frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 25 June 2025
DOI 10.3389/fsufs.2025.1518747

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OPEN ACCESS

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RECEIVED 28 October 2024
ACCEPTED 30 May 2025
PUBLISHED 25 June 2025

CITATION
dos Reis JC, Kamoi MYT, Tanure TMdP, Rodrigues MI, Etienne JJD, Valentim JF, Pereira MA and Wruck FdJ (2025) Integrated crop-livestock-forest systems: a path to improved agro-economic performance in the Brazilian Amazon and Cerrado. *Front. Sustain. Food Syst.* 9:1518747. doi: 10.3389/fsufs.2025.1518747

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Integrated crop-livestock-forest systems: a path to improved agro-economic performance in the Brazilian Amazon and Cerrado

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Diversified sustainable agricultural systems, such as integrated crop-livestock-forest systems (ICLFs), offer substantial potential for enhancing food production to meet the increasing global demand for agricultural goods while, simultaneously, conserving vital natural resources, including soil, water, and forests. However, a critical barrier to the widespread adoption of these sustainable systems in Brazil's Amazon and Cerrado biomes, its primary agricultural commodity-producing regions, is the lack of comprehensive economic information. This paper presents case studies that evaluate the economic performance of ICLFs compared to traditional agricultural practices in these biomes (extensive livestock and large-scale cropping systems). Additionally, we employ an economic impact analysis using an input–output matrix approach to assess the economic benefits associated with ICLF adoption. The findings indicate that integrated systems exhibit superior economic performance, particularly over the long-term, as evidenced by more favorable viability indicators, such as higher internal rates of return and profitability indexes. In the Cerrado biome, the gross profit per hectare is up to USD 200 higher compared to traditional livestock and USD 26.5 higher than crop farming. While these systems necessitate higher initial investments per hectare, they provide shorter payback periods and increased profitability. Furthermore, it is observed that an ICLF expansion over degraded pasture in Brazil would promote highly positive economic impacts. Approximately 61,000 and 50,000 additional jobs would be generated in the Cerrado and Amazon biomes, respectively. In terms of production value, it would be up to USD 19.7 billion higher in the Cerrado biome and USD 16 billion higher in the Amazon biome compared to traditional livestock farming. These findings reinforce the role of public policies aimed at promoting sustainable agriculture and achieving the targets established in the Brazilian Low-Carbon Agriculture Plan.

KEYWORDS

sustainable intensification, Amazon, Cerrado, integrated crop-livestock-forest, Input output analysis, public policies

1 Introduction

The low-carbon sustainable intensification of agricultural systems constitutes a strategic framework for optimizing resource utilization while, simultaneously, enhancing productivity, diversifying production, and preserving land for conservation and ecological restoration (Franzluebbers, 2007; Balbino et al., 2011; Lemaire et al., 2014; Thornton and Herrero, 2014). Moreover, diversified and sustainable agricultural systems present a promising and viable approach to strengthening household food security, increasing income, and enhancing resilience to both market fluctuations and climate-related risks (Garrett et al., 2017; Thornton and Herrero, 2014; Szymczak et al., 2020).

The adoption of sustainable agricultural systems in the Brazilian Amazon and Cerrado biomes holds global significance due to the region's substantial production of commodities, particularly grains and beef cattle, and the vital ecosystem services it provides (Andersen et al., 2002; Malhi et al., 2008; Coe et al., 2013). Moreover, agriculture has played a key role in generating trade surpluses for Brazil in recent years (Freitas, 2016; MAPA, 2023). However, it is also the primary driver of deforestation in these regions and a major contributor to greenhouse gas emissions, accounting for 31% of Brazil's direct emissions in 2020 (SIRENE, 2023).

Brazil has implemented a series of public policies aimed at promoting the adoption of sustainable agricultural systems in the Cerrado and Amazon regions. Key initiatives include the "Sectoral Climate Change Mitigation and Adaptation Plan for the Consolidation of a Low Carbon Economy in Agriculture" (ABC Plan and ABC + Plan) and the country's ratification of the Paris Agreement in 2015 (Brasil, 2010, 2012, 2016, 2021). These policies explicitly commit to expanding Integrated Crop-Livestock-Forest systems (ICLFs) as a strategy to enhance agricultural sustainability. The established target is to increase the current ICLF area from 17 million hectares to almost 30 million hectares by 2030, thereby reinforcing Brazil's efforts to mitigate climate change and promote sustainable land use practices.

The ICLFs are a Brazilian technology developed at the beginning of the 1990s to promote sustainable agricultural intensification and improve resource efficiency, especially in the Cerrado and Amazon biomes (Kluthcouski et al., 2003; Macedo, 2009; Balbino et al., 2011). The initial focus of integrated systems was to associate soil conservation practices, such as no-tillage, for protection and reduction of soil loss, nutrient leaching, and improving efficiency of use of lime and fertilizers used to adjust soil fertility to achieve high productivity of crops such as soy, corn and cotton. At the same time, use of no-tillage practices contributes to increase soil organic matter (carbon stock) and, as a consequence, enhancing soil quality and its productivity, particularly in Cerrado and Amazon regions, areas characterized by fragile soils and with limited fertility to support continuous production of large-scale commercial crops (Kluthcouski et al., 2003; Vilela et al., 2011; Salton et al., 2014). Furthermore, integrated systems can be used to recover degraded pasture areas by using the residual fertility from crops to restore soil quality and the additional revenues to fund further system improvements (Kluthcouski et al., 2003; de Oliveira Silva et al., 2017; Salton et al., 2014).

The main objective of ICLFs is to improve agricultural sustainability through the integration of various production activities in the same area by intercropping and rotations that aim to obtain synergies among agroecosystem components (Nair, 1991; Wilkins, 2008; Balbino et al., 2011). Integrated crop-livestock systems (ICLs) are substantially more common than integrated crop-livestock-forest systems in Brazil, accounting for 83% of the systems (Rede ILPF, 2017).

Despite their considerable potential, empirical data on the economic performance of sustainable agricultural systems in Brazil remain scarce. Furthermore, no comprehensive and publicly accessible database exists to facilitate systematic analysis. Such information is crucial for farmers and policymakers to assess these systems as viable alternatives to the dominant large-scale monoculture and extensive livestock production prevalent in the Brazilian Amazon and Cerrado regions. The absence of economic data represents a major constraint to the broader adoption of sustainable agricultural practices (Cortner et al., 2019; dos Reis et al., 2023; Tanure et al., 2024).

To advance over this gap on the sustainable agricultural systems research agenda and to assess whether integrated systems are economically better strategies for improving the economic performance of the agricultural sector in Brazilian Amazon and Cerrado, we present findings from two case studies evaluating the economic performance of Integrated Crop-Livestock-Forest systems, one in the Amazon biome and the other in the Cerrado. Moreover, these results are compared with the economic performance of a typical large-scale cropping system (soybean-corn) and a traditional extensive livestock system, the two most representative agricultural practices in Brazilian agriculture-forest frontier. Additionally, we provide an innovative economic impact analysis of the widespread adoption of Integrated Crop-Livestock-Forest systems in the Amazon and Cerrado regions, utilizing an input–output matrix approach.

2 Materials and methods

Data on typical large-scale crop and extensive livestock systems were provided by the Mato Grosso Institute of Agricultural Economics (IMEA). IMEA conducts an annual economic survey of key agricultural commodities in Mato Grosso, including soybean, corn, cotton, and beef cattle. These surveys, which involve focus groups with farmers and representatives from agricultural organizations, collect detailed information on costs, revenues, productivity, investments, farm size, management practices, labor, and infrastructure (IMEA 2024a). For integrated systems, we used economic data from the Technological and Economic Reference Units Project (TERU Project) (Farias Neto et al., 2019), a collaborative initiative between the Brazilian Agricultural Research Corporation (EMBRAPA) and IMEA, implemented in 2014 (Table 1 and Figure 1).

TABLE 1 Farm descriptions.

Productive systems	Production area (ha)	Period	Investment. ha^{-1} (USD)
ICLF-C (Cerrado)	600	2011–2017	1,024.30
ICLF-A (Amazon)	1,000	2008–2016	430.52
Livestock (Cerrado)	1,000	2016–2021	369.51
Crop (Cerrado)	600	2011–2017	1,078.89

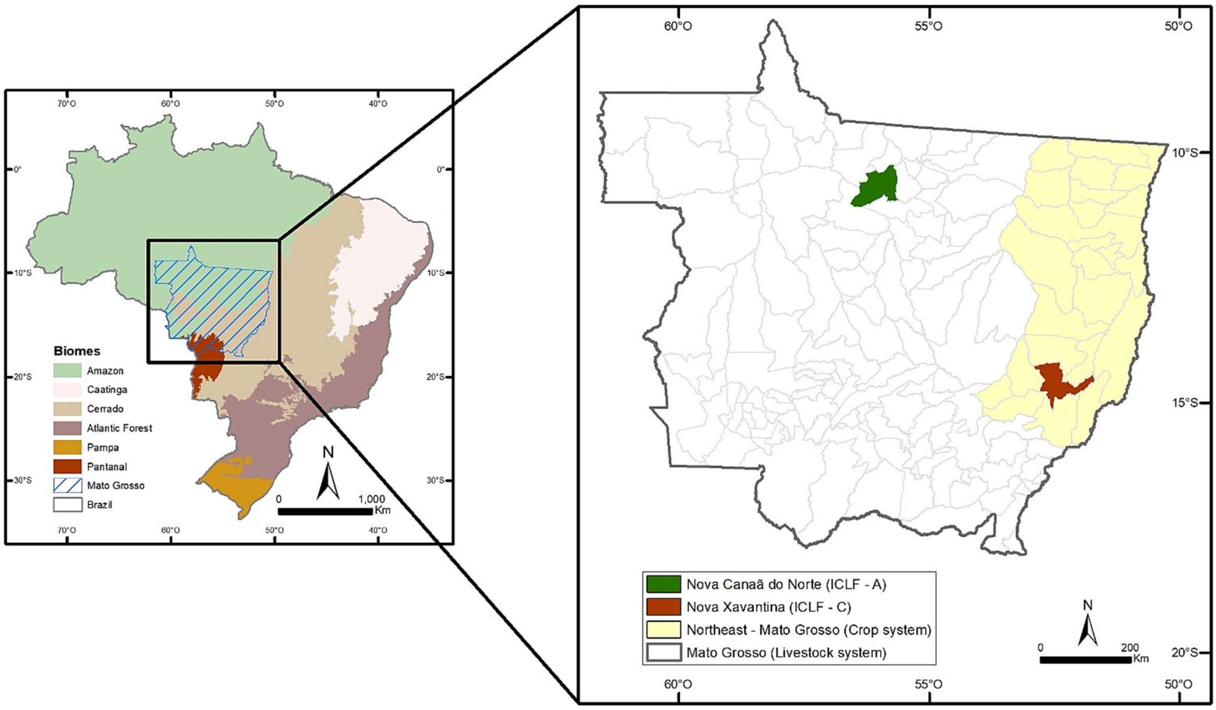

FIGURE 1
Case studies.

2.1 Systems description

The typical crop farm is defined by an intensive and specialized production system with two crop seasons per year: soybean (*Glycine max*) (October–February) and corn (*Zea mays*) (February–June/July), 600 ha of cultivated land area, and an initial investment of 1,078.89 USD.ha^{-1}. We excluded land acquisition cost, since this analysis is focused on assessing the production activity performed, and because land prices have risen sharply after 2008, following China's consolidation as the main Brazilian agricultural commodities importer. We chose the northeast region of Mato Grosso to define the typical crop farm since it concentrates 20% of soybean and 15% of corn production (IMEA, 2024a). Crop farms use a high level of technology in all production stages with high investment in infrastructure and inputs.

In contrast, the typical livestock farm is characterized by traditional cattle ranches with a low level of technology, low productivity and large area, and approximately 1,000 ha dedicated to rearing and fattening. We chose livestock data from the state level since it is the most representative of extensive cattle ranch farms. Typical cattle ranchers do not invest in sophisticated infrastructure, only basic equipment, such as corrals, troughs and fences, and do not invest in pasture management. Hence, this production system displayed the lowest investment value: 369.51 USD.ha^{-1}. The most common cattle breed is the Zebu (*Bos taurus indicus*), with an initial body weight of 330 ± 7.6 kg and a stocking rating of 0.84 head.ha^{-1}. The pasture is *Urochloa brizantha* cv. Marandu.

The integrated crop-livestock-forest system for the Amazon biome (ICLF-A) is located in the municipality of Nova Canaã do Norte, in the north region of Mato Grosso and in the Amazon Legal region, a new frontier for large-scale crop systems in the state and a region traditionally used for livestock. The ICLF system was implemented in 2008 as a strategy to recovery degraded pasture. The cultivated land area was 1,000 ha, and the initial investment was 430.52 USD.ha^{-1}. Eucalyptus (*Eucalyptus grancam* - hybrid) was planted in single-row (2 m intra-row and 20 m inter-row), resulting in a density of 125 trees ha^{-1}. Rice (*Oryza sativa*) and soybeans (*Glycine max*) were planted between the rows during three first agricultural years. From the fourth year onward, brachiaria (*Urochloa brizantha* cv. Marandu) was seeded and maintained in the area as forage for the animals, taking advantage of residual fertility from crop rotation and promoting high-quality pastures over subsequent years. The livestock system is managed to rear and fatten Zebu cattle (*Bos taurus indicus*) and Galician Blond (*Bos taurus taurus*).

The integrated crop-livestock-forest system for the Cerrado biome (ICLF-C) is located in the municipality of Nova Xavantina in northeast Mato Grosso, a traditional livestock region. The system was established in 2010 also as a strategy to reclaim degraded pastures, and the forest was cultivated for farmers' own use in drying soybeans (*Glycine max*), as well as in livestock infrastructure such as fences, troughs and corrals and for timber commercialization. The cultivated land area was 600 ha, and the initial investment was 1,024.30 USD.ha^{-1}. The land use management adopted was as following: over the first 4 years, the area was cultivated with soybean (*Glycine max*) and eucalyptus (*Eucalyptus urograndis*, clone H13) planted in triple-lines with an intra-row spacing of 2 m and an inter-row spacing of 3 m, with 23 m strips between each set of triple rows resulting in a density of 582 trees ha^{-1}. In 2013, pasture (*Urochloa ruziziensis*) was established after the soybean (*Glycine max*) harvest, and livestock activity remained until the forest was cut in 2017. The livestock system is managed for rearing and fattening, and the cattle breed is Zebu cattle (*Bos taurus indicus*), with an initial body weight of 251 ± 5.8 kg and a stoking rating of 4 head.ha^{-1}.

2.2 Economic analysis

We implement a comprehensive economic viability analysis to assess the performance of farming systems. This approach is well-established in economic literature for evaluating investment decisions (Gitman and Zutter, 2014). Using time series data for each farm, we conducted a long-term economic viability assessment. For integrated systems, the analysis considered the entire farm as a single unit, focusing on the synergies and complementarities of these systems, rather than comparing individual products or subsystems (Bell and Moore, 2012; Wilkins, 2008).

We employed five key indicators to assess the economic viability and potential economic returns of agricultural systems: (i) annual net present value (NPVA), (ii) internal rate of return (IRR), (iii) return on investment (ROI), (iv) profitability index (PI), and (v) payback (Gitman and Zutter, 2014) alongside traditional metrics as gross revenue, cost production, gross profit. The Gross revenue is determined by multiplying the production quantity by the marketing price. The production cost includes the direct inputs and services utilized in the manufacturing of a product unit, excluding administrative and financial expenses. Gross profit is the residual value obtained by subtracting the production cost from the gross revenue. The discounted cash flow included production costs, revenues, interest deductions, taxes, labor expenses, depreciation, and net investment in assets. All data were updated using the official inflation index in Brazil, the Broad Consumer Price Index (IPCA), provided by the Brazilian Institute of Geography and Statistics (IBGE) for 2023. We used the Weighted Average Cost of Capital (WACC) approach as a discounted rate to adjust the investment opportunity cost, based on the farmers' profile, to the economic risk of the activity being evaluated (Gitman and Zutter, 2014; Lapponi, 2013). All monetary values were expressed in dollars (USD).

2.3 Economic impact analysis

Regarding the potential for recovering degraded pasture areas through the adoption of ICLFs, we analyzed the prospective economic impacts of their expansion on Amazon and Cerrado regions. This analysis utilized data from the case study described in Section 2.1 and information on degraded pasture areas within these biomes. Brazilian pastures exhibit significant diversity in types and quality vary. According to MapBiomas (2024), the Cerrado biome contains approximately 14 million hectares of low-vigor pastures and 20.8 million hectares of medium-vigor pastures, while the Amazon biome holds around 8.5 million hectares of low-vigor and 22.2 million hectares of medium-vigor pastures, all suitable for restoration. Figure 2 illustrates the spatial distribution of pastures in Brazil, categorized by quality in the Cerrado and Amazon biomes.

The impact analysis involves expanding ICLFs alongside traditional systems (typical extensive livestock and typical large-scale crop - soybean/corn) in medium-vigor pasture regions. These areas, while already productive, offer significant potential for improvement through agricultural sustainable intensification, such adopting ICLFs. Given their intermediate level of degradation, the restoration costs are relatively lower than those from low-vigor pastures, making them ideal for initial recovery efforts. The exercise targets the recovering of 20.8 million hectares of medium-vigor pastures in the Cerrado biome and 22.2 million hectares in the Amazon biome.

The economic impact projections from expanding ICLFs adoption on medium-vigor pasture areas in Amazon and Cerrado were carried out using an Input/Output Model (I/OM). This approach was based on the most recent Input–Output Matrix for Brazilian economy (IBGE, 2018), referring to the year 2015, which captures intersectoral relationships and the monetary flows of production and demand within the Brazilian economy. While biome-specific I/O matrices would offer more precise projections, the national matrix was used due to the absence of regionally representative models.

The Input/Output Model (I/OM) represents the national productive structure and its interrelationships, which can be described using a system of simultaneous equations (Miller and Blair, 2009). The mathematical framework of an input–output system consists of a set of n linear equations, with n unknowns, expressed in matrix form using the following matrix notation:

$$\mathrm{x} = \left(I - A\right)^{-1} f = Lf \quad (1)$$

where X is the sectoral production vector, A is the technical coefficient matrix, which represents the intersectoral relationship in terms of purchases and sales of inputs, f is the final demand vector of the products of each sector and $(I - A)^{-1} = Lf$ is known as the Leontief inverse matrix, which quantifies the direct and indirect input requirements necessary to meet a unit of final demand in the economy (Equation 1).

Thus, changes in the final demand vector f, such as the increase in sales levels, represented by the gross revenues of the ICLF, livestock, and agriculture activities, following the expansion into degraded pasture, induce a production increase in the entire production throughout the entire supply chain. This response is modeled by the Leontief inverse matrix $(I - A)^{-1} = Lf$, which captures the direct and indirect effects across economy sectors. As the analyzed sectors expand, they demand more inputs from other sectors, thereby stimulating production increases in those related sectors as well. For instance, the increase in production promotes the increase of income, through the payment of wages. With higher income, there is an increase in the level of consumption by households, a component of the final demand, but which can be treated as an endogenous variable in the model. Therefore, the model captures the direct, indirect and induced effects of the production process. Such effects are expressed by the multipliers of production, income, employment and value-added, offering a comprehensive view of the economic effects.[1]

Miller and Blair (2009) argue that value added is the most effective measure of a sector's contribution to the economy, as it reflects the value created by that sector through production activities. Specifically, value added is defined as the difference between the total value of production and the cost of intermediate inputs.

1 Detailed information about multipliers is on Supplementary material.

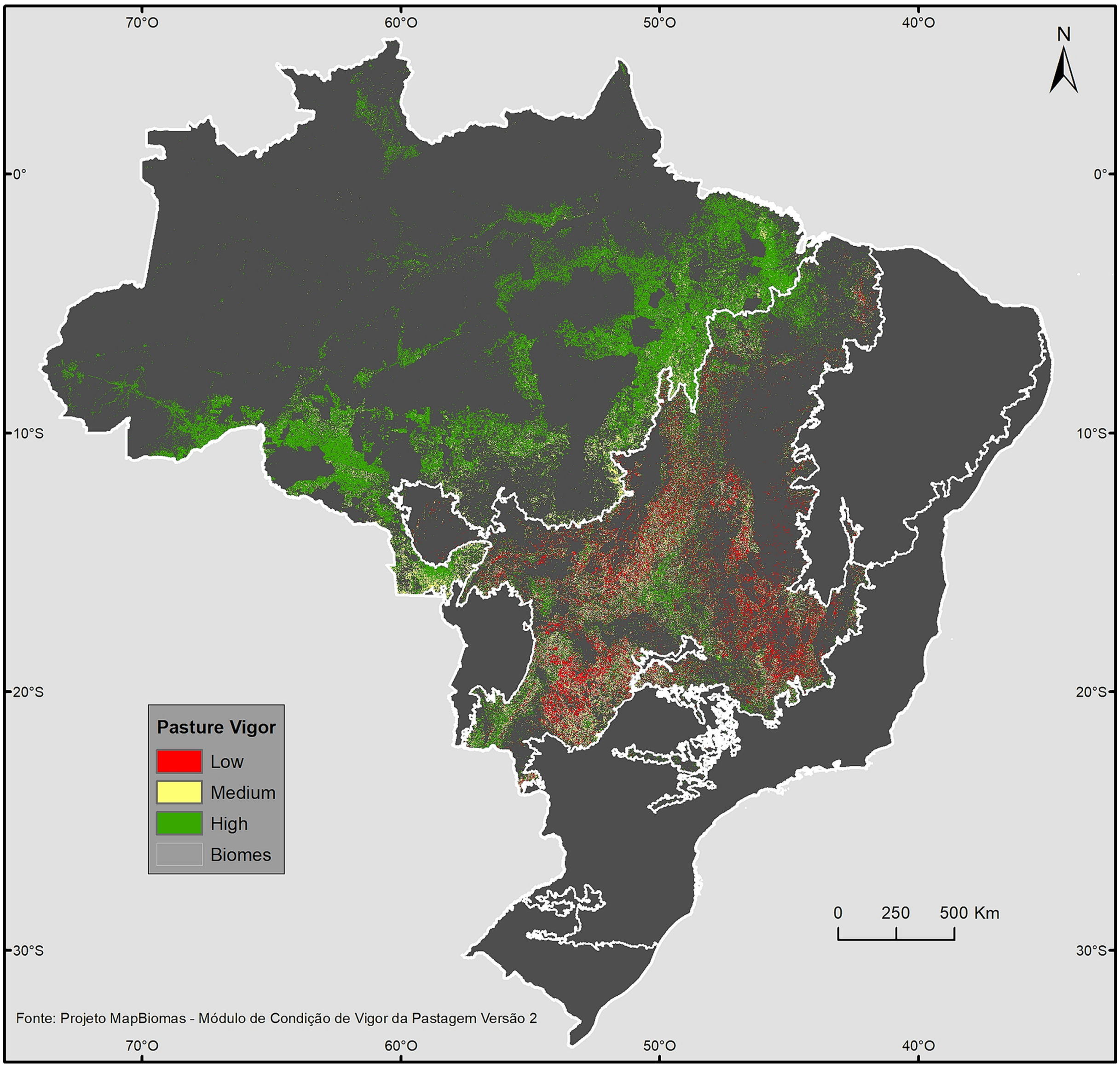

FIGURE 2
Pasture areas in the Cerrado and Amazon biomes.

3 Results

3.1 Economic results

The annual economic results underscore the significant impact of market prices on the performance of agricultural system (Tables 2, 3). Typical crop farm demonstrated high average production levels (soybean: 3,051.60 kg.ha^{-1}.year^{-1}; corn: 5,094.60 kg. ha^{-1}.year^{-1}), reflecting the benefits of intensive external input use, particularly fertilizers, pesticides, and high-tech seeds. Consequently, this farms presented higher average production costs (594.80 USD. ha^{-1}.year^{-1}). However, due to rising global agricultural commodity prices, especially for soybeans, this farm achieved high average gross revenue (933.13 USD.ha^{-1}.year^{-1}) and substantial average gross profit (338.33 USD.ha^{-1}.year^{-1}), which was double that of typical livestock farm.

In contrast, typical livestock farm exhibited low productivity (188.85 kg ha^{-1}.year^{-1}) and poor gross profit over the years, averaging 164.94 USD.ha^{-1}.year^{-1} (Table 3). However, the substantial increase in beef cattle prices after 2019 significantly boosted economic performance. For example, gross profit in 2020 was 135% higher than in the previous year and 3.75 times greater than in 2015, reflecting an average annual growth rate of 30% over 5 years. Annual gross revenue showed even more impressive results, with a growth rate of 34%. By 2020, typical livestock farms reached an average gross revenue of 1,229.37 USD.ha^{-1}.year^{-1}, comparable to that of large-scale crop farm.

Integrated crop-livestock-forest system in the Amazon biome (ICLF-A) achieved slightly higher annual crop yields than large-scale crop farm, producing (soybean: 3,243.00 kg.ha^{-1}.year^{-1}; and rice: 3,480.00 kg.ha^{-1}.year^{-1}). This system also recorded the highest livestock productivity (570.45 kg ha^{-1}.year^{-1}), three times that of typical livestock farms, and produced 3.91 m^3.ha^{-1}.year^{-1} of eucalyptus timber. This

TABLE 2 Average production levels of integrated crop-livestock-forest systems and large-scale cropping system in the Amazon and Cerrado biomes*.

Production System	Beef cattle (kg.ha^{-1}.year^{-1})	Soybean (kg.ha^{-1} year^{-1})	Rice (kg.ha^{-1} year^{-1})	Corn (kg.ha^{-1} year^{-1})	Wood (m^3.ha^{-1} year^{-1})
ICLF-C (Cerrado)	243.30	2,646.00	-	-	27,37
ICLF-A (Amazon)	570.45	3,243.00	3,480.00	-	3,91
Livestock (Cerrado)	188.85	-	-	-	-
Crop (Cerrado)	-	3,051.60	-	5,094.60	-

* Values for 2023.

diversified output contributed to substantial gross revenue (993.10 USD.ha^{-1}.year^{-1}) and a notable average annual gross revenue growth rate of 41% (Table 3). However, high production costs negatively impacted gross profit. Factors such as high transportation costs, rising input prices, particularly for calves, and limited regional demand for planted timber constrained its economic performance. The limited demand is largely due to the absence of key industrial facilities, such as pulp and paper mills, steel production plants, biomass energy production facilities, and furniture manufacturing industries.

Integrated crop-livestock-forest system in the Cerrado biome (ICLF-C) demonstrated the strongest economic performance, achieving the highest gross profit (364.87 USD.ha^{-1}.year^{-1}), which was 8% higher than that of large-scale crop farm and double that of typical livestock farm. This success is primarily due to the exceptional performance of the forest component and an effective livestock marketing strategy. The farm's long specialization and expertise in beef cattle production and established market connections contribute to its success. Additionally, its strategic location in northeastern Mato Grosso, near Cuiabá and the Goiás border, provides significant logistical advantages. This location also enhances opportunities for timber marketing, a key factor in maximizing returns from this product.

TABLE 3 Average yearly economic results of integrated crop-livestock-forest systems and large-scale cropping system in the Amazon and Cerrado biomes.

Production system	Gross revenue (USD.ha^{-1})*	Production cost (USD. ha^{-1})*	Gross profit (USD.ha^{-1})*
ICLF – C (Cerrado)	1,131.46	766.59	364.87
ICLF – A (Amazon)	993.10	858.77	134.33
Livestock (Cerrado)	584.32	419.38	164.94
Crop (Cerrado)	933.13	594.80	338.33

* Values update for 2023 prices (1 USD = 5.22 REAIS).

TABLE 4 Economic viability indicators: Weighted Average Cost of Capital (WACC), Annual Net Present Value (NPVA), Return on Investment (ROI) of integrated crop-livestock-forest systems in the Amazon and Cerrado biomes.

Indicators*	ICLF-C (Cerrado)	ICLF-A (Amazon)	Crop	Livestock
WACC	8.02%	7.88%	8.02%	8.30%
NPVA	87.44	31.95	6.62	2.10
IRR	15.78%	13.40%	8.81%	8.85%
ROI	12.93%	11.68%	8.50%	8.70%
Profitability index	1.36	1.32	1.03	1.02
Payback	7	8	7	5

* 2023 prices (1 USD = 5.22 REAIS).

3.2 Economic viability indicators

The economic viability indicators highlight the superior long-term performance of integrated systems (Table 4). The integrated crop-livestock-forest system in the Cerrado biome (ICLF-C) achieved the highest annual net present value per hectare (NPVA.ha^{-1}) of 87.44 USD and the highest profitability index, 1.36, indicating strong economic attractiveness. The NPVA, in our approach an estimative for Net Profit, for ICLF-C is 13 times higher than that of large-scale crop farm and 41 times greater than typical livestock farm. This significant difference from typical livestock is attributed to the integrated system's ability to take advantage of rising beef cattle prices and its strategic land-use practices, which ensure high-quality pastures during the dry season (May to September), thereby reducing the dependence on costly supplementary feed. However, due to its substantial initial investment (1,024.30 USD.ha^{-1}), this system has a longer payback period of 7 years.

The integrated crop-livestock-forest system for Amazon biome (ICLF-A) demonstrated a return on investment (ROI) and profitability index comparable to that of the integrated crop-livestock-forest system in the Cerrado biome (ICLF-C). Despite relatively lower annual gross profit, ICLF-A achieved an ROI 48% higher and an internal rate of return (IRR) 51% higher than large-scale crop farm. The significant difference between ICLF-A's IRR and the weighted average cost of capital (WACC) indicates its superior profitability as an investment. For example, the profitability index shows that every dollar invested in ICLF-A generated 32 cents in profit, compared to just 3 cents for large-scale crop farm and 2 cents for typical livestock farm. However, despite requiring an initial investment 2.4 times lower than ICLF-C, ICLF-A had a longer payback period of 8 years. These findings underscore the critical role of logistics and market connections in determining agricultural economic performance.

Compared to the most profitable integrated system (ICLF-C), the large-scale crop farm exhibited a 35% lower return on investment (ROI), despite similar investment levels (crop farm: 1,078.89 USD.ha^{-1}.year^{-1} and ICLF-C: 1,024.30 USD.ha^{-1}.year^{-1}). Although large-scale crop farm achieved higher gross profit, substantial administrative and financial expenses undermined their overall economic performance. This challenge is reflected in the crop farm's low profitability index and the minimal difference between its internal rate of return (IRR) and the weighted average cost of capital (WACC). These results highlight the high economic and market risks faced by

TABLE 5 Economic projections of costs and benefits of pasture recovery in the Cerrado and Amazon biomes within typical ICLF-C, ICLF-A, livestock and crop production.

Economic indicator	Production system			
	ICLF-A$^{\varphi}$	ICLF-C^{+}	Livestock^{+}	Annual Crop^{+}
Gross Revenue (USD)*	22.1	23.5	12.1	19.4
Production Cost (USD)*	19.1	15.9	8.7	12.3
Gross Profit (USD)*	2.9	7.6	3.4	7.0
Productivity beef cattle (Tonnes.ha^{-1})**	12.6	5.0	3.9	-
Productivity – soybean (Tonnes.ha^{-1})**	1,202.9	919.2	-	1,060.1

φ expansion over 22.2 million hectares in Amazon biome; + expansion over 20.8 million hectares in Cerrado biome * Values in billions; **Values in millions.

TABLE 6 Sectoral multipliers as indicators of performance of ICLF and typical livestock and annual cropping systems.

Multiplier	Production	Employment	Income	Gross value-added
ICLF*	2.54	9.62	0.41	1.24
Livestock	2.80	11.62	0.50	1.33
Crop	2.40	7.07	0.34	1.12

Source: Vale and Perobelli (2020).
* Multipliers refer to the aggregation of the agricultural, livestock, forestry, and fishing sectors listed in the 12×12 I/O matrix (IBGE, 2018).

large-scale crop farms, where, even in favorable pricing conditions, elevated production costs constrain economic returns.

Finally, the livestock farm exhibited the weakest economic viability indicators. The internal rate of return (IRR) was nearly equal to the weighted average cost of capital (WACC), indicating poor financial performance, as it merely generated enough revenue to sustain operations. A similar trend was observed in the profitability index, with the farm earning only two cents for every dollar invested. Additionally, the low net present value per hectare NPVA.ha^{-1} of 2.10 USD highlighted the farm's limited ability to generate net profit, thereby restricting investment in new technologies. Improving productivity and reducing operating costs, particularly supplementary feeding expenses, is crucial for livestock farmers to enhance economic performance. The relatively short payback period of 5 years can be attributed to the farm's lower investment level, 369.51 USD.ha^{-1}.

3.3 Potential economic impacts of ICLF expansion over the Cerrado and Amazon biomes

Table 5 presents projected annual financial results—gross revenue, production costs, and gross profit - as well as additional beef cattle and soybean production following the expansion of ICLFs and typical livestock and crop farms over medium-vigor pastures in the Cerrado biome. If ICLFs were implemented across all 20.8 million hectares of these pastures, they would generate 23.5 USD billion in annual gross revenue, with 15.9 USD billion in production costs, yielding a gross profit of 7.6 USD billion. This expansion would produce 5 million tons of beef cattle and 919 million tons of soybeans annually, highlighting the superior economic benefits of ICLFs compared to traditional systems. Also, ICLF's expansion over 22.2 million hectares in the Amazon biome would generate an annual gross revenue of around 22.1 USD billion. Even though the cost of production is higher, the yearly gross profit resulting from the expansion would reach 2.9 USD billion.

Table 6 presents the multipliers for production, employment, income, and gross value-added for ICLFs, livestock, and crop activities, highlighting each sector's contribution to the Brazilian economy. Since the Input–Output (I/O) matrix does not distinctly identify the ICLF sector, the agriculture sector multiplier was used as a proxy, derived from the aggregated 12×12 I/O matrix (IBGE, 2018; Vale and Perobelli, 2020), which includes agriculture, livestock, forestry, and fishing activities. In contrast, the multipliers for traditional livestock and crop systems were sourced from the more detailed 67×67 I/O matrix (IBGE, 2018; Vale and Perobelli, 2020), providing a more detailed representation of these sectors.

The production multiplier of 2.54 indicates that a 1 USD million increase in demand for ICLF activities leads to a 2.54 USD million rise in total economic output. Similarly, the employment multiplier of 9.62 suggests that a 1 USD million increase in ICLF demand creates 9.62 jobs in the economy. The income multiplier of 0.41 indicates that a 1 USD million demand increase in ICLF activities generates 0.41 USD million in additional income. Furthermore, the value-added multiplier of 1.24 shows that each 1 USD million in ICLF demand contributes 1.24 USD million to the economy's value-added. These interpretations similarly apply to the livestock and crop sectors.

The recovery of 20.8 million hectares in the Cerrado biome using ICLF systems is projected to yield 23.5 USD billion in gross revenue (Table 5). This recovery is estimated to generate 59.9 USD billion in total economic production, impacting the entire production chain and creating approximately 159,580 jobs (57,580 direct and 102,100 indirect). Also, this activity is expected to generate 9.8 USD billion in income and 29.3 USD billion in value-added. As ICLFs provide higher gross revenues than typical livestock or large-scale crop systems, their overall economic impact is expected to be significant. Expanding ICLFs across 22.2 million hectares in the Amazon biome, with a

TABLE 7 Production, employment and income projections, by type of production system in the Cerrado and Amazon biomes.

Sector/Projections	Production (USD)*	Employment	Income (USD)*	Value-added (USD)*
ICLF-C (Cerrado)	59.9	159,580.00	9.8	29.3
ICLF-A (Amazon)	56.2	149,550.00	9.1	27.4
Livestock (Cerrado)	40.2	99,540.00	6.1	16.3
Crop (Cerrado)	53.5	96,770.00	6.6	21.8

* Values in billions.

projected gross revenue of 993.10 USD per hectare (Table 3), would inject 56.2 USD billion into the Brazilian economy, creating around 53,860 direct jobs and 95,690 indirect jobs, and generating 9.1 USD billion in income and 27.4 USD billion in value-added (Table 7).

The combined expansion of ICLFs across both biomes is projected to create approximately 300,000 jobs, representing a significant 20.6% increase in formal employment within Brazil's agricultural sector. From a comparative perspective, ICLF-C would generate approximately 60,000 additional jobs, while ICLF-A would contribute 50,000 more jobs than traditional livestock farming. Moreover, this expansion is expected to lead to an 8.4% rise in agricultural value-added. Given the high level of informality in the agricultural sector, this growth is likely to absorb additional labor resources, thereby further stimulating economic growth and development.

4 Discussion

4.1 Land use strategy and location as crucial issues for improve economic results

The Integrated Crop-Livestock-Forest system in the Amazon biome (ICLF-A) is characterized by the incorporation of a single row of trees alongside high-yield livestock farming. Although its timber productivity is comparatively lower due to the reduced tree density per hectare, ICLF-A exhibits superior productivity in both beef cattle and soybean production compared to the Integrated Crop-Livestock-Forest system in the Cerrado (ICLF-C), as well as conventional livestock and large-scale monoculture cropping systems in the state of Mato Grosso. Situated in northern Mato Grosso, ICLF-A generally outperforms the northeastern region in terms of soybean productivity, a trend that can largely be attributed to the Amazon biome's higher levels of precipitation and more favorable soil conditions (INPE, 2024; IMEA, 2024b). Another crucial factor contributing to its efficiency is the strategic arrangement of trees in a single-row configuration, which minimizes shading effects and thereby prevents any significant reduction in agricultural or livestock productivity. In integrated production systems, the effective management of shaded areas is critical, as most plant species exhibit a strong dependence on sunlight for achieving optimal growth and yield (Magalhães et al., 2019).

Contrary to previous studies (dos Reis et al., 2023; dos Reis et al., 2020; Pereira, 2019) the integrated systems examined demonstrated higher production costs than the large-scale crop system. Both ICLF-A and ICLF-C involve rearing and fattening livestock systems in addition to agricultural expenses. Rearing and fattening livestock systems typically have higher costs compared to livestock breeding and full-cycle systems, primarily due to the expense of acquiring animals, particularly calves (IMEA, 2024a). Beyond animal acquisition, the largest expense was for food and supplementation, as this farm heavily invested in herd nutrition, unlike ICLF-C and the extensive livestock system. Consequently, despite generating a revenue of USD 993 USD ha^{-1} $year^{-1}$, the high production costs in ICLF-A resulted in the lowest profit among the four systems. Nonetheless, viability indicators affirm the system's economic sustainability and its competitiveness with monoculture systems.

Assessing the initial investment required for implementing agricultural systems - including expenditures on machinery, equipment, and infrastructure - reveals that the large-scale crop system and the Integrated Crop-Livestock-Forest system in the Cerrado (ICLF-C) incurred the highest costs. These findings align with those reported by Lazzarotto et al. (2010), indicating that the capital-intensive nature of these systems presents a significant financial barrier to their widespread adoption. Agricultural systems typically demand greater investments than livestock systems due to the need for machinery (Balbino et al., 2011; Pereira, 2019). Also, notably, both the large-scale crop system and ICLF-C span 600 hectares, while other systems cover 1,000 hectares, leading to a higher per-hectare investment. However, the high prices and productivity of agricultural products, driven primarily by the adoption of advanced technologies and export demand, resulted in these systems demonstrating the most favorable economic viability indicators (Table 4). Specifically, both systems exhibited shorter payback periods than ICLF-A. Payback indicates the time required to recover the initial investment, also serves as a measure of financial risk, i.e., shorter payback periods reflect lower investment risk (Lapponi, 2013).

4.2 ICLF as a strategy to recover degraded pastures in the Brazilian agricultural frontier

Projections of the economic impacts from expanding ICLF in the Amazon and Cerrado biomes highlight the superior benefits of integrated systems compared to extensive cattle ranching and large-scale monocropping. Although these projections do not account for the direct costs of restoring degraded pastures, since they assume that recovery would occur through ICLF implementation, the results in Table 5, particularly those related to value added, underscore the potential of ICLFs as an economically viable strategy to enhance agricultural production in these biomes. Moreover, ICLF offers a promising solution to the global challenge of increasing food production while preserving essential ecosystem services.

The direct costs of recovering moderately degraded pastures differ by biome. According to Carlos et al. (2022), the recovery cost is USD 266.13 ha^{-1} in the Amazon biome, slightly higher than the USD 231.92 ha^{-1} in the Cerrado. This difference is mainly due to increased transportation costs for inputs in the Amazon. That study estimates the total cost of recovering moderately degraded pastures at USD 16.7 billion in the Amazon and USD 14.4 billion in the Cerrado. Given these figures, our findings (Table 5) indicate that adopting a typical extensive livestock farming system would not generate sufficient resources to cover these recovery costs. This conclusion is consistent with other studies (Bowman et al., 2012; Oliveira et al., 2018; Pereira et al., 2024) that emphasize the difficulties traditional cattle farmers face in generating the necessary income to intensify production through new technologies.

4.3 Public policies, barriers and incentives to widespread adoption of ICLFs in Brazilian agricultural frontier

The Safra Plan, Brazil's primary credit instrument for agricultural production, allocated a budget of R$ 364.22 billion for the 2023/2024 season, with over R$ 71.6 billion earmarked for small farmers. The plan offers preferential interest rates ranging from 4 to 12.5%, providing a financial incentive relative to prevailing market rates for the agricultural sector (Brasil, 2024). However, the funding dedicated to supporting sustainable agricultural systems remains limited. For the 2023/2024 season, only R$ 5.8 billion (1.6% of the total Safra Plan budget) was allocated to the ABC Program (RenovAgro). This allocation highlights that current funding levels would be inadequate if there were a rapid increase in farmer adoption of ICLF in the Brazilian agricultural frontier.

On the other hand, bureaucracy, operational issues and lack of information about economic performance of sustainable agricultural systems explain the insufficient result of this financing line. Financial agents possess limited understanding and insufficient information regarding the economic potential of sustainable agricultural systems (Cortner et al., 2019). Moreover, they lack suitable tools to assess the financing projects. Also, due to legal requirements, particularly those related to compliance to environmental law, and the need to meet performance targets, financial agents tend to favor credit lines that are less restrictive in terms of regulatory and bureaucratic requirements and for which they have more operational familiarity (Tanure et al., 2024). Furthermore, poorly defined land tenure rights pose a significant barrier to farmers' access to credit and incentivize deforestation as a means of establishing land ownership, particularly in the Amazon biome. Funding institutions tend to connect credit operations to farmer's payment capacity, and land tenure is a usual instrument to hedge these financial operations. Therefore, the limited land use regularization tends to increase risk perception by financial institutions (Schembergue et al., 2017; Luiz et al., 2023; Silva et al., 2023). The deficiencies in operational infrastructure and lack of qualified human resources results in low efficiency and efficacy of the Brazilian land regularization system, exacerbating this problem.

Additionally, the credit offered is not aligned with the cash-flow dynamics of sustainable agricultural systems (dos Reis et al., 2023, 2020). Existing funding lines tend to prioritize annual profit outcomes over risk reduction, partly due to limited data on the financial returns of different ICLFs. These systems often display short-term negative economic results due to higher initial investments and the operational challenges faced by new adopters of more intensive and diversified production systems. Furthermore, credit lines intended to promote the adoption of sustainable agricultural systems offer insufficient grace periods for achieving productive maturity and generating positive cash flows. This misalignment between credit lines and the financial results of ICLFs limits their broader adoption.

Given the identified limitations, improvements could be considered. For instance, adjust the credit systems to embrace a longer-term perspective is crucial for supporting the transition to sustainable agricultural systems. The credit systems should consider the outcomes of farm transformation, including economic risk mitigation, reduction of negative social and environmental externalities, and enhancement of soil health and quality, in relation to the private returns from agricultural production. Alongside the provision of subsidized credit, it is imperative to tailor payments flow to align with the cash flow generation capacity inherent in sustainable agricultural systems, particularly those that include perennial plant species and livestock (Garrett et al., 2020).

Finally, the credit lines could be tailored to link payments to the quantity of produce generated, akin to the mechanism observed with the Rural Producer's Certificate (CPR). The CPR functions as a security instrument tied to a commitment to future delivery of agricultural goods, thereby providing financial support to producers throughout the production and marketing phases (Brasil, 1994). Moreover, a significant enhancement to RenovAgro credit policy would be integrating credit disbursement with the provision of specialized rural technical assistance. Such assistance is indispensable, as the requisite knowledge and skills for managing diversified agricultural systems are frequently lacking following years of specialization (Price and Hacker, 2009; Milhorance and Bursztyn, 2019). The absence of such technical support is frequently cited by farmers as a relevant barrier to the adoption of sustainable agricultural practices (Cortner et al., 2019; Tanure et al., 2024).

5 Implications for other regions and next steps

Despite the context-dependent characteristic of our findings, the potential economic performance of adopting sustainable agricultural systems in the Brazilian Amazon and Cerrado biomes can serve as a reference for other tropical regions. In these areas, sustainable soil management and carbon sequestration are essential strategies to preserve long-term agricultural productivity (Howden et al., 2007; Lobell et al., 2008; Tubiello et al., 2015). Our results also confirm the potential of integrated systems to restore degraded pastures at a relatively low cost, while generating revenue from crop and forest products. This issue is particularly relevant for regions facing pasture degradation, and where cattle ranchers have limited financial capacity (Calle et al., 2009; Campos et al., 2009; Bottazzi et al., 2014; Haile et al., 2019; Krishnamurthy et al., 2019).

Our results were derived from representative case studies in the Amazon and Cerrado biomes. However, impact analysis such as that carried out in this study could be enhanced by the use of comprehensive databases, which are currently lacking in Brazil. The difficulty of this type of analysis lies in the fact that standardized data from representative farms, collected over a long-time period, are needed. Expanding data collection efforts to include more farms is essential for advancing this research.

Furthermore, the input–output matrices provided by the IBGE present limitations since, despite being the most recent available from official sources, it refers to 2015. Although the economic impact projection exercise provides a good approximation of the economic effects of ILPF expansion in Brazil, in the next stages of the research, further disaggregation of the ICLF sector within a inter-regional input–output matrix would allow for more precise estimations of the economic impacts associated with increased demand due to the adoption of ICLFs in Amazon and Cerrado biomes.

6 Final remarks

The results presented confirm the perspective that integrated systems demonstrate better economic performance compared to traditional agricultural systems used in the Amazon and Cerrado biomes. Beyond providing data to support public policy initiatives for expanding sustainable agricultural systems in Brazil, this study holds global significance given Brazil's substantial agricultural production and its crucial role in meeting the rising global food demand. Also, the findings contribute to the broader goal of improving resource efficiency, particularly natural resource use, to reduce agriculture's environmental impact, mainly soil loss, deforestation and greenhouse gas emissions.

Furthermore, our findings demonstrated that despite the presence of public policies specifically designed to promote the adoption of sustainable agricultural systems in Brazil, both institutional and operational enhancements are necessary to enhance their effectiveness. It is crucial that, in addition to providing credit at subsidized interest rates and mandating compliance with environmental legislation to access these resources, these policies are structured to influence producers' decision-making processes. This approach should ensure that the positive externalities generated by sustainable agricultural systems are recognized by farmers as tangible benefits. Farmers, as decision-makers, must realize that their investment in more complex and diversified systems will be appropriately rewarded by society, considering the superior social benefits associated with sustainable agricultural practices in comparison to conventional crop and livestock systems.

Data availability statement

Datasets are available upon request from he corresponding author.

Author contributions

JR: Conceptualization, Funding acquisition, Investigation, Methodology, Writing – original draft. MK: Data curation, Methodology, Writing – review & editing. TT: Methodology, Writing – review & editing. MR: Writing – review & editing. JE: Writing – review & editing. JV: Conceptualization, Funding acquisition, Writing – review & editing. MP: Writing – review & editing. FW: Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This research was supported by the World Bank (PO: 7211294) and The Brazilian Agricultural Research Corporation.

Acknowledgments

The authors thank the Brazilian Agricultural Research Corporation and the World Bank for their support and funding of this research. Additionally, we acknowledge the Mato Grosso Institute of Agricultural Economics (IMEA) for providing economic data from typical large-scale crop and extensive livestock systems and Thaise Sussane de Souza Lopes (Embrapa Cerrados) for her collaboration in the development of the figures. We extend our appreciation to all colleagues and reviewers who offered valuable suggestions for enhancing the manuscript. Any remaining errors and limitations are the sole responsibility of the authors.

Conflict of interest

MK was employed by the External Consultant.

The remaining 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.

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The authors declare that no Gen AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2025.1518747/full#supplementary-material

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