

- **Environmental:** The environmental dimension of the Agricultural Sustainability Index comprehensively assesses the ability of Brazilian municipalities to sustain agricultural practices that preserve natural resources and minimize environmental impacts. Indicators such as soil erosion, burned areas, and carbon loss are critical for measuring soil degradation and ecosystem quality, directly reflecting environmental sustainability. The reliance on external inputs, such as fertilizers and pesticides, indicates the sustainability of agricultural practices, with lower dependence suggesting more sustainable methods. CO_2e emissions provide a crucial indicator for evaluating the contribution of agricultural practices to climate change. Crop diversity reflects agricultural concentration, an important factor for the resilience of agricultural systems. Additionally, organic farming promotes soil health and reduces chemical pollution, serving as a positive indicator of environmental sustainability. Further details on each of the indicators that comprise this environmental dimension can be found in the Supplementary Material.

- **Social:** The social dimension of the agricultural sustainability index provides an assessment of how agricultural practices impact the quality of life and well-being of rural communities. Key indicators include child malnutrition, which reflects food security and the health of children, emphasizing the importance of sustainable agricultural practices in ensuring proper nutrition. Electricity access serves as an indicator of the development and quality of rural infrastructure, which is essential for improving living conditions. Average schooling is crucial for measuring human capital and the capacity to adopt new technologies and practices, directly affecting rural community progress. Additionally, land distribution as measured by the Gini Index highlights the concentration of land ownership, pointing to issues of inequality and land access, which are vital for social sustainability in the agricultural sector. Together, these indicators offer a broad understanding of the social impacts of agricultural practices and their implications for rural development and equity. Further details on each of the indicators that comprise this social dimension can be found in the Supplementary Material.
- **Economic:** The economic dimension of the Agricultural Sustainability Index assesses the economic viability of agricultural systems in Brazilian municipalities. The Price volatility indicator consists of the price volatility in the agricultural market, reflecting its stability and the economic security of farmers. Additionally, access to credit is crucial for farmers' ability to invest in sustainable technologies and practices. Commercial openness to exports demonstrates the integration of municipalities into the global market, influencing both competitiveness and market diversification. Another important aspect is the agricultural GDP per capita, which provides an indicator of economic yield. Finally, infrastructure, which is represented by the essential facilities for product commercialization, contributes to the economic viability of agricultural systems. Further details on each of the indicators that comprise the economic dimension can be found in the Supplementary Material.

2.1. Selected sustainability indicators

The selection of indicators was based on the availability of Brazilian public data at the municipal level, always using the most recent data available. Seventeen indicators were chosen to compose the index, distributed across seven environmental, five social and five economic indicators (Fig. 1).

In Table 1, we present a brief description of each indicator and how each one was obtained. More details can be found in Supplementary Material.

For each indicator listed in Table 1, when official data were not reported for a given municipality—such as in the case of Commercial Openness—we assumed that the municipality did not engage in the corresponding activity. Therefore, municipalities without reported data for a specific indicator were assigned a value of zero for that indicator.

2.2. Agricultural sustainability index in Brazil

Each indicator underwent standardization to a 0 to 1 scale using the Minimum-Maximum normalization technique (EQ. (1)). This method guarantees that each indicator contributes equally to subsequent

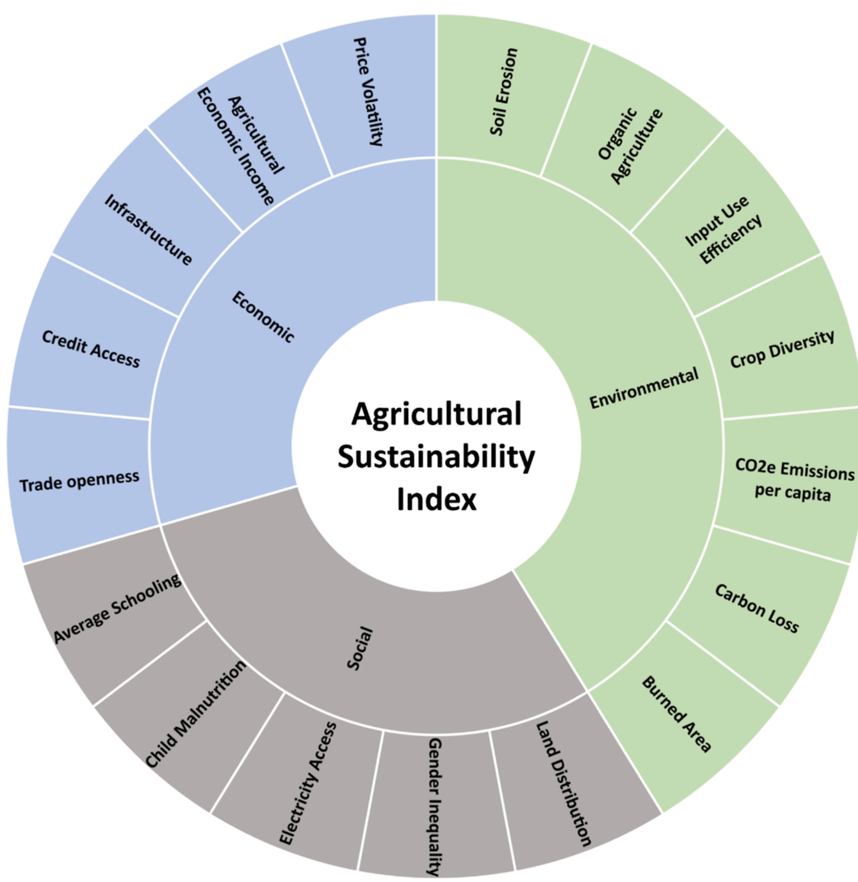

Fig. 1. Agricultural sustainability index. Environmental, social, and economic variables for the Municipal Agricultural Sustainability Index in Brazil, adapted from X. Zhang et al. (2021).

Table 1
Overview of indicators for the agricultural sustainability index.

Dimension	Indicator	Description	Calculation/Data Sources
Environmental $i = 1$	**Burned Area** $j = 1$	Measures the extent of burned areas using Landsat images and supervised classification algorithms. Spatial distribution shown in Supplementary Figure S1.	Calculation: Five-year average of burned areas (2015–2020). Data Sources: MapBiomas Fire project (MapBiomas, 2022).
	Carbon Loss $j = 2$	Measures the reduction in soil carbon stocks between 1985 and 2021. Spatial distribution shown in Supplementary Figure S2.	Data Sources: Maps from the "Annual Mapping of Soil Organic Carbon Stock in Brazil 1985–2021″ by MapBiomas (2023), high-resolution satellite images, legacy soil data, digital soil mapping techniques and machine learning were used to determine soil carbon stocks.
	CO2e Emissions per Capita $j = 3$	Measures gross CO2 equivalent emissions (tons of CO2e per capita) using the GWP-AR5 standard. Spatial distribution shown in Supplementary Figure S4.	Data Sources: SEEG by the Climate Observatory, based on the Brazilian Greenhouse Gas Emissions and Removals Inventory.
	Crop Diversity $j = 4$	Indicates the diversity of crop cultivation within a municipality. Spatial distribution shown in Supplementary Figure S5.	Calculation: this index is the sum of the planted areas of the two main crops. Data Sources: 2024 Municipal Agricultural Production data (IBGE, 2024).
	Input Use Efficiency $j = 5$	The input use efficiency indicator assesses the relationship between fertilizer use and the increase in productivity for different crops within a municipality. Spatial distribution shown in Supplementary Figure S3.	The Input Use Efficiency indicator is calculated as the weighted average of the correlation between the variation rate of fertilizer use and productivity for different crops within a municipality.
	Organic Agriculture $j = 6$	Indicates the percentage of agricultural establishments practicing organic farming. Spatial distribution shown in Supplementary Figure S7.	Data Sources: 2017 Agricultural Census from the Brazilian Institute of Geography and Statistics (IBGE)
	Soil Erosion $j = 7$	Represents the average soil lost per municipality over 20 years (2002–2021). The soil loss was calculated in tons per square kilometer. Calculated using the Revised Universal Soil Erosion Equation (RUSLE). Spatial distribution shown in Supplementary Figure S1.	The calculation of soil loss was performed using the Revised Universal Soil Loss Equation (RUSLE). Calculation: $A = R \times K \times LS \times C \times PA$. These factors were defined based on remote sensing products, available climate information from the Data Sources: Climatic data from WorldClim BIO V1, soil texture maps, digital elevation models (STRM) and MODIS satellite images.
Social $i = 2$	**Average Schooling** $j = 1$	Average years of schooling of farmers. Spatial distribution shown in Supplementary Figure S15.	Calculation: Based on responses to the 2017 Agricultural Census, converted to years of education. Data Sources: 2017 Agricultural Census (IBGE, 2017).
	Child Malnutrition $j = 2$	Percentage of children under 5 years old who are malnourished based on BMI (Weight x Age) below the 0.1 percentile. Spatial distribution shown in Supplementary Figure S13.	Data Sources: SISVAN from the Ministry of Health (Ministry of Health, 2023).
	Electricity Access $j = 3$	Percentage of agricultural establishments with access to electricity. Spatial distribution shown in Supplementary Figure S14.	Data Sources: 2017 Agricultural Census (IBGE, 2017).
	Gender Inequality $j = 4$	The Gender Wage Gap Indicator in the agricultural sector in Brazil measures the hourly wage disparity between men and women, controlling for variables such as race, education, employment duration, and job position. Spatial distribution shown in Supplementary Figure S17.	The indicator uses a multiple linear regression model, based on the adapted Oaxaca decomposition, to analyze the gender wage gap in the agricultural sector, considering variables such as race, education, employment duration, and job position, based on data from RAIS 2022.
	Land Distribution $j = 5$	Gini Index for Agricultural Land Inequality, where 0 represents perfect equality and 1 represents maximum inequality. Spatial distribution shown in Supplementary Figure S16.	Calculation: Based on the Lorenz curve using data from the 2017 Agricultural Census. Data Sources: 2017 Agricultural Census (IBGE, 2017).
Economic $i = 3$	**Commercial Openness** $j = 1$	Measures the export activities of	Calculation: Average

(continued on next page)

Table 1 (*continued*)

Dimension	Indicator	Description	Calculation/Data Sources
		municipalities. Spatial distribution shown in Supplementary Figure S11.	agricultural exports from 2019 to 2023. Data Sources: SECEX database (Secretariat of Foreign Trade, 2023).
	Credit Access $j = 2$	Total rural credit granted in each municipality. Spatial distribution shown in Supplementary Figure S10.	Data Sources: Various financial institutions providing rural credit data (BACEN, 2024).
	Economic Income $j = 3$	Assesses the economic efficiency of the agricultural sector in Brazilian municipalities by relating the Agricultural Value Added to the number of people employed in the sector. Spatial distribution shown in Supplementary Figure S12.	Calculation: Agricultural Value Added per people employed in the agricultural sector. Data Sources: 2017 Agricultural Census (IBGE, 2017).
	Infrastructure $j = 4$	Assesses the presence of agricultural commercialization and exhibition facilities. Spatial distribution shown in Supplementary Figure S9.	Calculation: Principal Component Analysis (PCA) of the presence of various infrastructures. Data Sources: 2020 MUNIC survey (IBGE, 2020).
	Price volatility $j = 5$	Evaluates the price volatility of agricultural commodities. Spatial distribution shown in Supplementary Figure S8.	Calculation: Standard deviation of monthly price variations, weighted by the planted area proportion. Data Sources: CEPEA, Notícias Agrícolas, Consecana PR, PAM 2024 (IBGE, 2024).

SEEG: Greenhouse Gas Emissions and Removals Estimation System; CR2 Index: Crop diversification Index; SISVAN: Food and Nutrition Surveillance System; CEPEA: Center for Advanced Studies in Applied Economics; PAM: Municipal Agricultural Survey; MUNIC: Municipal Basic Information Survey; SECEX: Secretariat of Foreign Trade.

analyses, neutralizing the impact of varying magnitudes and units.

$$Y_{i,j,k} = \frac{X_{i,j,k} - \min(X_{i,j})}{\max(X_{i,j}) - \min(X_{i,j})} \quad (1)$$

Where $Y_{i,j,k}$ and $X_{i,j,k}$ are the normalized value (between 0 and 1) and observed value of indicator j , according to dimension i , for municipality k ; and $\min(X_{i,j})$ and $\max(X_{i,j})$ are the minimum and maximum observed values of indicator j , according to dimension i (TABLE 1).

Standardized indicator values near zero denote locations with reduced sustainability, whereas values approaching one signify locations with enhanced sustainability. The index for each environmental, social, and economic dimension is derived from the arithmetic mean of the normalized indicators specific to that dimension, as outlined in Eq. (2).

$$D_{i,k} = \frac{1}{n_i} \sum_{j=1}^{n_i} Y_{i,j,k} \quad (2)$$

Where $D_{i,k}$ is the value of dimension i (environmental - $i = 1$, social - $i = 2$ and economic - $i = 3$) for municipality k , n_i is the number of indicators in each dimension (environmental - $n_1 = 7$, social - $n_2 = 5$ and economic - $n_3 = 5$ - dimension) (TABLE 1).

To minimize penalization of municipalities with robust local economies but low export rates, the market access variable's weight was adjusted in the Economic Indicator calculation. Specifically, the indicator was derived as the weighted average of five economic sub-indicators, with a weight of 0.1 assigned to market access and 0.225 to each of the remaining sub-indicators.

The Agricultural Sustainability Index (ASI) is determined by the geometric mean of three dimensions: environmental ($i = 1$), social ($i = 2$), and economic ($i = 3$), as shown in Eq. (3). This method reduces the effect of outliers, preventing any single dimension from skewing the overall index, thus offering a comprehensive performance assessment.

$$ASI_k = \sqrt[3]{\prod_{i=1}^{3} D_{i,k}} \quad (3)$$

Where ASI_k is the Agricultural Sustainability Index for municipality k .

To assess sustainability across Brazilian biomes, a distinct indicator has been created for each biome. This indicator is derived by averaging the municipal indicators across environmental, social, and economic dimensions for each biome, mirroring the approach taken for the municipal indices.

$$B_{i,b} = \frac{1}{n_i} \cdot \frac{1}{q_b} \cdot \sum_{k=1}^{q_b} \sum_{j=1}^{n_i} Y_{i,j,k} \quad (4)$$

$$ASI_b = \sqrt[3]{\prod_{i=1}^{3} B_{i,b}} \quad (5)$$

Where is the dimension i index (environmental - $i = 1$, social - $i = 2$, and economic - $i = 3$ - dimension) for biome b , q_b is the number of municipalities in each biome b (Amazon - $b = 1$, Caatinga - $b = 2$, Cerrado - $b = 3$, Atlantic Forest - $b = 4$, Pantanal - $b = 5$ and Pampas - $b = 6$ - biome), ASI_b is the Agricultural Sustainability Index for biome b . The equal-weight approach to calculating the ASI followed the quantitative framework by Zhang et al. (2021) for evaluating sustainability in agriculture.

3. Results

3.1. Spatial distribution of the agricultural sustainability index in Brazil

The Agricultural Sustainability Index ranges from 0 to 1, with 0 representing the locations with the lowest sustainability values and 1 representing the most sustainable locations (Fig. 2). In Brazil, the Agricultural Sustainability Index varied from a minimum value of 0.12 to a maximum value of 0.67, with a mean and median of 0.42. In 80 % of Brazilian municipalities, the index values range between 0.32 (10th percentile) and 0.52 (90th percentile). Overall, municipalities in the South and Southeast regions exhibited higher Agricultural Sustainability Index values, largely greater than 0.5, whereas those in the North and Northeast regions had lower values, often ranging between 0.3 and 0.4.

When stratifying the Agricultural Sustainability Index into its three dimensions—environmental (Fig. 3a), social (Fig. 3b), and economic (Fig. 3c)—it is revealed that the economic dimension is the most limiting for the majority of Brazilian municipalities. Specifically, the economic dimension ranged from values close to 0.01 up to 1.0, with a mean and median close to 0.27. For the economic dimension (Fig. 3a), in 80 % of

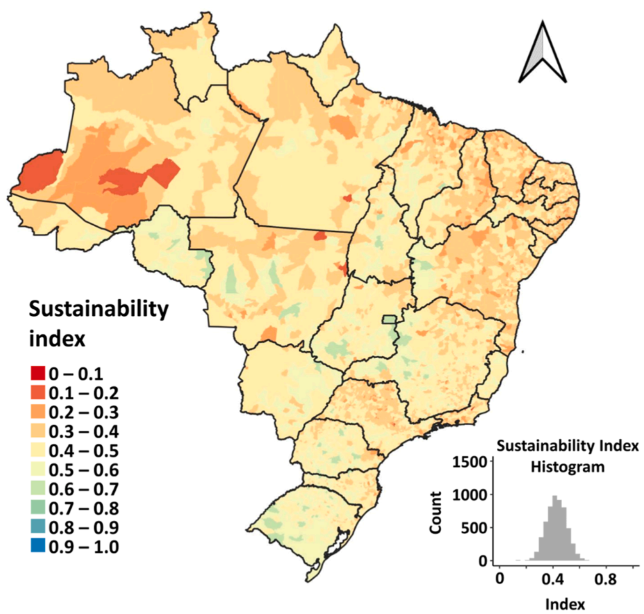

Fig. 2. Agricultural Sustainability Index (ASI) in Brazil. The Agricultural Sustainability Index was computed across all 5570 municipalities in Brazil. This index was derived from 17 specific indicators that cover the three dimensions of sustainability: Environmental, Economic, and Social. The 17 indicators were chosen to compose the index, distributed as follows: seven environmental, five social and five economic indicators (Fig. 1). The inset shows the histogram with the distribution of the Agricultural Sustainability Index across all Brazilian municipalities.

Brazilian municipalities, the values range between 0.14 (10th percentile) and 0.42 (90th percentile). The lowest economic dimension values are found in the Northeast and Southeast regions of Brazil. The highest indices were found in the western part of the state of Bahia and the central part of the state of Mato Grosso.

The social (Fig. 3b) and environmental indices (Fig. 3c) have similar distribution ranges, with a mean and median close to 0.55, and in 80 % of Brazilian municipalities, the values range between 0.40 (10th percentile) and 0.70 (90th percentile). However, there is a considerable difference in the spatial distribution of the social and environmental indices. The social dimension (Fig. 3b) is lower in northern Brazil, mainly in areas where the Amazon rainforest is preserved, contrasting with the high environmental dimension values in these regions. Low social dimension values are also observed in the Northeast, particularly in the states of Bahia and Maranhão. The highest social dimension values are in the South, Southeast, and Central-West regions, especially in Espírito Santo, southern Minas Gerais, and Goiás. The state of Mato Grosso stands out negatively concerning the environmental dimension (Fig. 3c). Low values of this dimension are also observed in southern Pará and southern Amazonas.

3.2. Agricultural sustainability index in Brazilian biomes

We also analyzed the sustainability index and their economic, social, and environmental dimensions, considering their respective means across the six Brazilian biomes: Amazon, Caatinga, Pantanal, Atlantic Forest, Cerrado, and Pampas (Fig. 4). This analysis reveals significant variations in all indices between the Brazilian biomes. The economic dimension, which has the lowest average among the biomes, has the lowest mean value in the Pantanal at 0.12, while in the Pampas in the south of Brazil, the mean value is 0.41. Similarly, the environmental dimension also has its lowest value in the Pantanal, at 0.34, while the difference between all other biomes for this dimension is very small, ranging from 0.53 in the Atlantic Forest to 0.57 in the Caatinga. The social indicator, in contrast, has the highest mean values in the Pampas and the Pantanal, both exceeding 0.6, while the Amazon is the biome with the lowest value, with a mean of 0.48. The overall indicator, synthesizing the three aspects, shows an average of 0.416. The Pampa biome stands out positively with the highest overall indicator of 0.52, though it is still only halfway to its sustainable potential, suggesting a better integration of sustainability dimensions. In contrast, the Pantanal has the lowest overall indicator, with a value of 0.3, followed by the Amazon and Caatinga, reflecting the comprehensive and interconnected challenges these regions face.

When analyzing the indicators that compose the index in each biome (Fig. 5), the lowest values in the environmental dimension are observed in the percentage of area dedicated to organic agriculture, as well as in

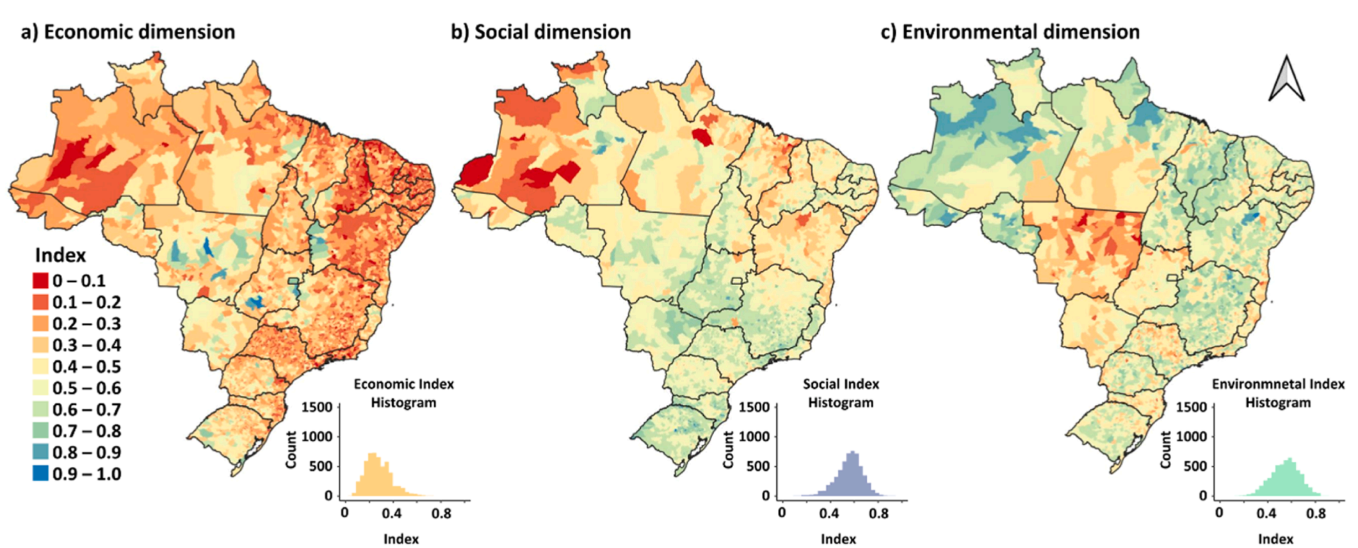

Fig. 3. Agricultural environmental, social, and economic dimensions in Brazil. Agricultural (**a**) environmental, (**b**) social, and (**c**) economic dimensions in Brazil were computed across all 5570 municipalities. The environmental dimension was composed of seven indicators: Burned Area, Carbon Loss, CO_{2e} Emissions per capita, Crop Diversity, Input Use Efficiency, Organic Agriculture and Soil Erosion. The social dimension was composed of five indicators: Average Schooling, Child Malnutrition, Electricity Access, Gender Inequality and Land Concentration. The economic dimension was composed of five indicators: Credit Access, Economic Income, Price volatility, Sales Infrastructure and Trade Openness (Fig. 1). The inset shows the histogram with the distribution of the (a) environmental, (b) social, and (c) economic dimensions across all Brazilian municipalities.

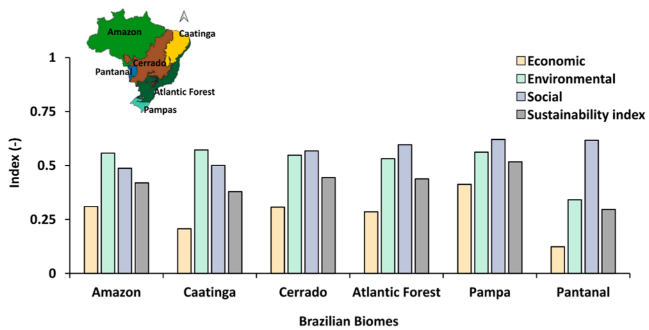

Fig. 4. Agricultural environmental, social and economic dimensions, and Agricultural Sustainability Index in the Brazilian biomes. Arithmetic means of the Agricultural environmental, social and economic dimensions, and the Agricultural Sustainability Index calculated considering the values of each index for each municipality within each of the six biomes in Brazil. The inset shows the map of the distribution of the biomes, with the Amazon biome represented in light green, Caatinga in yellow, Cerrado in brown, Pantanal in blue, Atlantic Forest in dark green, and Pampas in light blue.

the diversification of agriculture with different crops. In the Pantanal, low values are also found for burned area, soil erosion, and carbon loss (Fig. 5A). Overall, all biomes also show low values for input use efficiency (fertilizers and pesticides), with an average below 0.5 for all regions except for the Pampas, which has an average of 0.7 for this input use efficiency indicator (Fig. 5A).

Within the social dimension, across all biomes, the lowest values are related to land distribution and gender inequality indices, followed by low average schooling (i.e., education) (Fig. 5b). The highest values pertain to electricity access and child malnutrition indicators, suggesting more positive outcomes in these areas (Fig. 5b). Regarding the economic dimension, low values (below 0.3) are observed for all indicators in the Pantanal, with particularly low values (below 0.1) for commercial openness indicators, rural credit access, and economic income (Fig. 5a). Similarly, in all other Brazilian biomes, these indicators also show the lowest values compared to all other economic indicators.

3.3. Limiting factors for the agricultural sustainability index

We also analyzed the most limiting dimension factor for the Agricultural Sustainability Index, among the environmental, social and economic dimensions across Brazil (Fig. 6a). It is observed that, for most of the South, Southeast, and Northeast regions of Brazil, the most limiting factor for achieving higher values in the Agricultural Sustainability Index is the economic dimension. In the Central-West region, particularly in the states of Mato Grosso and Mato Grosso do Sul, the Agricultural Sustainability Index is more constrained by low values in the environmental indices. In the western part of Bahia and the western Amazon, the social dimension is identified as the most limiting factor for the Agricultural Sustainability Index (Fig. 6a).

A more detailed analysis was conducted for the lowest-20 and top-20 municipalities based on the Agricultural Sustainability Index within Brazil (Fig. 6). For the lowest-20 municipalities, represented by red circles in Fig. 6a, which are predominantly located in the Northeast region of Brazil, particularly in the state of Pernambuco, with some others scattered across the North and Southeast regions, we examined in detail the distribution of the indicators that compose the environmental, social, and economic dimensions. Regarding the environmental dimension, the primary limitations are the low percentage of area under organic agriculture and low crop diversity (Fig. 6b). For the social dimension, high gender inequality, low average electricity access, poor land distribution, and low average schooling levels of the population are significant limiting factors (Fig. 6c). In terms of the economic dimension, these municipalities exhibit low values across all five analyzed indicators, including limited access to credit, poor infrastructure, low economic income and high price volatility (Fig. 6d).

For the top-20 municipalities with the highest Agricultural Sustainability Index, mostly located in the South of Brazil and represented by yellow diamonds in Fig. 6a, the major limitation for achieving higher environmental indices is the low percentage of area under organic agriculture and low crop diversity (Fig. 6e). For the social dimension, the primary limitations are related to gender inequality and land distribution (Fig. 6f). For the economic dimension, the main limitations are access to credit and economic income (Fig. 6g).

4. Discussion

Among emerging countries, Brazil has distinguished itself globally, particularly due to its substantial food production capacity, a result of its vast continental dimensions (L. C. P. Dias et al., 2016; Tollefson, 2010). However, recent discussions suggest that food production and agricultural exploitation should not be pursued indiscriminately (Sparovek et al., 2019), and agriculture in Brazil is already showing some signs of collapse (Nóia-Júnior et al., 2025; Nóia Júnior et al., 2021). For instance, a recent study indicates that to achieve the full wheat yield potential under a mid-century high warming climate scenario (RCP8.5), a 52 % increase in global average yield would require a fourfold increase in fertilizer use compared to current levels (Martre et al., 2024). This increase in fertilizer use would inevitably lead to higher environmental impacts from agricultural production. The reality is that increasing global food demand necessitates greater food production without exceeding planetary boundaries, while simultaneously adapting to climate change. To address this challenge, agriculture must be sustainable. Given Brazil's vast size, it is crucial to monitor the country's sustainability. Concerns for sustainability should extend beyond the

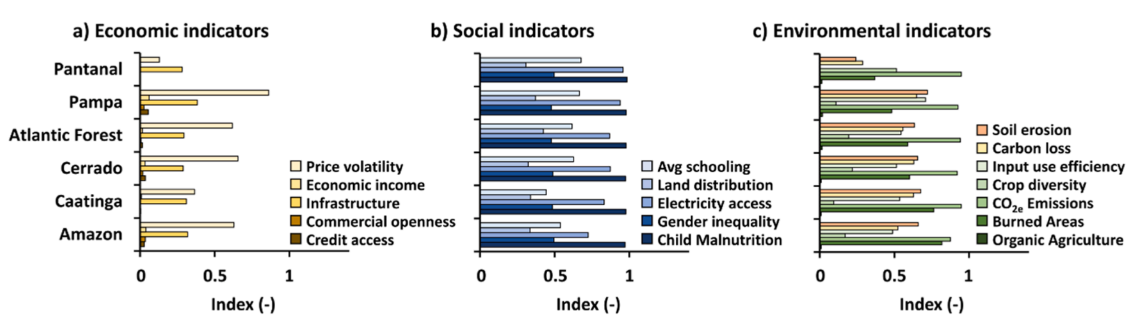

Fig. 5. Economic, Social, and Environmental indicators for each Brazilian biome. The arithmetic mean of these indicators is calculated by considering the values of each index for each municipality within the six biomes in Brazil. The environmental dimension was composed of seven indicators: Burned Area, Carbon Loss, CO_{2e} Emissions per capita, Crop Diversity, Input Use Efficiency, Organic Agriculture and Soil Erosion. The social dimension was composed of five indicators: Average Schooling, Child Malnutrition, Electricity Access, Gender Inequality and Land Concentration. The economic dimension was composed of five indicators: Credit Access, Economic Income, Price volatility, Sales Infrastructure and Trade Openness (Fig. 1).

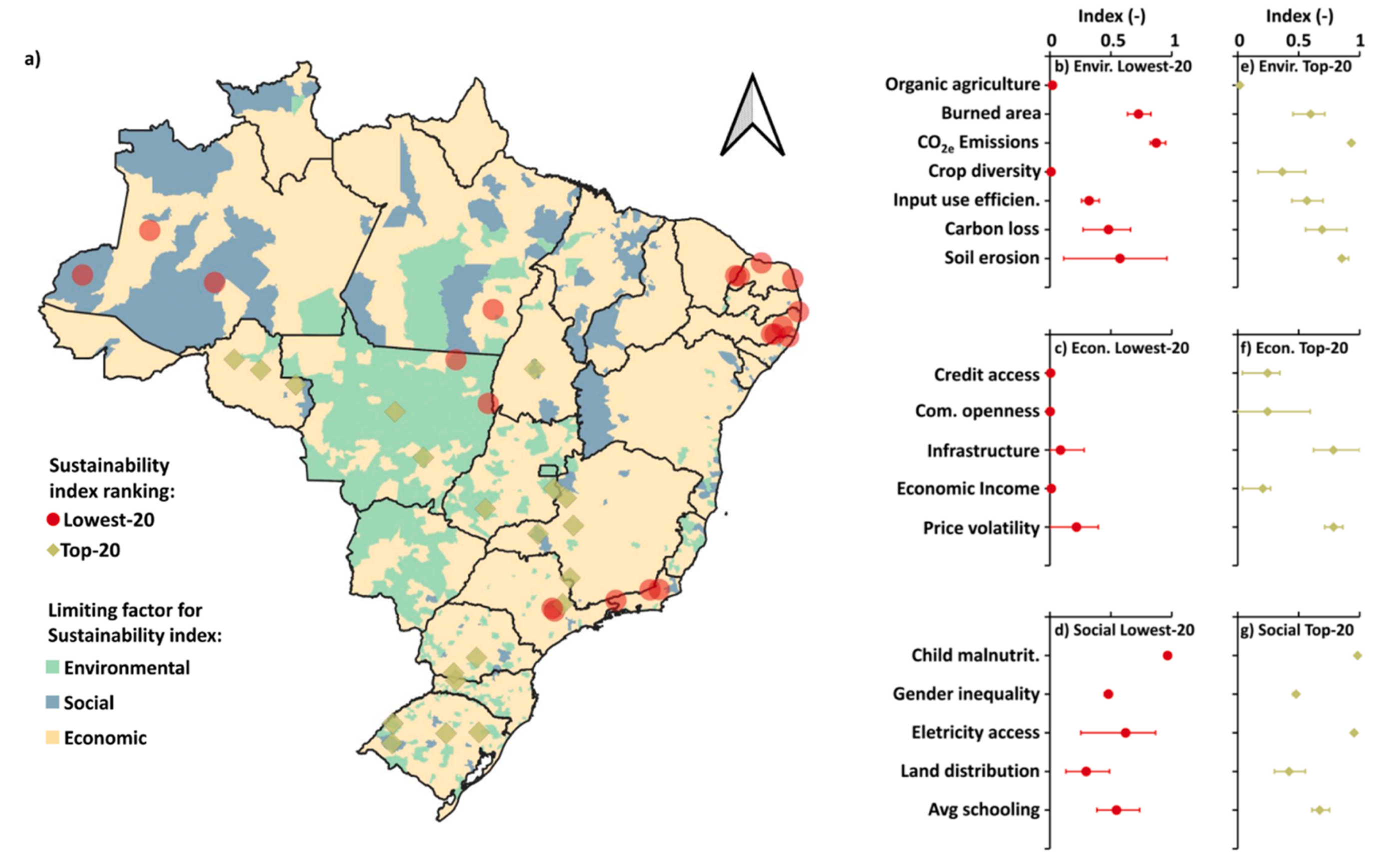

Fig. 6. Limiting Factors for Agricultural Sustainability Index in Brazil. (**a**) Spatial distribution of the most limiting factor for the Agricultural Sustainability Index. The spatial distribution of the Lowest-20 (red circles) and Top-20 (yellow diamonds) municipalities based on the Agricultural Sustainability Index is shown in (**a**). For the municipalities depicted in (**b-d**) Lowest-20 and (**e-f**) Top-20, the mean values for each indicator that composes the indices are shown: (**b** and **e**) environmental, (**c** and **f**) social, and (**d** and **g**) economic. The environmental dimension was composed of seven indicators: Burned Area, Carbon Loss, CO_{2e} Emissions per capita, Crop Diversity, Input Use Efficiency, Organic Agriculture and Soil Erosion. The social dimension was composed of five indicators: Average Schooling, Child Malnutrition, Electricity Access, Gender Inequality and Land Concentration. The economic dimension was composed of five indicators: Credit Access, Economic Income, Price volatility, Sales Infrastructure and Trade Openness (Fig. 1). In (**b-g**), the indices are represented as arithmetic means, with bars indicating the 20th percentile (lower bar) and 80th percentile (upper bar) of the data distribution within the selected 20 municipalities of each group.

environmental scope (Rosano-Peña et al., 2021)—commonly the primary focus in agricultural studies—to also include social and economic aspects of agricultural activities. In this context, the results presented in this study through the development of the Agricultural Sustainability Index in Brazil significantly contribute to advancing agricultural sustainability in the country. By quantifying current sustainability levels at a municipal scale—an approach not previously undertaken—this work provides valuable insights into the sustainability of Brazilian agriculture, supporting efforts to achieve a balanced and sustainable agricultural system.

Our results indicate significant spatial variability in the Agricultural Sustainability Index, with a low average of 0.43, a minimum value of 0.127, and a maximum of 0.675 (Fig. 2). No municipality achieved an index higher than 0.7 on a scale of 0 to 1. On this scale, 1 represents a hypothetical municipality that ranks first in Economic, Social, and Environmental indices, reflecting the potential for sustainability across all Brazilian municipalities. These results highlight that much remains to be done to achieve sustainable development, particularly in regions such as the North and Northeast of the country, where the lowest Agricultural Sustainability Index values were found. A study that assessed the suitability of Brazil for grain cultivation indicated that agricultural activity in the Brazilian Northeast is constrained by the region's low suitability for grain cultivation (Safanelli et al., 2023). This is due to the predominant climate of the central-northeast, classified by Köppen as hot and semi-arid (BSh), with annual precipitation falling below potential evapotranspiration (Alvares et al., 2017). The Brazilian Northeast, particularly the Caatinga biome, has limited resources and is primarily focused on subsistence farming (EMBRAPA TERRITORIAL, 2022). In contrast, the Northern region of Brazil, which has favorable conditions for agricultural cultivation, suffers from ongoing deforestation for agricultural purposes (Rajão et al., 2020). Despite this, the main limiting factors for sustainability in this region are social and economic (Fig. 6). We disaggregated the social, economic, and environmental components across the entire Brazilian territory and its biomes, and this is discussed in the following paragraphs.

Disaggregating the Agricultural Sustainability Index into environmental, social and economic dimensions reveals that most municipalities in the North of Brazil exhibit low values in the economic and social dimensions, resulting in a reduced overall Agricultural Sustainability Index. This region is predominantly covered by the Amazon Rainforest, which remains largely preserved, as reflected in high environmental dimension values. However, this preservation is intrinsically linked to low economic and social values, characterized by inadequate infrastructure, limited access to rural credit, low economic income, poor electricity access, gender inequality, and low educational attainment (Guedes et al., 2012). According to Dias et al. (2021), the lack of infrastructure in these areas—evidenced by insufficient paved roads and the absence of essential public services such as sanitation, education, and healthcare—perpetuates social and economic exclusion. This structural deficiency prevents the efficient integration of these municipalities into regional and national markets, hindering production flow and restricting socioeconomic development opportunities (V. M. Dias et al., 2021). However, a recent study indicates that the presence of paved roads, for example, in the Amazon may facilitate illegal deforestation, potentially triggering local, regional, or even biome-wide forest collapse (Flores et al., 2024). Nevertheless, low investment in infrastructure, which generates a range of social and economic problems as mentioned, cannot be justified solely by environmental preservation. In such cases, combating illegal environmental exploitation should be accompanied by infrastructure investment and agricultural subsidies to strengthen the local population (P. Souza et al., 2020). Educating and empowering local communities to participate in environmental protection is essential for achieving a balanced approach to sustainability (Y. Zhang et al., 2020).

Parts of the North and Central-West (parts of Amazon, Pantanal and Cerrado Biomes) regions face significant challenges related to illegal deforestation, particularly in the deforestation belt encompassing Mato Grosso do Sul, Mato Grosso, Rondônia, Amazonas, and Pará (zu Ermgassen et al., 2020). According to Skidmore et al. (2021), the lowest environmental dimension values in these regions (Fig. 6) are associated with a high number of fires, which lead to the conversion of forest areas into pastures (Safanelli et al., 2023). Additionally, low percentages of organic agriculture and reduced crop diversity further contribute to these low environmental dimension values (Fig. 5). The Cerrado biome was the most deforested biome in Brazil in 2023, totaling 1.11 million hectares (MapBiomas, 2024). The Pantanal, the biome with the lowest environmental dimension in Brazil (Fig. 4), has suffered extensive damage, with over 372,000 hectares destroyed by fires in 2024 alone, and significant impacts on native wildlife (INPE, 2024). Fires in the Pantanal between January 2020 and 2022 may have affected at least 65 million native vertebrates and 4 billion invertebrates, based on known species densities (Berlinck et al., 2022). To improve the environmental indicators in the Cerrado, Pantanal and elsewhere in Brazil, sustainability measures should include tax incentives for environmental services, expansion of protected areas, and promotion of green infrastructure technologies. Effective wildfire management requires continuous fire risk monitoring, strategically located firefighter brigades, community education on fire management, strict enforcement of fire-use policies, and wildlife rescue and rehabilitation centers. These strategies are essential for harmonizing economic development with biodiversity conservation and traditional practices in the Pantanal (Berlinck et al., 2022).

Lower environmental dimension values are observed in the mountainous region (known in Portuguese as *"Mares de Morro"*), which includes, among others, the states of Rio de Janeiro, Espírito Santo, and parts of Santa Catarina and Paraná (Fig. 3). This region, part of the Atlantic Forest biome, has experienced the replacement of the native Atlantic Forest with agricultural crops and pastures (Ramos et al., 2022). de Lima et al. (2020) estimate that deforestation in the remaining Atlantic Forest from 1985 to 2017 equates to a loss of 55−70 thousand km^2 of forests, which corresponds to a financial loss of US$2.3 − 2.6 billion in carbon credits. The combination of a lack of sustainable agricultural practices, heavily undulating terrain, and torrential rains results in high soil erosion (Burak et al., 2022). Consequently, this has led to reduced environmental dimension values in municipalities within this region (Fig. 3). A recent study suggests that traditional pasture management practices in the Atlantic Rainforest need to be reconsidered (Rocha Junior et al., 2017). To mitigate soil degradation in this region, farmers should adopt edaphic practices such as applying lime and fertilizers to improve pasture growth and soil cover, as well as techniques to increase soil roughness and enhance its water and nutrient retention in the hilly areas of the Brazilian Atlantic Rainforest biome (Ali and Ali, 2023).

Regarding the economic dimension, we observed that, in general, in all other Brazilian biomes, the commercial openness, rural credit access, and agricultural economic income indicators also show the lowest values compared to all other economic indicators (Fig. 5). It is important to note that we utilized a previously developed approach (X. Zhang et al., 2021) where commercial openness activity reflects the region's capacity to export agricultural products, an important factor for local sustainability, which is not necessarily accompanied by a reduction in under-nourished populations in many countries (X. Zhang et al., 2021). Often, even if a region is a strong exporter of agricultural products and generates significant economic income, it may not necessarily have an adequate land distribution (which is highlighted here as one of the main limiting factors for the social dimension among Brazilian biomes in Fig. 5), leading to a concentration of wealth generated by agricultural exports. For example, a recent study shows that 0.01 % of the country's richest people experienced a 248 % increase in their income from rural activities over the last five years in Brazil (Gobetti, 2024). Rural credit access potentially helps farmers and agribusinesses reduce costs, increase their innovative capacities, and reduce food losses along the supply chain, making it a crucial economic sustainability indicator (X. Zhang et al., 2021). However, we indicate that this is one of the main limiting factors for a higher economic sustainability in Brazil (Fig. 5). It is also worth noting that this credit is often used to finance the purchase of agricultural inputs rather than acquiring new land, which negatively impacts the social dimension of land distribution. To improve the current situation, it is essential to enhance land distribution policies to promote more equitable land allocation and address wealth concentration, reflecting Brazil's progress in reducing deforestation while increasing agricultural economical income. Expanding the utilization of rural credit to include land acquisition and sustainable farming practices is crucial, given the complexities and inefficiencies of the current rural credit system. Additionally, providing targeted support for smallholder farmers can improve their access to resources and technology, thereby enhancing productivity and sustainability. This is supported by evidence showing that rural credit positively impacts land and labor productivity (P. Souza et al., 2020). Lastly, developing comprehensive data collection and monitoring systems for sustainability will enhance the understanding of how agricultural exports, credit access, and all other relevant indicators impact economic, environmental, and social sustainability.

This study presents the Agricultural Sustainability Index across Brazil, highlighting significant regional variations. The analysis indicates higher sustainability in the South and Southeast, while the North and Northeast face major economic and social constraints. Unlike existing methods, which often focus solely on individual aspects of sustainability (Marion et al., 2022; Moreno García et al., 2021), the ASI developed for this study integrates environmental, social, and economic dimensions into a composite index. This integration allows for a more holistic view of sustainability at the municipal level, a scale previously underexplored in sustainability assessments (Hayati et al., 2011; Wood et al., 2015; X. Zhang et al., 2021).

One of the main advantages of the ASI over other indices is its ability to capture spatial variability within a large and diverse country like Brazil. Most existing indices apply a uniform standard across all regions, which can obscure local challenges and opportunities (X. Zhang et al., 2021). In contrast, the ASI reflects the specific conditions and needs of each municipality, thus providing more targeted insights for policy and decision-making. Furthermore, the ASI incorporates data on economic openness and rural credit access which are often neglected in other sustainability indices yet are crucial for understanding the economic drivers that impact sustainability (Allouche, 2011; Safanelli et al., 2023).

Future research should refine or expand the indicators used, particularly those related to agricultural trade openness, rural credit access, and land distribution, and incorporate dynamic factors such as climate change and technological advancements. Additionally, it is crucial that future studies assess the weight assignment in calculating the ASI. Although this study adopts an equal-weight approach for all indicators, the actual impact of different dimensions on agricultural sustainability may vary significantly. The importance of each indicator may differ according to specific regional conditions; therefore, the weighting of each indicator to compose the ASI should be carefully evaluated by each study according to its specific objectives (i.e. studies and policies with a greater focus on the environment may assign higher weights to environmental indices). Future research could perform a spatial sensitivity analysis, exploring how changes in the weight of each indicator affect the spatial distribution and the values of the ASI. Similarly, regression analyses could be employed to identify the spatial and temporal correlations between indicators, revealing interconnected impacts whereby policies targeting one indicator could also affect others. This would provide a better understanding of regional dynamics and facilitate the implementation of more effective and locally adapted policies.

The results of our study highlight the need for tailored policy interventions to enhance agricultural sustainability in Brazil. In the economically and socially constrained North, enhancing infrastructure and integrating digital technologies such as satellite imaging, indoor controlled vertical farming and artificial intelligence improve production efficiencies (Asseng et al., 2020; Asseng and Asche, 2019; Lakshmi and Corbett, 2020). In the climatically challenging Northeast, policies should bolster rural credit access to foster the adoption of water-efficient technologies and digital weather forecasting tools (Nóia Júnior et al., 2024; Zachow et al., 2023), aiding in climate adaptation. Meanwhile, South and Southeast of Brazil, the focus should be on implementing cutting-edge technologies such as blockchain, IoT, and AI analytics to improve supply chain transparency, monitor crop health (von Bloh et al., 2023), and optimize resource use (Asseng and Asche, 2019). These region-specific strategies may ensure the sector's competitiveness, and foster economic, environmental, and social sustainability across Brazil.

To improve sustainability, policymakers need to adopt targeted strategies for specific regional challenges, such as infrastructure deficits in the North and Northeast and soil degradation in the Atlantic Forest biome. Emphasizing integrated approaches that balance economic, social, and environmental goals is essential, including reforms in land distribution and enhanced rural credit access. Engaging stakeholders and investing in sustainable agricultural practices will foster a more resilient and balanced sector, aligning development objectives with conservation goals.

5. Conclusion

This study has developed and applied the Agricultural Sustainability Index (ASI) to quantitatively evaluate the sustainability of agricultural practices across Brazil's diverse municipalities, providing a detailed examination of regional disparities and associated challenges. The ASI encompasses environmental, social, and economic dimensions, offering a holistic evaluation of sustainability at a municipal level. It demonstrates that while some areas, such as the South and Southeast, achieve higher sustainability scores, regions like the North and Northeast are impeded by significant socio-economic limitations. Our results advance the discussion on sustainable agriculture and provide key insights for policy development in Brazil.

CRediT authorship contribution statement

Bruno Fardim Christo: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Gabriel Akira Andrade Okawati:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization. **Daniel M. de Vasconcellos:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **Jorge Tadeu Fim Rosas:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Marcela Almeida de Araujo:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Durval Dourado-Neto:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization. **Rogério de S. Nóia-Júnior:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envc.2025.101133.

Data availability

Data will be made available on request.

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